Technical Series

Automation solution guide

Practical aspects of industrial control technology

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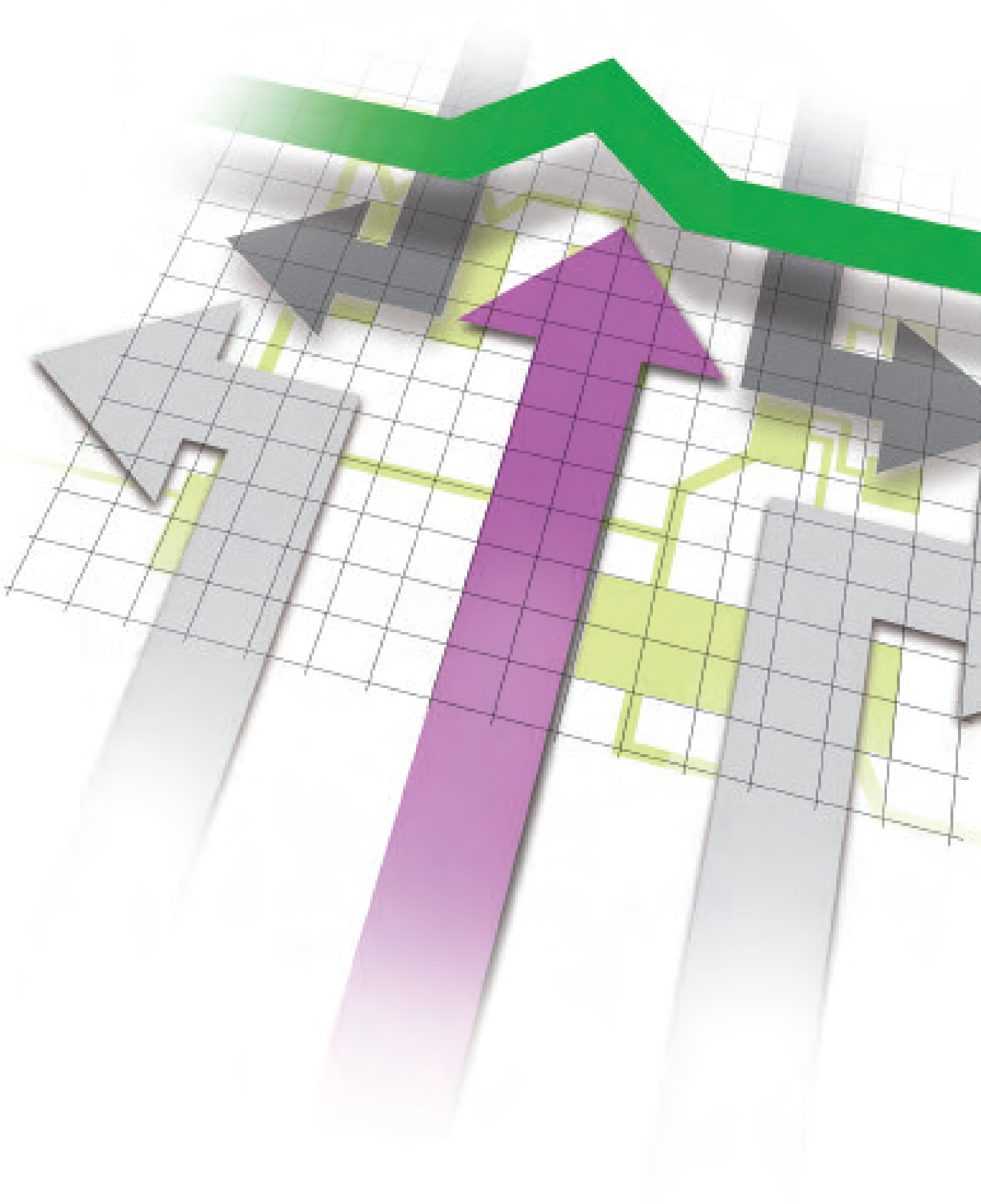

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Automation solution guide

Practical aspects of industrial automation technology

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Summary

Detailed summary

Automation solution guide

Detailed summary

1 chapter
Automation solution guide

From the needs,
choose an architecture,
then a technology
to lead to a product

1. Automation solution guide

Summary

1. Automation solution guide

1.1 Introduction
1.2 The automation equipment

1.1 Introduction

Progress in industrial automation has helped industry to increase its productivity and lower its costs. Widespread use of electronics and powerful, flexible software have given rise to more efficient modular designs and new maintenance tools.

Customer demands have also evolved substantially; competition, productivity and quality requirements compel them to adopt a process-based approach.

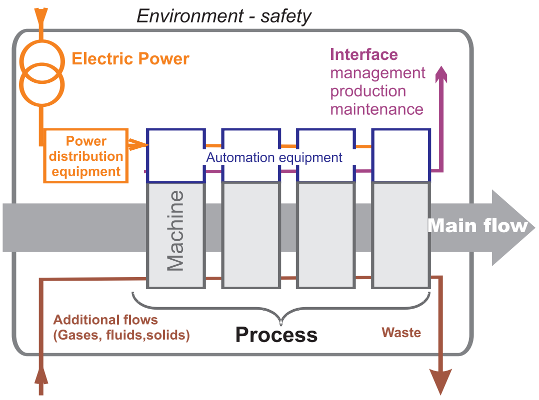


Fig. 1 Customer value creation process

Customer value creation process

The customer value creation process is based on the main flow (⇨ *Fig. 1*), i.e. core business, such as product manufacturing, transport of persons or conveyance of a load.

This process requires equipment in the form of machines and automated devices. This equipment can be confined to a single place, such as a factory, or else spread over extensive areas, as is the case for a water treatment and distribution plant.

To work smoothly, the process requires additional flows such as electricity, air, water, gas and packaging.

The process engenders waste which must be collected, transported, treated and discarded.

1.2 The automation equipment

Automation equipment features five basic functions linked by power and control systems (⇨ *Fig. 2*).

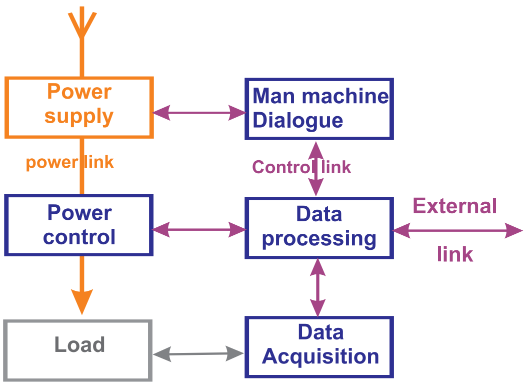


Fig. 2 Five basic functions

Five basic functions

Electrical power supply

Ensures the distribution of power to the power devicescapacity and control parts.
It must be uninterrupted and protected in compliance with electrical installation and machines standards. This function is usually ensured by a circuit-breaker or fuse holder switch.

Power control

Controls loads driven by the automatic device, either a contactor is used as a direct on line starter or an electronic controller is used to graduate the power supply of a motor or heater.

Dialogue

Commonly named man-machine interface, it is the link between the operator and the machine. It is function is to give orders and monitor the status of the process Control is made by push buttons, keyboards and touch screens and viewed through indicator lights, illuminated indicator banks and screens.

Data processing

The software, part of the automation equipment, fusing the orders given by the operator and the process status measurements is the brain of the equipment. It controls the preactuators and sends information when and where required. The automation engineer has a wide range of options, from the simplest (as a set of push buttons directly controlling a contactor), through programmable logic systems to a collaborative link between the automated devices and computers. Today as simple low-cost automated devices are available, relay diagrams have practically disappeared.

- **Data acquisition**

Data acquisition is mandatory to send feedback is to the controller or the PLC. Due to technological progress most of all physical value can now be detected or measured.

The equipment must satisfy the external constraints

- to ensure the safety of the people and the production tools,
- to respect the requirements of the environment such as the temperature, the shock protection, dust or environments aggressive.

Power links

These are the connections between parts and include cables, busbars, connectors and mechanical protection such as ducts and shields. Current values range from a few to several thousand amperes. They must be tailored to cover electrodynamic and mechanical stress as well as heat stress.

Control links

These are used to drive and control the automated devices. Conventional cabling systems with separate wires are gradually being replaced by ready-made connections with connectors and communication buses.

Lifecycle of an automated equipment

An equipment is designed, then used and maintained throughout its lifecycle. This lifecycle depends on the users and their needs, the customer's requirements and external obligations (laws, standards, etc.). The steps are as follows:

- definition of the machine or process by the customer,
- choice of automation equipment,
- component supply,
- commissioning, tests,
- operation,
- maintenance,
- dismantling, recycling, destruction.

Cost of an equipment

Cost reduction is an issue at every level during the choice and decision-making process. It's tightly bound with the customer needs. Though this guide only describes the technical aspects, it has been written with cost-effectiveness in mind.

Evolution of user needs and market pressure

Over the last few years, the automated device market has been subject to great economic and technological pressure. The main customer priorities are now:

- shorten time to market,
- expand the offer through flexible design so that new products can be marketed without having to overhaul the entire offer,
- expand the offer through customisation,
- cost reduction.

This situation has created new needs:

- reduction of development time,
- reduction of complexity,
- greater flexibility in particular when manufacturers have to change series,
- gathering information for production management and maintenance (cost reduction, down times, etc.).

To meet these requirements, an offer for reliable and powerful products must include "ready-to-use" architectures enabling intermediate players such as systems integrators and OEMs to specify and build the perfect solution for any end user. The *figure 3* illustrates the relationship between market players and Schneider Electric offer.

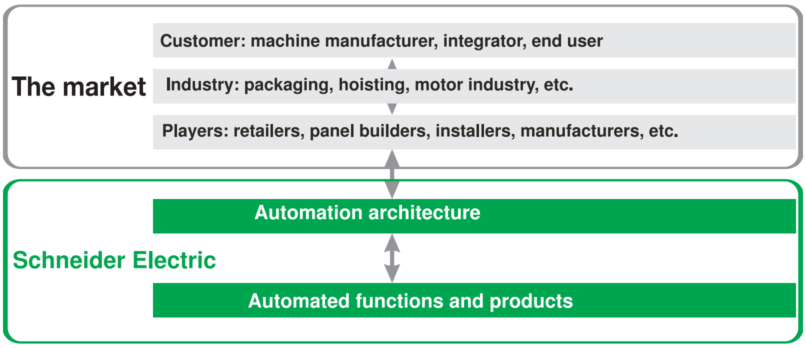


Fig. 3 *Automatism market players*

Architectures add value to the intermediate players, starting with the retailer or wholesaler, panel builder, machine installer or manufacturer. It is a global approach that enables them to respond more reliably, exactly and faster to end customers in different industries such as food, infrastructure or building.

1.3 Automation architectures

In the late 1990s, the conventional prioritised approach both in manufacturing processes (CIM: Computer Integrated Manufacturing) and in continuous processes (PWS: Plant Wide Systems) gave way to a decentralised approach. Automated functions were implemented as close as possible to the process (see the definition of these terms in the software section.)

The development of web processes based on Ethernet and the TCP/IP protocol began to penetrate complex automated systems. These gradually split up and were integrated into other functions, thus giving rise to smart devices.

This architecture made it possible to have transparent interconnection between the control systems and IT management tools (MES, ERP).

At the same time, the components (actuators, speed controllers, sensors, input/output devices, etc.) gradually evolved into smart devices by integrating programming and communication features.

Smart devices

These include nano-automated devices, automated cells (such as Power Logic, Sepam, Dialpact, etc.) and components with a regulating function, such as speed controllers. These products are smart enough to manage process functions locally and to interact with each other. Transparent communication means that tasks can be reconfigured and diagnoses made – these possibilities are perfectly in line with the web process (individual addressing, information formatted to be ready to use, information provider management).

The product line of smart devices products are systematically plug and play for power controllers, control bus and sensors. This approach means equipment can be replaced quickly and easily in the event of failure.

The integration of browsers into keyboard and screen systems, radio controls and other MMIs has accelerated deployment of web technologies right up to the component level *(see chapter 9 for explanations of connection and classes)*.

The integration of control functions into smart devices has reduced the data flow on networks, thereby lowering costs, reducing the power of the automated devices and speeding up response times. There is less need for synchronisation because the smart devices process locally.

Networks

At the same time, networks have been widely accepted and have converged on a limited number of standards which cover 80% of applications. There are many options open to designers (CANopen, AS-Interface, Profibus, DeviceNet, etc.) but the trend is towards a standard single network. In this framework, Ethernet, which has already won over the industrial computerisation sector, can also address needs for ground buses.

A great many elements are now directly network-connectable. This is the result of the combined effects of web-technology distribution, rationalisation of communication standards, the sharp drop in the price of information technology and the integration of electronics into electro-mechanical components.

These developments have led to the definition of field buses adapted to communication between components and automated devices such as Modbus, CANopen, AS-Interface, Device Net, Interbus S, Profibus, Fip, etc.

The increasing need for exchange prompts customers to give priority to the choice of network ahead of automated equipment.

Software and development tools

Programming tools have greatly expanded, from software dependent on hardware platforms to purely functional software downloaded onto a variety of hardware configurations. Communication between components is generated automatically. The information the programs produce is accessed by a unifying tool and shares a common distributed database, which considerably cuts down on the time taken to capture information (parameters, variables, etc.).

So far, industrial automated device programming language concepts have not changed, with practically all suppliers promoting offers based on the IEC 61131-3 standard, sometimes enhanced by tools supporting collaborative control.

Future improvements mainly concern the information generated by products designed to:

- automatically generate the automated device configuration and input/output naming,
- import and export functions to and from the automated device's software and the components' software,
- integrate electrical diagrams into diagnostics tools,
- generate a common database, even for a simple configuration,
- offer total transparency,
- offer a single ergonomics which can be learnt once and for all for several uses.

Software is an obligatory ingredient of widely different products and is used not only for programming, but also for configuration, parameter setting and diagnosis. These separate features can be included in the same program.

1.4 Architecture definition

An architecture is designed to integrate, interface and coordinate the automated functions required for a machine or process with the object of productivity and environmental safety.
A limited number of architectures can meet most automation requirements. To keep matters simple, Schneider Electric proposes to classify architectures on the basis of two structure levels (⇨ *Fig. 4)*:
- functional integration based on the number of automation panels or enclosures,
- the number of automated control functions, i.e. the number of control units in e.g. an automated device.

Automation architecture	Number of panels	Number of control units
All in one device All functions in a single device	0	1
All in one panel All functions in a single panel	1	1
Distributed peripheral Functions distributed over several panels	Several	1
Collaborative control Several collaborative control functions	Several	Several

↑ *Fig. 4* *Type of architectures*

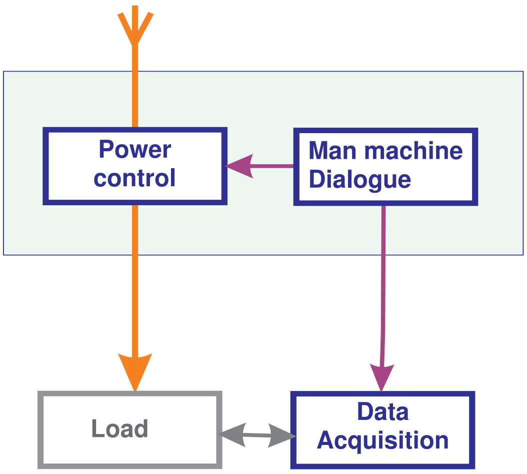
These architectures are explained and illustrated in the following paragraphs.

All in one device

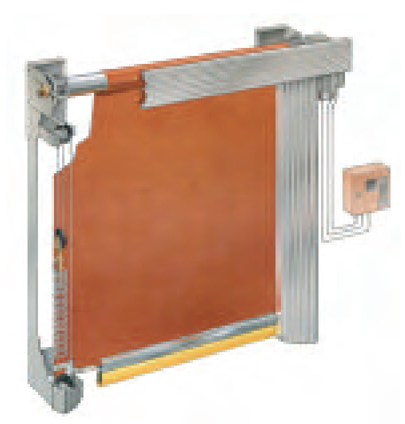
The most compact structure, with all the functions in a single product, this architecture can range from the simplest to the most complex as illustrated in the two examples below.

Remote controlled sliding door *(⇨ Fig. 6)*

This only has a few functions *(⇨ Fig. 5)*, the control being limited to direct command of the power controller by the sensor and the dialogue to two buttons. The power controller also includes the power supply and the protection of the power circuit.



↑ *Fig. 5* *Simple architecture "All in on device"*



↑ *Fig. 6* *Remote controlled sliding door*

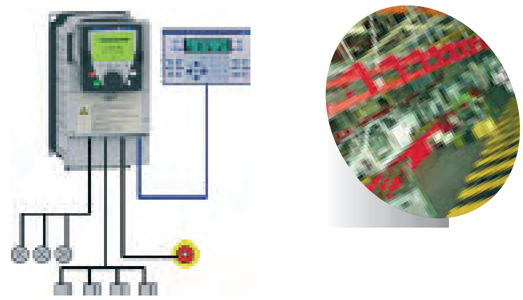


Fig. 8 Section of a conveyor system driven by an ATV71 with an integrated controller card

Conveyor system section *(⇨ Fig. 8)*

Power control dialog, processing and detection are integrated into the speed controller *(⇨ Fig. 7)*. The other automated parts are linked via a communication bus. The power supply requires an electrical distribution panel covering all the automated equipment in the system.

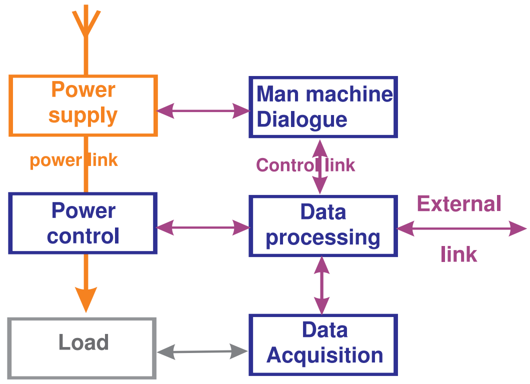


Fig. 7 *"All in One device" complex architecture*

Fig. 10 *LGP pump*

All in one panel

This is the most common architecture *(⇨ Fig. 9)*, with the automated functions centralised in a single place which, depending on the case, is a single enclosure or built into the machine and has a single control function *(application examples fig. 10,11,12)*.

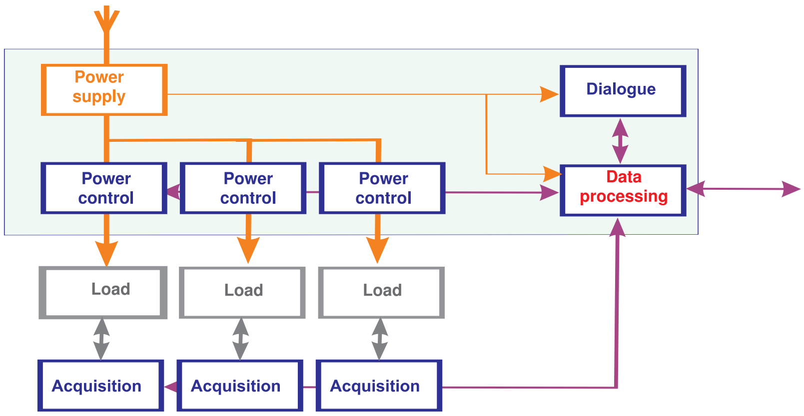


Fig. 9 *"All in one panel" architecture*

Fig. 11 *Textile inspection machine*

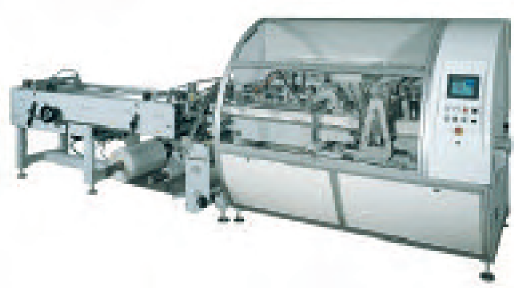
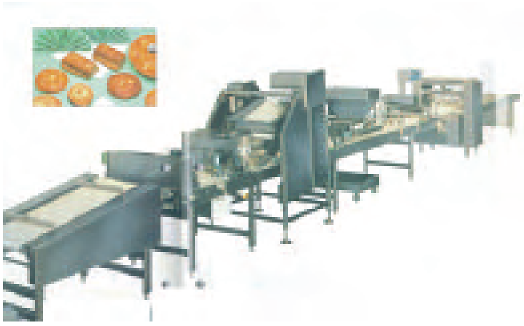


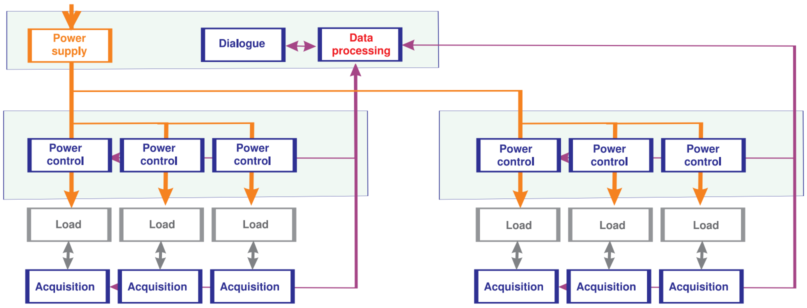
Fig. 12 *Packaging machine*



↑ Fig. 14 *Industrial bakery machine*

Distributed peripheral (⇨ Fig. 13)

This architecture has a single central automated device to drive several automated distribution panels. It is suited to plant-wide machines and procedures and modular machines (⇨ Fig. 14). The link is controlled by a ground bus. The power supply is centralised and often includes the parts for controlling and operating the safety system.

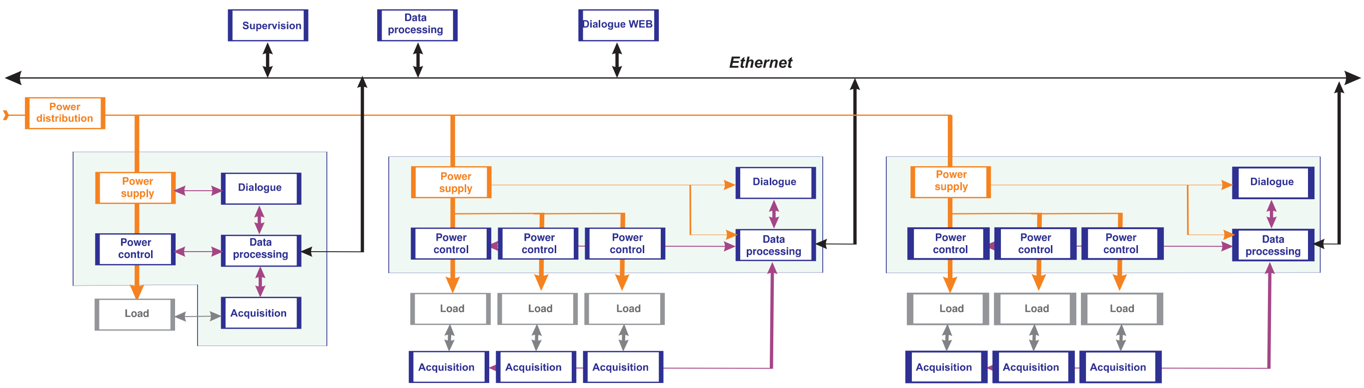


↑ Fig. 13 *"Distributed peripheral" architecture*

Collaborative control

Several machines or parts of a procedure have their own controllers (⇨ Fig. 15). They are linked together and collaborate in operating the system. This architecture is designed for large procedures such as in the petrochemical and steel industries or for infrastructures such as airports or water treatment plants (⇨ Fig.16).

↑ Fig. 16 *Water treatment*



↑ Fig. 15 *"Collaborative control" architecture*

1.5 Choice of automated equipment

Architecture implementation

We propose to help the customer by addressing their problem to guide them and optimise their choice of architecture and the products and services it will include. This process starts by ascertaining the customer's needs and structuring questions as we shall describe.

To make it easier to choose, Schneider Electric has optimised a number of variants based on the most common architectures.

The first involves compact applications where the automated devices are grouped into an all-in-one panel.

The second relates to procedure-distributed applications. The automated devices are divided up into several panels known as distributed peripherals.

The other two (All in One Device and Collaborative Control) are not left out, but are presented differently. The all-in-one device is comparable to a single device and is treated as such. The collaborative control structure mainly involves data exchange between devices and is described in the section on links and exchanges. Its details are in the sections on automated devices and software.

Choices offered by Schneider Electric

Both architecture concepts above can be implemented in many ways. To make it easier for the customer to choose, Schneider Electric has opted for a total of 10 possible implementations to offer optimal combinations.

To prevent any confusion between the architecture concepts described above and the practical solutions Schneider Electric proposes, the latter will be referred to as ***preferred implementations***.

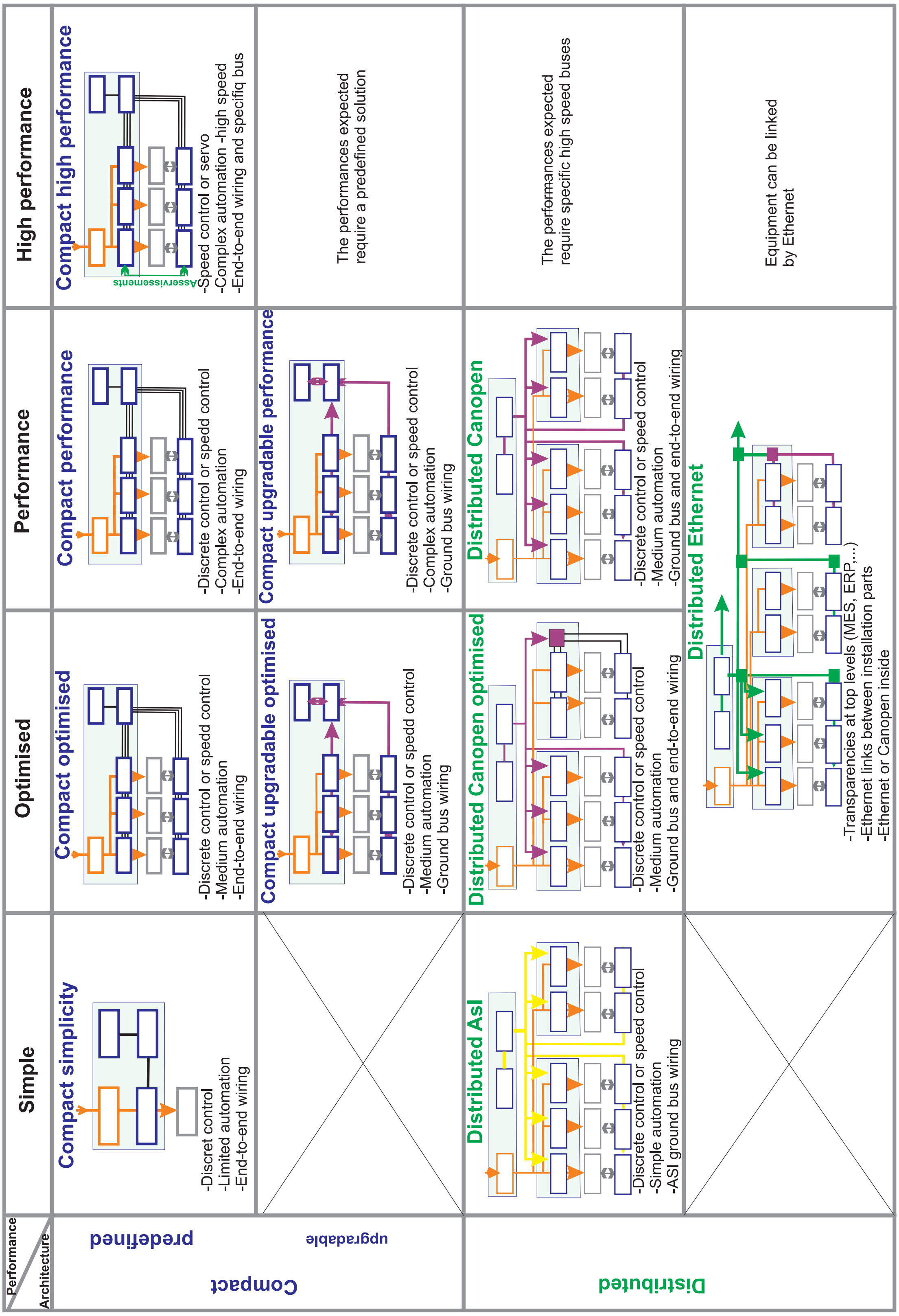
The table *(⇨ Fig. 17)* below shows a summary of this approach.

Automation architecture	Schneider Electric orientations	proposed implementations
All in one device All functions in a single device	Same as one produit	Products such as Tesys U ATV71 Controller Inside
All in one panel **All functions in a single panel**	**Compact architecture**	6 implementations
Distributed peripheral Functions distributed over several panels	**Distributed architecture**	4 implementations
Collaborative control Several collaborative control functions	Same as data exchange between automated devices	Combinaison of the implementations above

Fig. 17 *Choice of Schneider Electric implementations*

Preferred implementations

These implementations are the result of an optimization between the expressed needs and technologies available. The table *(⇨ Fig. 18)* below shows a summary of them; they are described in greater detail in the documents provided by Schneider Electric.



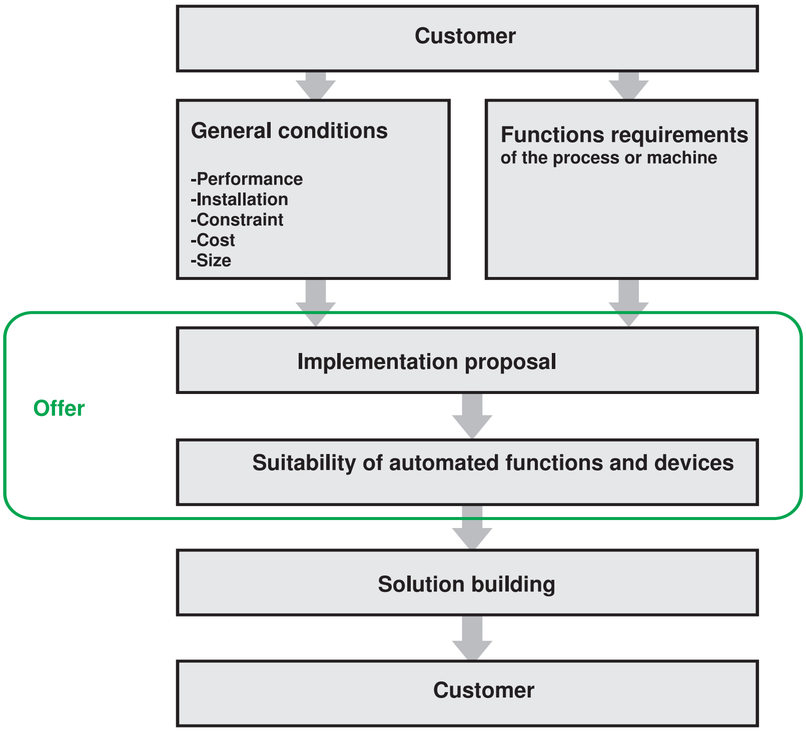
⇧ Fig. 18 *Preferred implementations characteristics (refer to fig 5 to 11)*

Choice of a preferred implementation

The solution approach to these implementations, which includes all the customer's requirements, has many advantages:

- simplified choice of automation systems,
- peace of mind and confidence for the user because the devices are interoperable and performance levels are guaranteed,
- once the implementation is chosen, the customer will have an adequately precise framework, alongside the catalogue and specific guides, to select the requisite automated functions and devices,
- commissioning is facilitated by the work completed upstream.

The table *(⇨ Fig. 19)* below summarises the proposed approach:



↑ Fig. 19 *Step by step approach for automatism choice*

To assist customers choice, Schneider Electric has drawn up a complete guide with questions divided into four themes given the mnemonic of PICCS (Performance, Installation, Constraints, Cost, Size). An example is given *(⇨ Fig. 20 and 21)* below. For all the implementations available, please refer to the catalogues. Here we are just illustrating the approach with examples.

Type of implemenation		Compact					
Name of implementation		***Simple***	***optimised***	***optimised upgradeable***	***performance***	***high performance***	***upgradeable performance***
General conditions							
Performance	Installed capacity	low	low to high	low to medium	low to medium	low to medium	low to medium
	Precision, rate	none	medium	medium	medium	high	medium
	number of motors	1 to 4	1 to 10	1 to 50	1 to 10	1 to 10	1 to 50
	types of motor	Asynchronous Direct	Asynchronous Speed Control	Asynchronous Speed Control	Asynchronous FVC / servosystem	Synchronous servosystem	Asynchronous FVC Synchronous servosystem
	Data exchange	no	no	yes	no	possible	yes
	Number of inputs/outputs	<20	<100	<100	<100	>100	>100
	Dialogue types and functions	buttons lights	buttons lights displays	buttons keyboard displays	buttons keyboard displays	buttons keyboard displays	buttons keyboard displays
	Processing system	wired or preset	preset	basic programmable functions	advanced workshop software functions	advanced workshop software functions+ application	advanced workshop software functions
	Remote services (diagnosis, update, etc.)	no	no	possible	no	no	possible
Installation	Number of panels	1	1	1	1	1	1
	Constant or upgradeable	constant	constant	upgradeable	constant	constant	upgradeable
Environment **C**onditions	Atmosphere (temperature, dust, etc.)	limited	yes	yes	yes	yes	yes
	Safety (people, equipment)	Emergency stop	Emergency stop	automated functions	simple functions	automated functions	automated functions
Cost	cost of machine or installation	equipment	equipment	update maintenance	equipment	machine	update maintenance
	design costs	no	no	yes	no	yes	yes
	operating cost	no	yes	yes	no	yes	yes
Surface area and size	size of installation	small	medium	medium	medium	medium	medium
	Inhouse network	none	none	yes	none	none or specific bus	yes
	Length of external network						

↑ Fig. 20 *Guide for compact architectures*

Type of implemenation		**Distributed**			
	Name of implementation	***As-Interface***	***optimised CANopen***	***CANopen***	***Ethernet Transparent Factory***
General conditions					
Performance	Installed capacity	low to medium	low to high	low to high	low to high
	Precision, rate	low to medium	medium	medium	depending on ground bus
	number of motors	1 to 10	1 to 10	<20	>20
	types of motor	Asynchronous Direct	Asynchronous Speed Control	Asynchronous Speed Control	all types contingent on ground bus
	Data exchange	no	possible	possible	yes
	Number of inputs/outputs	<100	<100	>100	>100
	Dialogue types and functions	keyboards displays	keyboards displays	keyboards displays	keyboards PC displays
	Processing system	basic programmable functions	advanced workshop software functions	advanced workshop software functions	software workshop + collaboration other systems
	Remote services (diagnosis, update, etc.)	no	possible	possible	yes
Installation	Number of panels	<5	<10	<10	n
	Constant or upgradeable	upgradeable	upgradeable	upgradeable	upgradeable
Environment **C**onditions	Atmosphere (temperature, dust, etc.)	yes	yes	yes	yes
	Safety (people, equipment)	automated functions	automated functions	automated functions	automated functions
Cost	cost of machine or installation	update maintenance	update maintenance	update maintenance	global
	design costs	yes	yes	yes	yes
	operating cost	yes	yes	yes	yes
Surface area and size	size of installation	medium	medium	medium	large
	Inhouse network	ASI	CANopen	CANopen	ground network
	Length of external network	100m	250m	250m	>250m

↑ *Fig. 21* *Guide for distributed architectures*

1.5 Choice of automated equipment

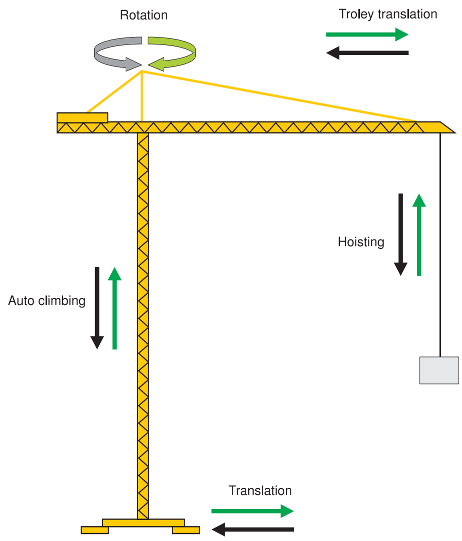


Fig. 22 *Tower crane*

We shall take three different applications and ascertain the most suitable architecture(s) for each of them.

Tower crane

Notwithstanding its apparent simplicity, this machine *(⇨ Fig. 22)* has to comply with stringent safety and environmental standards. Market competition forces manufacturers to consider the cost of every element.

The features of this type of crane are:

- power of the installation from 10 kW to 115 kW depending on the load to hoist (2 to 350 metric tons),
- hoisting, rotation, trolleying and translation are driven by three-phase AC motors with two or three gears or AC drives. Braking is mechanical or electric,
- the system requires about a dozen of sensors and the man-machine interface can be in the cabin or remote-controlled.

The choice of implementation naturally focuses on an ***optimised compact*** system in a single panel at the basement of the crane.

The highlighted colour coding in the selection table above shows the options at a glance *(⇨ Fig. 23)*.

Type of implemenation	***Name of implementatic***	**Compact** *Simple*	*optimised*	*optimised upgradeable*
General conditions				
Performance	Installed capacity	low	low to high	low to medium
	Precision, rate	none	medium	medium
	number of motors	1 to 4	1 to 10	1 to 50
	types of motor	Asynchronous Direct	Asynchronous Speed Control	Asynchronous Speed Control
	Data exchange	no	no	yes
	Number of inputs/outputs	<20	<100	<100
	Dialogue types and functions	buttons lights	buttons lights displays	buttons keyboard displays
	Processing system	wired or preset	preset	basic programmable functions
	Remote services (diagnosis, update, etc.)	no	no	possible
Installation	Number of panels	1	1	1
	Constant or upgradeable	constant	constant	upgradeable
Environment Conditions	Atmosphere (temperature, dust, etc.)	limited	yes	yes
	Safety (people, equipment)	Emergency stop	Emergency stop	automated functions
Cost	cost of machine or installation	equipment	equipment	update maintenance
	design costs	no	no	yes
	operating cost	no	yes	yes
Surface area and size	size of installation	small	medium	medium
	Inhouse network	none	none	yes
	Length of external network			
colour codes	***suitable***			
	unsuitable			

Fig. 23 *Implementation choice for a tower crane*

The ***Simple Compact*** is eliminated because its options are too limited. Both ***Optimised Compact*** and ***Evolutive Optimised Compact*** are suitable *(⇨ Fig. 24 and 25)*. The latter is even more suitable if the machine is a modular design or if remote maintenance is required.

1.5 Choice of automated equipment

The choice of components naturally depends on the customer's constraints and those of the chosen implementation. The figures below illustrate both possible implementations:

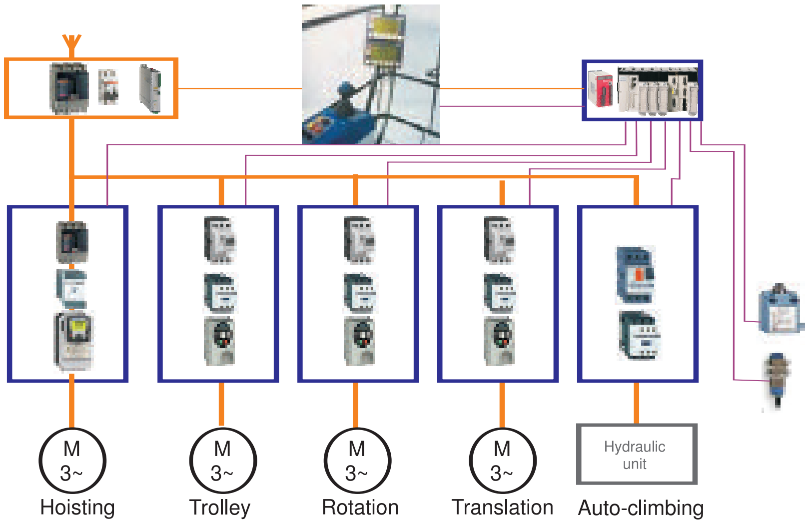


Fig. 24 *Compact optimised solution*

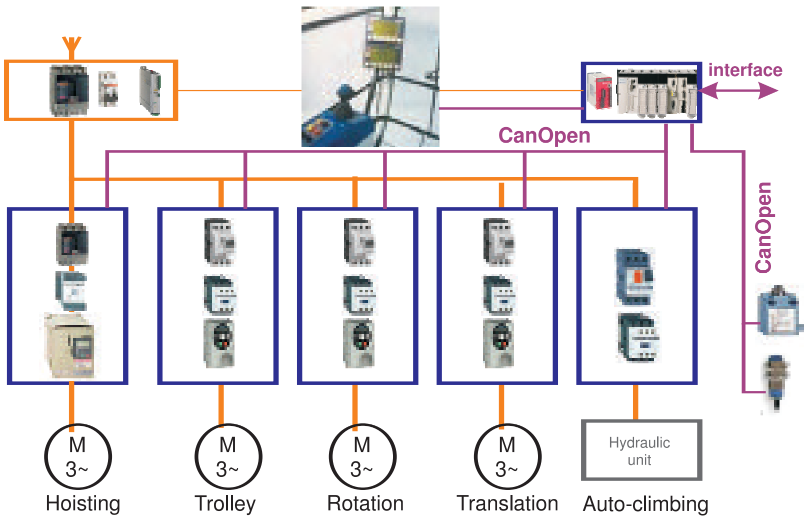
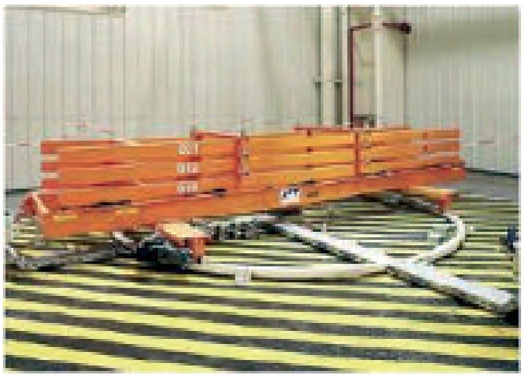


Fig. 25 *Evolutive optimised compact solution*

1.5 Choice of automated equipment



↑ *Fig. 26* *Revolving table*

↑ *Fig. 27* *Conveyor*

The components are described in detail in the following sections.

☐ Conveyors and revolving tables

This kind of unit is very common in the manufacturing industry *(⇨ Fig. 26 and 27)*. The type of machine greatly depends on the surroundings.
Its output has to be adjusted to the product and it is controlled by upstream and downstream automation. One automated device will control several sections in a conveyor and each element will have one or more panels.
The main features are:
- low power installation,
- medium performance requirements,
- per section, 2 to 10 three-phase AC motors with AC drives,
- 10 to 50 inputs/outputs,
- interface by keyboard and display,
- real-time knowledge of the type and number of products conveyed.

Since there are several linked equipments, the choice should focus on a distributed architecture.

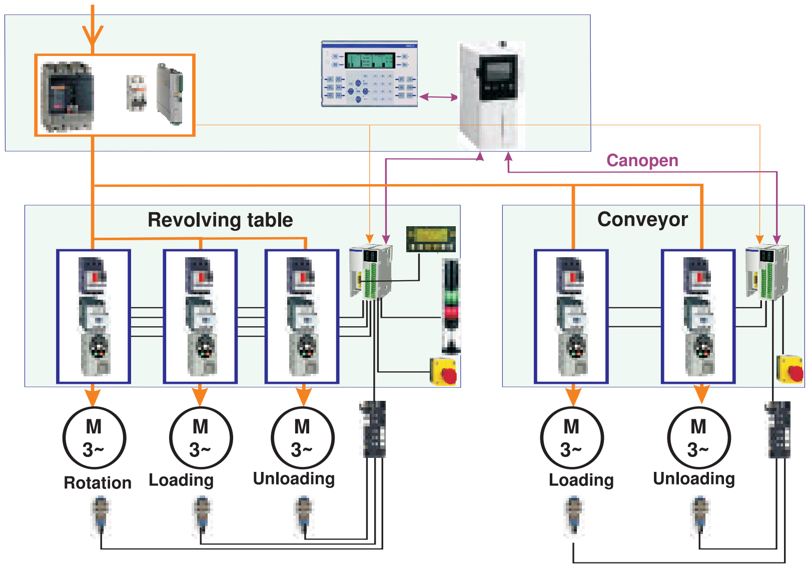
The selection table highlights the best solutions *(⇨ Fig. 28)*. The ASI bus one is a bit restricted because of the difficulties in speed control and the Ethernet one, except in some specific cases, is likely to be too expensive.

Type of implementation		**Distributed**			
	Name of implementation	***As-Interface***	***optimised CANopen***	***CANopen***	***Ethernet Transparent Factory***
General conditions					
Performance	Installed capacity	low to medium	low to high	low to high	low to high
	Precision, rate	low to medium	medium	medium	depending on ground bus
	number of motors	1 to 10	1 to 10	<20	>20
	types of motor	Asynchronous Direct	Asynchronous Speed Control	Asynchronous Speed Control	all types contingent on ground bus
	Data exchange	no	possible	possible	yes
	Number of inputs/outputs	<100	<100	>100	>100
	Dialogue types and functions	keyboards displays	keyboards displays	keyboards displays	keyboards PC displays
	Processing system	basic programmable functions	advanced workshop software functions	advanced workshop software functions	software workshop + collaboration other systems
	Remote services (diagnosis, update, etc.)	no	possible	possible	yes
Installation	Number of panels	<5	<10	<10	n
	Constant or upgradeable	upgradeable	upgradeable	upgradeable	upgradeable
Environment Conditions	Atmosphere (temperature, dust, etc.)	yes	yes	yes	yes
	Safety (people, equipment)	automated functions	automated functions	automated functions	automated functions
Cost	cost of machine or installation	update maintenance	update maintenance	update maintenance	global
	design costs	yes	yes	yes	yes
	operating cost	yes	yes	yes	yes
Surface area and size	size of installation	medium	medium	medium	large
	Inhouse network	ASI	CANopen	CANopen	ground network
	Length of external network	100m	250m	250m	>250m
colour codes	***suitable*** / ***unsuitable***				

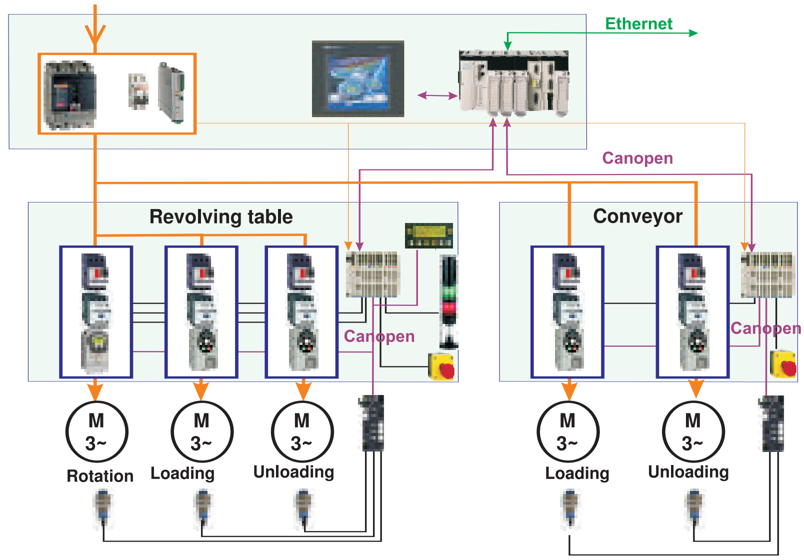
↑ *Fig. 28* *Conveying system choice*

This leaves the two CANopen field bus solutions. The first, which is more economical *(⇨ Fig. 29)*, ensures the basic requisite functions and the second *(⇨ Fig. 30)* ensures transparency and synchronisation with automated devices outside the section involved. It is also easy to upgrade: a new configuration can be downloaded whenever a series is changed and so forth.

◻ Electrical diagram



↑ Fig. 29 *Optimised CANopen solution*



↑ Fig. 30 *CANopen solution*

◻ Drinking water supply

This example *(⇨ Fig. 31)* illustrates part of an infrastructure for water treatment and distribution. It consists of a set of units spread over a territorial area.

This kind of application must be standalone and ensure a continuous supply. Customers give great attention to supervision and maintenance of the installation.

The features of the station are:
- 4 pumps of 7.5 kW with AC drives,
- a dozen of sensors (pressure, output, etc.),
- an automated device to control pump sequencing and communication,
- remote supervision of the installation.

↑ Fig. 31 *Water treatment pumping station*

1.5 Choice of automated equipment

The choice will focus on a distributed implementation. The table *(⇨ Fig. 32)* below shows the best one.

The most suitable implementation is the Ethernet one *(⇨ Fig. 33 and 34)*, ensuring total transparency in the installation. The ASI bus is limited by its low data exchange capacity. The CANopen ones can be used with a modem but their possibilities are still restricted.

Type of implementation		**Distributed**			
	Name of implementation	***As-Interface***	***optimised CANopen***	***CANopen***	***Ethernet***
General conditions					***Transparent Factory***
Performance	Installed capacity	low to medium	low to high	low to high	low to high
	Precision, rate	low to medium	medium	medium	depending on ground bus
	number of motors	1 to 10	1 to 10	<20	>20
	types of motor	Asynchronous Direct	Asynchronous Speed Control	Asynchronous Speed Control	all types contingent on ground bus
	Data exchange	no	possible	possible	yes
	Number of inputs/outputs	<100	<100	>100	>100
	Dialogue types and functions	keyboards displays	keyboards displays	keyboards displays	keyboards PC displays
	Processing system	basic programmable functions	advanced workshop software functions	advanced workshop software functions	software workshop + collaboration other systems
	Remote services (diagnosis, update, etc.)	no	possible	possible	yes
Installation	Number of panels	<5	<10	<10	n
	Constant or upgradeable	upgradeable	upgradeable	upgradeable	upgradeable
Environment Conditions	Atmosphere (temperature, dust, etc.)	yes	yes	yes	yes
	Safety (people, equipment)	automated functions	automated functions	automated functions	automated functions
Cost	cost of machine or installation	update maintenance	update maintenance	update maintenance	global
	design costs	yes	yes	yes	yes
	operating cost	yes	yes	yes	yes
Surface area and size	size of installation	medium	medium	medium	large
	Inhouse network	ASI	CANopen	CANopen	ground network
	Length of external network	100m	250m	250m	>250m
colour codes	***suitable*** ***unsuitable***				

↑ Fig. 32 *Water treatment pumping station architeture choice*

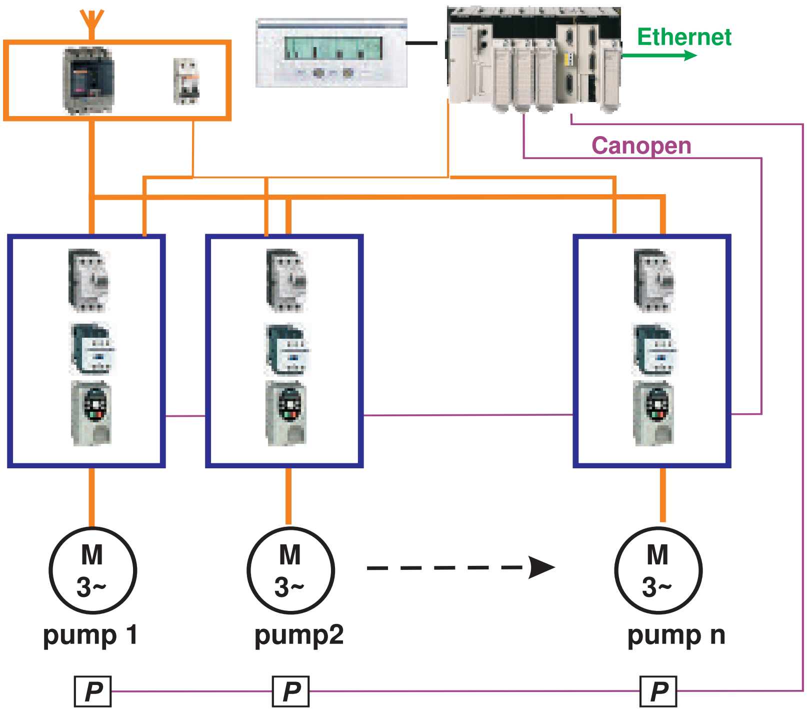


Fig. 33 Solution 1 from a PLC

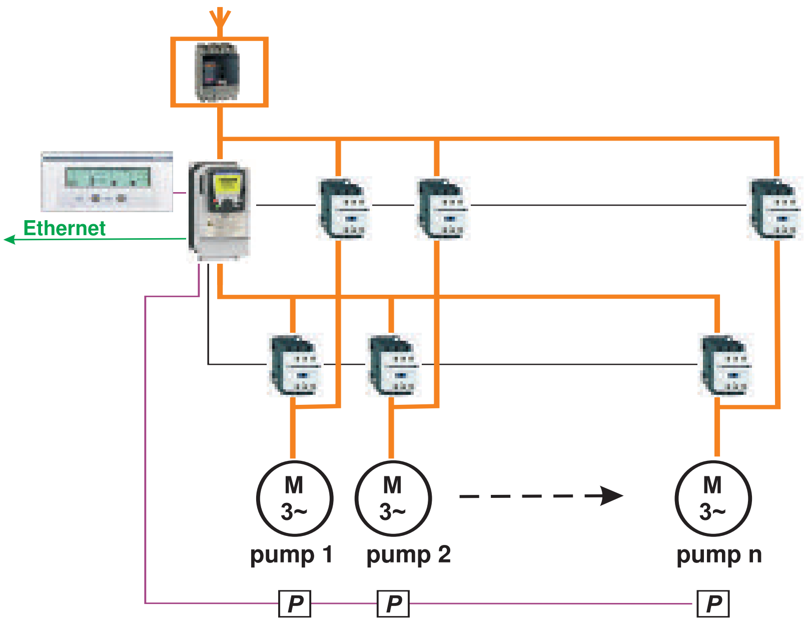


Fig. 34 Solution 2 from a speed drive

2

chapter
Electrical power supply

Reminder of rules, regulations and practices in order to select properly the power supply of the machine. Introduction to the power supply and control functions

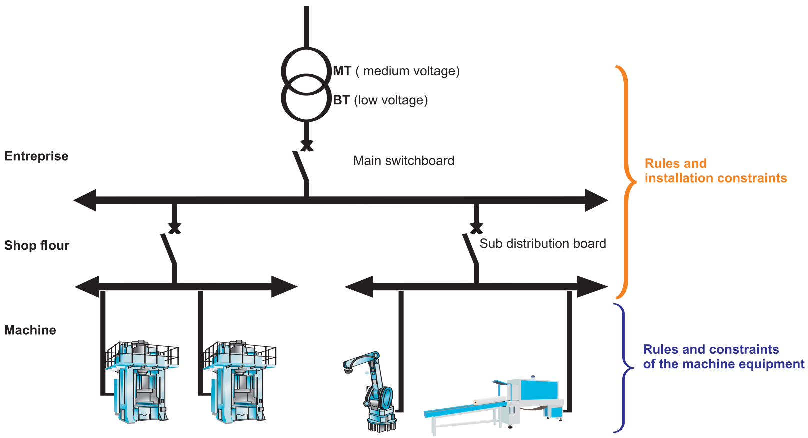
2. Electrical power supply

Summary

2. Electrical power supply

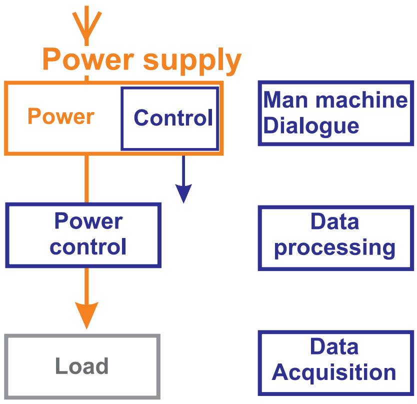
2.1 Introduction

This section explains how electrical systems in machinery are supplied with electricity. A supply system acts as an interface between the mains installation and the machinery and must meet the technical standards and constraints of both *(⇨ Fig. 1)*. It is the latter which is described here and readers are advised to refer to the *Electrical installation guide* for further information.



↑ *Fig. 1* *Electrical power supply architecture*

2.2 Power supply to machinery



↑ *Fig. 2* *Power supply functions*

As illustrated in the diagram *(⇨ Fig. 2)*, an electrical power supply is divided into two units.

The power unit feeds machine loads such as motors or heating circuits via the control components (pre-actuators). Voltage usually ranges from 200V to 660V in 3-phase and 120V to 230V in single phase.

The control unit powers automation components such as contactor coils, solenoid valves, PLCs, sensors, etc. Voltage is usually low (120V to 200V in single phase) and extra low (12 to 48V).

This unit is often called the “head” and governs a set of functions described in subsection 2.4.

2.3 Standards and conventions

As we have already said, an electrical power supply is governed by constraints in two areas:

Electrical distribution system

Each country has its own conventions and defines its own rules. This means there are a great many different standards, such as C15-100 in France. We can however summarise the constraints and conventions regarding equipment powering devices as follows:

- mains voltage. A table of voltages per country is provided in the *Electrical installation guide* and the characteristics of public distribution networks are given in EN 50160:1999,
- neutral distribution and system earthing,
- wiring practices,
- product standards and clearance distances,
- types of fuses for fuse-holders or fused switches.

Machinery

Standards have been brought in line with IEC 60 204-1 to facilitate export and use the same machines through the world. Few countries have retained some specific rules; elements of the main ones are given in the table in (⇨ *Fig. 3)* below.

TNC diagrams are not permitted in low-voltage installations in buildings (Norway).
TT power diagrams are not permitted (USA).
The neutral conductor break is mandatory in TN-S diagrams (France and Norway).
The distribution of a neutral conductor in an IT diagram is not permitted (USA and Norway).
The maximum rated voltage of an AC control circuit is 120V (USA).
The minimum gauge of copper conductors is specified in ANSI/NFPA 79 in American sizes (AWG) (USA). Annex G of the standard gives the equivalent in mm² of the AWG.
WHITE or GREY is used to identify neutral earthed conductors instead of BLUE (USA and Canada).
Marking requirements for rating plates (USA).

↑ *Fig. 3* *Specific features of standards and practices in a number of countries*

Three zones of influence

Notwithstanding the differences in standards and practicies amongst countries, there are three major zones of influence: Europe, USA and Japan (⇨ *Fig. 4)*.

	Zone of influence	USA	Europe	Japan
Electrical distribution	3-phase supply voltage	480V	400V	200V
	LV installation rules / standards	NEC	IEC 60364	JIS C 0364
Machine powering equipment standards	See differences above	IEC60204-1	IEC60204-1	JIS-B 9960
Head device	Circuit breaker	UL 489	IEC60947	JIS-C 8201-2-1
	Switch / fuses	UL98	IEC 60269 Different fuses per country	JIS-C 8269
	Motor contactors / circuit breakers	UL508	IEC 60947	JIS-C 8201-4-1
Type of upstream connection	<100A	>100A connectors	Connectors, screw brackets, elastic connections	Lug clamps
	>100A	Parallel wires	Wires with lugs or busbars	Wires with lug clamps

↑ *Fig. 4* *Requirements in the zones of influence*

2.4 Power supply functions

There are three separate functions:

■ Supply and cut off the machine power and control units with attention to the following points

□ Break capacity

Depending on the power installed, the prospective short-circuit current in the event of an incident can range from a few kA to several hundred kA, so the device must be sized accordingly.

□ Short-circuit endurance

A short-circuit downstream of the electrical equipment must not cause destruction of the device.

□ Connection capacity

Internal wires in equipment are always in copper but it should be noted that aluminium is used in electrical system distribution. The input device should therefore withstand both types of connection.

□ Manual control and remote control on cabinet

Safety rules require direct control from the electrical cabinet to switch off or disconnect the installation.

■ Personal protection

Electrical cabinets are usually locked during operation, so operators do not have access to them. Regulations stipulate personal protection rules for working inside of electrical devices, in particular for starting and maintenance. Personal protection requires compliance with a number of rules:

- IP20 protection against contact with internal connections,
- disconnection.

This function ensures the installation is completely or partly disconnected from any source of electrical power for safety reasons.

• Insulation
Insulation must be ensured when a control device is open, i.e. the leakage current must be below the danger threshold.

• Padlocking
This function is intended to prevent any unauthorised person from switching on electrical devices.

• Control insulation
This must be adequate to protect people and electrical equipment from over-voltage and other electrical pollution.

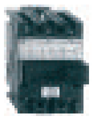
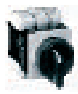
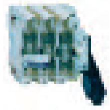
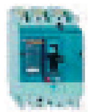
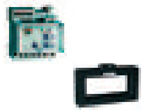
• Equipotential connection
Installation rules can stipulate earthing or insulation according to the system eathing used.

■ Distribution network protection

Protection from incidents due to the machine must include break capacity and coordination and discrimination. An incident should never have adverse effects on the rest of the distribution system.

Power unit supply

The table *(⇨ Fig. 5)* summarises the power units and functions covering the requisite functions.

Function	Fuse holder 	Dimmer 	INS switch 	Fused switch 	Magnetic circuit-breaker 	line circuit-breaker 	Differential relay 
Disconnection	XX	XX	XX	XX	XX	XX	
Switch-off		X	XX	XX	XX	XX	
Short-circuits protection	XX			XX	X	XX	
Isulation	XX	XX	XX	XX	XX	XX	
Short-circuits immunity	X	X	XX	XX	X	XX	
Padlocking	XX	XX	XX	XX	X	XX	
Protection from earth faults						option	XX

↑ *Fig. 5* *Comparative device table*

2.5 Power supply to the control circuit

The power supply to the control circuit is governed by regulatory and technological constraints. The need for personal protection has led to the use of extra low voltages (ELV), i.e. less than 50V. Electronic components are now widespread and require direct current to power them.

Apart from simple or specific applications which still use low voltage, DC ELV power supplies are now commonly used.

24V power supplies

Here we describe different types of 24V sources. This voltage is now standard in industry and most manufacturers have extensive product ranges. Standardisation helps to limit the risk of incompatibility between products.

- **This solution has a number of benefits**
  - saving in space and equipment,
  - improved reliability and circuit-break detection available on some PLCs,
  - personal safety,
  - operating continuity ensured by backup systems or voltage drop filters,
  - no capacitive effect in wiring,
  - environmental protection due to lower electricity consumption.
- **But there are also some drawbacks**
  - low voltage limits cable length,
  - the number of contacts in series or sensors is limited,
  - caution must be taken with earth links,
  - contacts can deteriorate quickly in hostile environments (dust, chemicals, etc.),
  - there may be problems of compatibility between PLC output specifications and contactor sensors and coils. It is advised to use low-consumption contactors which are well suited to this kind of use.

24V direct current technologies

Technologies have also progressed in this area. Conventional power supplies use a transformer with separate windings which convert the voltage and insulate LV from ELV. Improvements in switching technology along with lower costs make this an advantageous alternative in several ways. A description of both technologies follows.

Rectified power supplies

These consist of an LV/ELV transformer followed by a bridge rectifier and a filter *(⇨ Fig. 6)*.

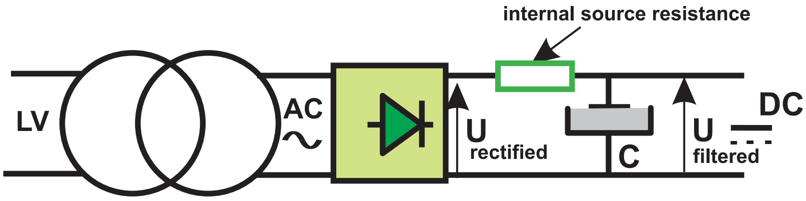


Fig. 6 *Working diagram of a 24V power supply*

Upstream power to the transformer can be single or 3-phase; the latter *(⇨ Fig. 7)* dispenses with the need for smoothing capacitors. Though this solution is more reliable, its immunity to micro-breaks is lessened.

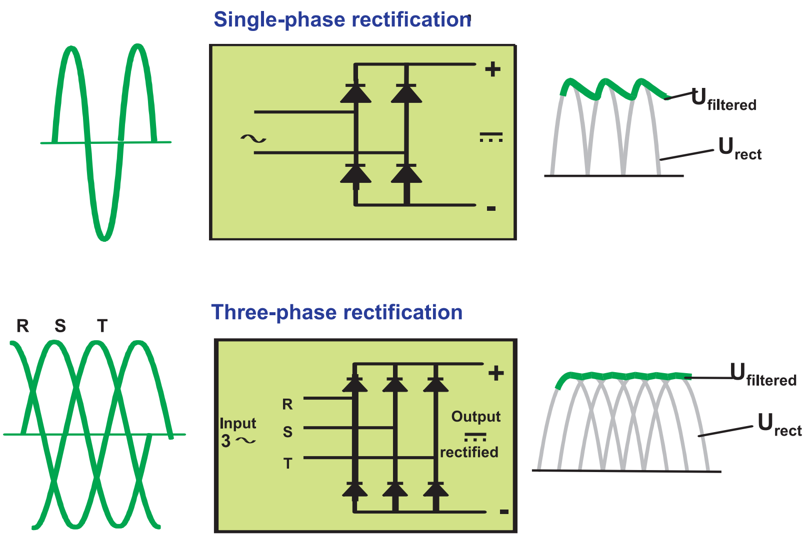


Fig. 7 *Single-phase and 3-phase rectification*

Switching power supplies (⇨ *Fig. 8*)

The working principle involves switching the voltage from a rectified source to a high frequency of a few dozen to several hundred kHz. This makes possible to power a ferrite transformer with a better power weight ratio than conventional 50Hz transformers. The output is then rectified and filtered.

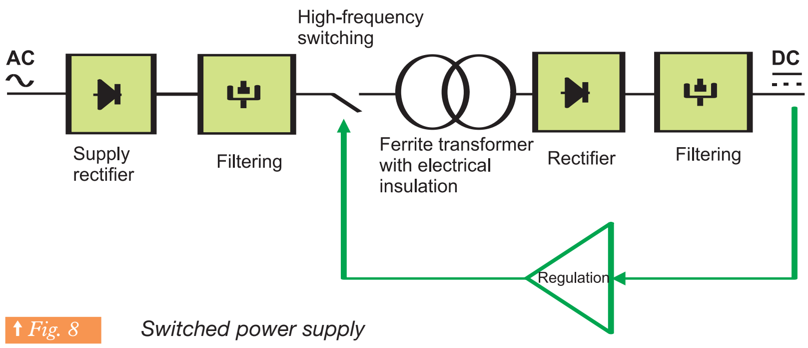


Fig. 8 *Switched power supply*

A loop feedback controls the high-frequency switch cycle time to ensure the requisite regulation characteristic (⇨ *Fig. 9*).

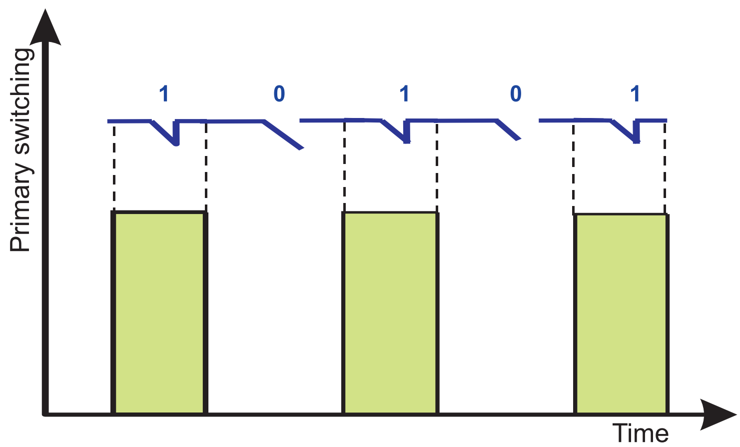


Fig. 9 *Principle of switched power supplies*

Conclusion

The table (⇨ *Fig. 10*) gives a brief comparison of the two technologies. For more details, see the section on product implementation.

Comparison for a 10A/24V DC source	Regulated switched power	Rectified filtered power
Input voltage range	Wide range of 85 to 264V	Set ranges of 110V to 230V
Overall dimensions	3dm²	7dm²
Weight	1.5kg	6kg
Efficiency	Up to 85%	Up to 75%
Output voltage adjustment	Yes	No
Microbreak immunity	High >20ms	Low <5ms
Load regulation	1 to 3%	5%
Line regulation	<1%	5-10% depending on mains
EMC pollution	Requires careful design	Naturally low
Harmonic pollution	As per EN61000-3-2 with filter	Basically as per standard EN61000-3-2
Reliability, lifetime	Good	Very good

Fig. 10 *Comparison of direct current power supplies*

3

chapter
Motors and loads

Introduction to motor technology
Information on loads and motor electrical behaviour

Summary

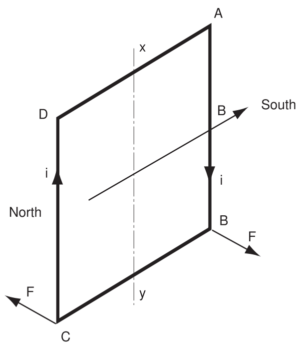
3. Motors and loads

3.1 Three phase asynchronous motors

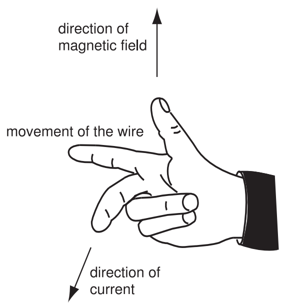
This section describes the physical and electrical aspects of motors. The operating principle of the most common types of motors is explained in detail.

The powering, starting and speed control of the motors are explained in brief. For fuller information, see the relevant section.

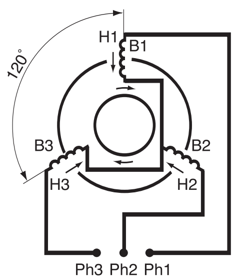
3.1 Three phase asynchronous motors



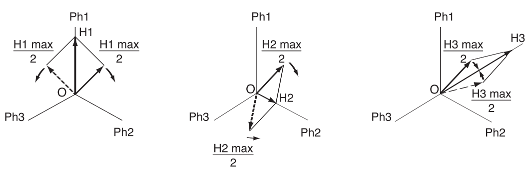
↑ *Fig. 1* *An induced current is generated in a short-circuited shading ring*



↑ *Fig. 2* *Rule of three fingers of the right hand to find the direction of the force*



↑ *Fig. 3* *Principle of the 3-phase asynchronous motor*



↑ *Fig. 4* *Fields generated by the three phases*

The first part deals with 3-phase asynchronous motors, the one most usually used for driving machines. These motors have a number of advantages that make them the obvious choice for many uses: they are standardised, rugged, easy to operate and maintain and cost-effective.

Operating principle

The operating principle of an asynchronous motor involves creating an induced current in a conductor when the latter cuts off the lines of force in a magnetic field, hence the name “induction motor”. The combined action of the induced current and the magnetic field exerts a driving force on the motor rotor.

Let’s take a shading ring ABCD in a magnetic field B, rotating round an axis xy *(⇨ Fig. 1)*.

If, for instance, we turn the magnetic field clockwise, the shading ring undergoes a variable flux and an induced electromotive force is produced which generates an induced current (Faraday’s law).

According to Lenz’s law, the direction of the current is such that its electromagnetic action counters the cause that generated it. Each conductor is therefore subject to a Lorentz force F in the opposite direction to its own movement in relation to the induction field.

An easy way to define the direction of force F for each conductor is to use the rule of three fingers of the right hand (action of the field on a current, *(⇨ Fig. 2)*.

The thumb is set in the direction of the inductor field. The index gives the direction of the force.

The middle finger is set in the direction of the induced current. The shading ring is therefore subject to a torque which causes it to rotate in the same direction as the inductor field, called a rotating field. The shading ring rotates and the resulting electromotive torque balances the load torque.

Generating the rotating field

Three windings, offset geometrically by 120, are each powered by one of the phases in a 3-phase AC power supply *(⇨ Fig. 3)*.

The windings are crossed by AC currents with the same electrical phase shift, each of which produces an alternating sine-wave magnetic field. This field, which always follows the same axis, is at its peak when the current in the winding is at its peak.

The field generated by each winding is the result of two fields rotating in opposite directions, each of which has a constant value of half that of the peak field. At any instant t1 in the period *(⇨ Fig. 4)*, the fields produced by each winding can be represented as follows:

- field H1 decreases. Both fields in it tend to move away from the OH1 axis,
- field H2 increases. Both fields in it tend to move towards the OH2 axis,
- field H3 increases. Both fields in it tend to move towards the OH3 axis.

The flux corresponding to phase 3 is negative. The field therefore moves in the opposite direction to the coil.

Number of poles	Speed of rotation in rpm		
	50 Hz	60 Hz	100 Hz
2	3000	3600	6000
4	1500	1800	3000
6	1000	1200	2000
8	750	900	1500
10	600	720	1200
12	500	600	1000
16	375	540	750

↑ *Fig. 5* *Synchronous speeds based on number of poles and current frequency*

If we overlay the 3 diagrams, we can see that:
- the three anticlockwise fields are offset by 120° and cancel each other out,
- the three clockwise fields are overlaid and combine to form the rotating field with a constant amplitude of 3Hmax/2. This is a field with one pair of poles,
- this field completes a revolution during a power supply period. Its speed depends on the mains frequency (f) and the number of pairs of poles (p). This is called "synchronous speed".

Slip

A driving torque can only exist if there is an induced current in the shading ring. It is determined by the current in the ring and can only exist if there is a flux variation in the ring. Therefore, there must be a difference in speed in the shading ring and the rotating field. This is why an electric motor operating to the principle described above is called an "asynchronous motor".
The difference between the synchronous speed (Ns) and the shading ring speed (N) is called "slip" (s) and is expressed as a percentage of the synchronous speed.

s = [(Ns - N) / Ns] x 100.

In operation, the rotor current frequency is obtained by multiplying the power supply frequency by the slip. When the motor is started, the rotor current frequency is at its maximum and equal to that of the stator current.
The stator current frequency gradually decreases as the motor gathers speed.

The slip in the steady state varies according to the motor load. Depending on the mains voltage, it will be less if the load is low and will increase if the motor is supplied at a voltage below the rated one.

Synchronous speed

The synchronous speed of 3-phase asynchronous motors is proportional to the power supply frequency and inversely proportional to the number of pairs in the stator.

Example: **Ns = 60 f/p**.

Where: Ns: synchronous speed in rpm
f: frequency in Hz
p: number of pairs of poles.

The table *(⇨ Fig. 5)* gives the speeds of the rotating field, or synchronous speeds, depending on the number of poles, for industrial frequencies of 50Hz and 60Hz and a frequency of 100Hz.

In practice, it is not always possible to increase the speed of an asynchronous motor by powering it at a frequency higher that it was designed for, even when the voltage is right. Its mechanical and electrical capacities must be ascertained first.

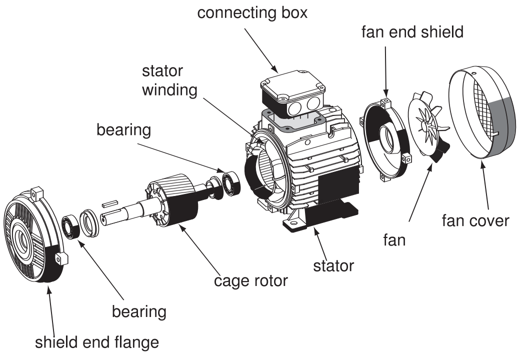
As already mentioned, on account of the slip, the rotation speeds of loaded asynchronous motors are slightly lower than the synchronous speeds given in the table.

Structure

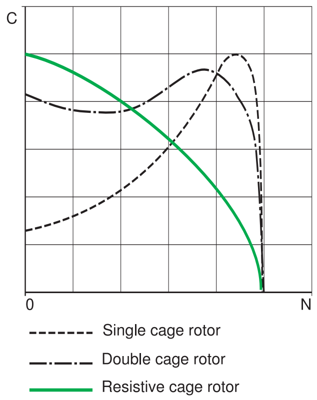
A 3-phase asynchronous squirrel cage motor consists of two main parts: an inductor or stator and an armature or rotor.

Stator

This is the immobile part of the motor. A body in cast iron or a light alloy houses a ring of thin silicon steel plates (around 0.5mm thick). The plates are insulated from each other by oxidation or an insulating varnish.
The "lamination" of the magnetic circuit reduces losses by hysteresis and eddy currents.



↑ *Fig. 6* *Exploded view of a squirrel cage rotor*



↑ *Fig. 7* *Torque/speed curves of cage rotor types (at nominal voltage)*

The plates have notches for the stator windings that will produce the rotating field to fit into (three windings for a 3-phase motor). Each winding is made up of several coils. The way the coils are joined together determines the number of pairs of poles on the motor and hence the speed of rotation.

□ Rotor

This is the mobile part of the motor. Like the magnetic circuit of the stator, it consists of stacked plates insulated from each other and forming a cylinder keyed to the motor shaft.

The technology used for this element divides asynchronous motors into two families: squirrel cage rotor and wound slip ring motors.

Types of rotor

□ Squirrel cage rotors

There are several types of squirrel cage rotor, all of them designed as shown in *figure 6*.

From the least common to the most common:

• Resistant rotor

The resistant rotor is mainly found as a single cage (see the definition of single-cage motors below). The cage is closed by two resistant rings (special alloy, reduced section, stainless steel rings, etc.).

These motors have a substantial slip at the rated torque. The starting torque is high and the starting current low *(⇨ Fig. 7)*.

Their efficiency is low due to losses in the rotor.

These motors are designed for uses requiring a slip to adapt the speed according to the torque, such as:
- several motors mechanically linked to spread the load, such as a rolling mill train or a hoist gantry,
- winders powered by Alquist (see note) motors designed for this purpose,
- uses requiring a high starting torque with a limited current inrush (hoisting tackle or conveyors).

Their speed can be controlled by changing the voltage alone, though this function is being replaced by frequency converters. Most of the motors are self-cooling but some resistant cage motors are motor cooled (drive separate from the fan).

Note: these force cooled asynchronous high-slip motors are used with a speed controller and their stalling current is close to their rated current; they have a very steep torque/speed ratio. With a variable power supply, this ratio can be adapted to adjust the motor torque to the requisite traction.

• Single cage rotor

In the notches or grooves round the rotor (on the outside of the cylinder made up of stacked plates), there are conductors linked at each end by a metal ring. The driving torque generated by the rotating field is exerted on these conductors. For the torque to be regular, the conductors are slightly tilted in relation to the motor axis. The general effect is of a squirrel cage, whence the name.

The squirrel cage is usually entirely moulded (only very large motors have conductors inserted into the notches). The aluminium is pressure-injected and the cooling ribs, cast at the same time, ensure the short-circuiting of the stator conductors.

These motors have a fairly low starting torque and the current absorbed when they are switched on is much higher than the rated current *(⇨ Fig. 7)*.

On the other hand, they have a low slip at the rated torque. They are mainly used at high power to boost the efficiency of installations with pumps and fans. Used in combination with frequency converters for speed control, they are the perfect solution to problems of starting torque and current.

- **Double cage rotor**

This has two concentric cages, one outside, of small section and fairly high resistance, and one inside, of high section and lower resistance.

- On first starting, the rotor current frequency is high and the resulting skin effect causes the entire rotor current to circulate round the edge of the rotor and thus in a small section of the conductors. The torque produced by the resistant outer cage is high and the inrush is low *(⇨ Fig. 7)*.
- At the end of starting, the frequency drops in the rotor, making it easier for the flux to cross the inner cage. The motor behaves pretty much as though it were made from a single non-resistant cage. In the steady state, the speed is only slightly less than with a single-cage motor.

- **Deep-notch rotor**

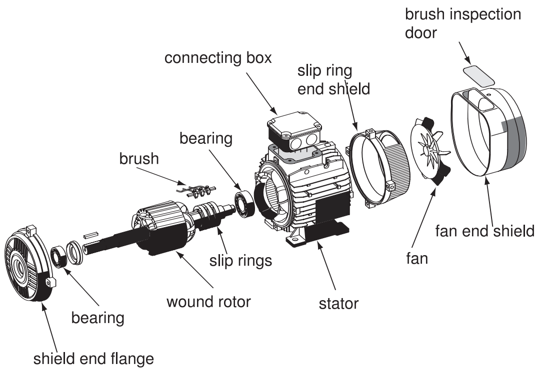
This is the standard rotor.

Its conductors are moulded into the trapezoid notches with the short side on the outside of the rotor.

It works in a similar way to the double-cage rotor: the strength of the rotor current varies inversely with its frequency.

Thus:

- on first starting, the torque is high and the inrush low,
- in the steady state, the speed is pretty much the same as with a single-cage rotor.



↑ *Fig. 8* *Exploded view of a slip ring rotor motor*

□ Wound rotor (slip ring rotor)

This has windings in the notches round the edge of the rotor identical to those of the stator *(⇨ Fig. 8)*.

The rotor is usually 3-phase. One end of each winding is connected to a common point (star connection). The free ends can be connected to a centrifugal coupler or to three insulated copper rings built into the rotor.

These rings are rubbed by graphite brushes connected to the starting device.

Depending on the value of the resistors in the rotor circuit, this type of motor can develop a starting torque of up to 2.5 times the rated torque.

The starting current is virtually proportional to the torque developed on the motor shaft.

This solution is giving way to electronic systems combined with a standard squirrel cage motor. These make it easier to solve maintenance problems (replacement of worn motor brushes, maintenance of adjustment resistors), reduce power dissipation in the resistors and radically improve the installation's efficiency.

3.2 Single-phase motors

The single-phase motor, though less used in industry than the 3-phase, is fairly widely used in low-power devices and in buildings with 230V single-phase mains voltage.

Squirrel cage single-phase motors

For the same power, these are bulkier than 3-phase motors.

Their efficiency and power factor are much lower than a 3-phase motor and vary considerably with the motor size and the manufacturer.

In Europe, the single-phase motor is little used in industry but commonly used in the USA up to about ten kW.

Though not very widely used, a squirrel cage single-phase motor can be powered via a frequency converter, but very few manufacturers offer this kind of product.

Structure

Like the 3-phase motor, the single-phase motor consists of two parts: the stator and the rotor.

- **Stator**

This has an even number of poles and its coils are connected to the mains supply.

- **Rotor**

Usually a squirrel cage.

Operating principle

Let's take a stator with two windings connected to the mains supply L1 and N (⇨ *Fig. 9*).

The single-phase alternating current generates a single alternating field H in the rotor – a superposition of the fields H1 and H2 with the same value and rotating in opposite directions.

At standstill, the stator being powered, these fields have the same slip in relation to the rotor and hence generate two equal and opposing torques.

The motor cannot start.

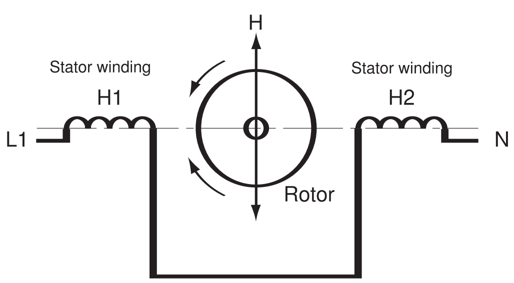
A mechanical pulse on the rotor causes unequal slips. One of the torques decreases while the other increases. The resulting torque starts the motor in the direction it was run in.

To overcome this problem at the starting stage, another coil offset by 90° is inserted in the stator.

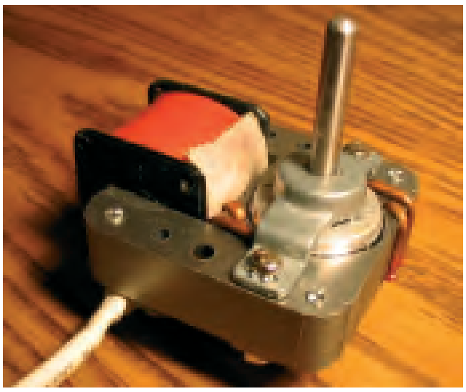
This auxiliary phase is powered by a phase shift device (capacitor or inductor); once the motor has started, the auxiliary phase can be stopped by a centrifugal contact.

Another solution involves the use of short circuit phase-shift rings, built in the stator which make the field slip and allow the motor to start. This kind of motor is only found in low-power devices (no more than 100W) (⇨ *Fig. 10*).

A 3-phase motor (up to 4kw) can also be used in a single phase arrangement: the starting capacitor is fitted in series or parallel with the idle winder. This system can only be considered as a stopgap because the performance of the motors is seriously reduced. Manufacturers leaflets give information regarding wiring, capacitors values and derating.



↑ *Fig. 9* *Operating principle of a single-phase asynchronous motor*



↑ *Fig. 10* *Single phase short circuit phase-shift rings*

↑ *Fig. 11* *Universal single phase motor*

Universal single-phase motors

Though little used in industry, this is most widely-made motor in the world. It is used in domestic appliances and portable tools.

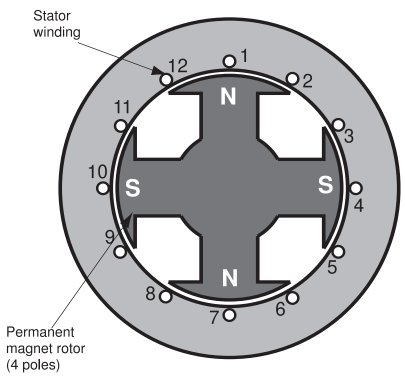
Its structure is similar to that of a series wound direct current motor *(⇨ Fig. 11)*. As the unit is powered by alternating current, the flux in the machine is inverted at the same time as the voltage, so the torque is always in the same direction.

It has a wound stator and a rotor with windings connected to rings. It is switched by brushes and a collector.

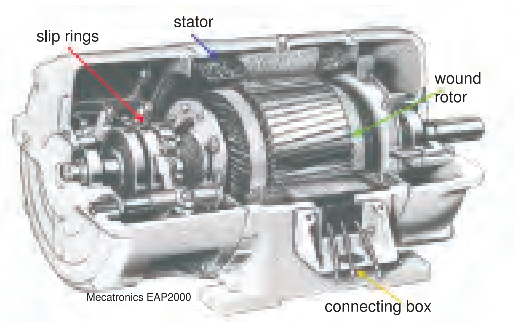
It powers up to 1000W and its no-load rotation speed is around 10,000 rpm. These motors are designed for inside use.

Their efficiency is rather poor.

3.3 Synchronous motors



↑ *Fig. 12* *Cross section of a 4 pole permanent magnet motor*



↑ *Fig. 13* *Synchronous wound rotor motor*

Magnetic rotor synchronous motors

Structure

Like the asynchronous motor, the synchronous motor consists of a stator and a rotor separated by an air gap. It is different in that the flux in the air gap is not due to an element in the stator current but is created by permanent magnets or by the inductor current from an outside source of direct current powering a winding in the rotor.

• **Stator**
The stator consists of a body and a magnetic circuit usually made of silicon steel plates and a 3-phase coil, similar to that of an asynchronous motor, powered by a 3-phase alternating current to produce a rotating field.

• **Rotor**
The rotor has permanent magnets or magnetising coils through which runs a direct current creating intercalated north-south poles. Unlike asynchronous machines, the rotor spins at the speed of the rotating field with no slip.

There are thus two distinct types of synchronous motor: magnetic motors and coil rotor motors.

- In the former, the rotor is fitted with permanent magnets *(⇨ Fig. 12)*, usually in rare earth to produce a high field in a small space.
  The stator has 3-phase windings.
  These motors support high overload currents for quick acceleration. They are always fitted with a speed controller. Motor-speed controller units are designed for specific markets such as robots or machine tools where smaller motors, acceleration and bandwidth are mandatory.
- The other synchronous machines have a wound rotor *(⇨ Fig. 13)*. The rotor is connected rings although other arrangements can be found as rotating diodes for example. These machine are reversible and can work as generators (alternators) or motors. For a long while, they were mainly used as alternators – as motors they were practically only ever used when it was necessary to drive loads at a set speed in spite of the fairly high variations in their load torque.

The development of direct frequency converters (of cycloconverter type) or indirect converters switching naturally due to the ability of synchronous machines to provide reactive power has made it possible to produce variable-speed electrical drives that are powerful, reliable and very competitive compared to rival solutions when power exceeds one megawatt.

Though industry does sometimes use asynchronous motors in the 150kW to 5MW power range, it is at over 5MW that electrical drives using synchronous motors have found their place, mostly in combination with speed controllers.

Operating characteristics

The driving torque of a synchronous machine is proportional to the voltage at its terminals whereas that of an asynchronous machine is proportional to the square of the voltage.

Unlike an asynchronous motor, it can work with a power factor equal to the unit or very close to it.

Compared to an asynchronous motor, a synchronous one has a number of advantages with regard to its powering by a mains supply with constant voltage and frequency:

- the motor speed is constant, whatever the load,
- it can provide reactive power and help improve the power factor of an installation,
- it can support fairly big drops in voltage (around 50%) without stalling due to its overexcitation capacity.

However, a synchronous motor powered directly by a mains supply with constant voltage and frequency does have two disadvantages:

- it is dificult to start; if it has no speed controller, it has to be no-load started, either directly for small motors or by a starting motor which drives it at a nearly synchronous speed before switching to direct mains supply,
- it can stall if the load torque exceeds its maximum electromagnetic torque and, when it does, the entire starting process must be run again.

Other types of synchronous motors

To conclude this overview of industrial motors, we can mention linear motors, synchronised asynchronous motors and stepper motors.

Linear motors

Their structure is the same as that of rotary synchronous motors: they consist of a stator (plate) and a rotor (forcer) developed in line. In general, the plate moves on a slide along the forcer.

As this type of motor dispenses with any kind of intermediate kinematics to transform movement, there is no play or mechanical wear in this drive.

Synchronised asynchronous motors

These are induction motors. At the starting stage, the motor works in asynchronous mode and changes to synchronous mode when it is almost at synchronous speed.

If the mechanical load is too great, it can no longer run in synchronous mode and switches back to asynchronous mode.

This feature is the result of a specific rotor structure and is usually for low-power motors.

Stepper motors

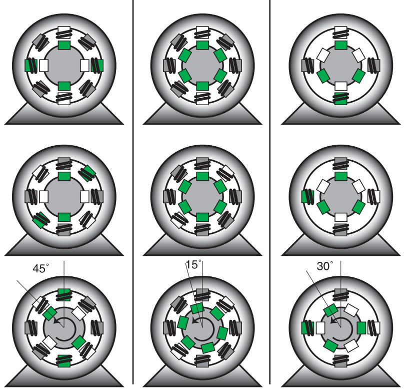
The stepper motor runs according to the electrical pulses that power its coils. Depending on the electricity supply, it can be:

- unipolar if the coils are always powered in the same direction by a single voltage;
- bipolar if the coils are powered first in one direction then in the other. They create alternating north and south poles.

Stepper motors can be variable reluctance, magnetic or both *(⇨ Fig. 14)*.

The minimum angle of rotation between two electrical pulse changes is called a step. A motor is characterised by the number of steps per revolution (i.e. 360°). The common values are 48, 100 or 200 steps per revolution.

Type	**Permanent magnet bipolar**	**Variable reluctance unipolar**	**Hybrid Bipolar**
Caracteristics	2 phases, 4 wires	4 phases, 8 wires	2 phases 14 wires
No. of steps/rev.	8	24	12
Operating stages			
Step 1			
Intermediate state			
Step 2			



↑ *Fig. 14* *Type of stepper motors*

Schneider Electric

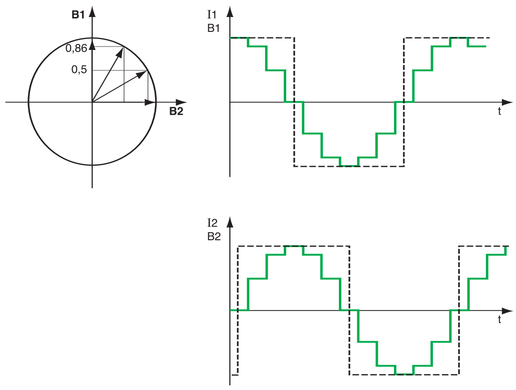


Fig. 15 *Current steps in motor coils to shorten its step*

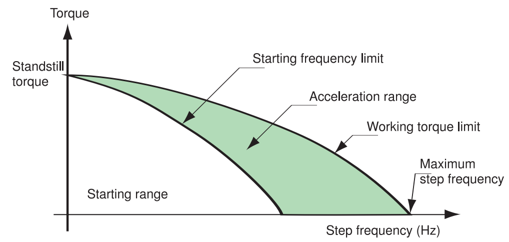


Fig. 16 *Maximum torque depending on step frequency*

The motor rotates discontinuously. To improve the resolution, the number of steps can be increased electronically (micro-stepping). This solution is described in greater detail in the section on electronic speed control.

Varying the current in the coils by graduation *(⇨ Fig. 15)* results in a field which slides from one step to the next and effectively shortens the step.

Some circuits for micro-steps multiply by 500 the number of steps in a motor, changing, e.g. from 200 to 100,000 steps.

Electronics can be used to control the chronology of the pulses and count them. Stepper motors and their control circuits regulate the speed and amplitude of axis rotation with great precision.

They thus behave in a similar way to a synchronous motor when the shaft is in constant rotation, i.e. specific limits of frequency, torque and inertia in the driven load *(⇨ Fig. 16)*.

When these limits are exceeded, the motor stalls and comes to a standstill.

Precise angular positioning is possible without a measuring loop. These motors, usually rated less than a kW, are for small low-voltage equipment. In industry, they are used for positioning purposes such as stop setting for cutting to length, valve control, optical or measuring devices, press or machine tool loading/unloading, etc.

The simplicity of this solution makes it particularly cost-effective (no feedback loop). Magnetic stepper motors also have the advantage of a standstill torque when there is no power. However, the initial position of the mobile part must be known and integrated by the electronics to ensure efficient control.

3.4 Direct current motors commonly named DC motors

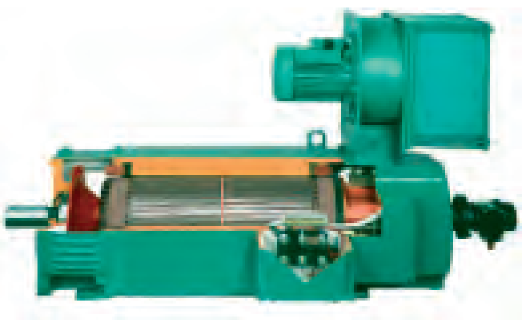


Fig. 17 *DC motor*

Separate excitation, DC motors *(⇨ Fig. 17)* are still used for variable speed drive, though they are seriously rivalled by asynchronous motors fitted with frequency converters.

Very easy to miniaturise, they are ideal for low-power and low-voltage machines. They also lend themselves very well to speed control up to several megawatts with inexpensive and simple high-performance electronic technologies (variation range commonly of 1 to 100).

They also have features for precise torque adjustment in motor or generator application. Their rated rotation speed, independent of the mains frequency, is easy to adapt for all uses at the manufacturing stage.

On the other hand, they are not as rugged as asynchronous motors and their parts and upkeep are much more expensive as they require regular maintenance of the collectors and brushes.

Structure

A DC motor consists of the following components:

Inductor or stator

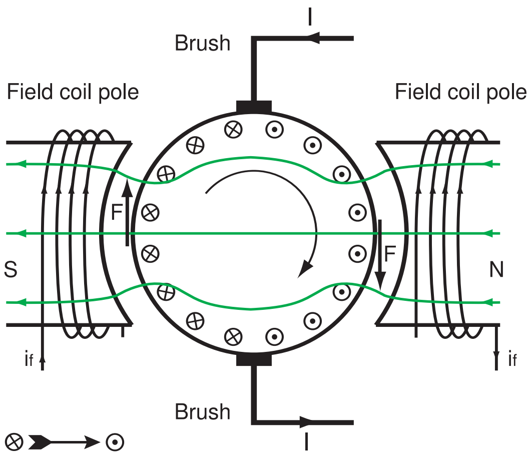
This is a part of the immobile magnetic circuit with a coil wound on it to produce a magnetic field, this winding can be replaced by permanent magnets specially in the low power range. The resulting electromagnet has a cylindrical cavity between its poles.

Armature or rotor

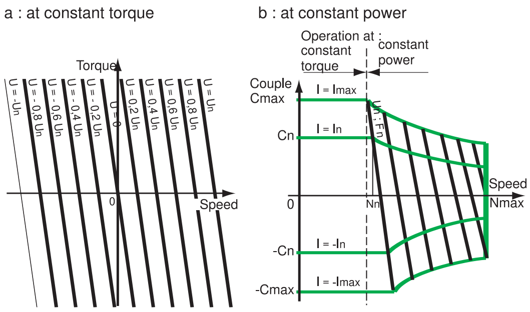
This is a cylinder of magnetic plates insulated from each other and perpendicular to the cylinder axis. The armature is mobile, rotates on its axis and is separated from the inductor by an air gap. The conductors are distributed regularly around it.

Collector and brushes

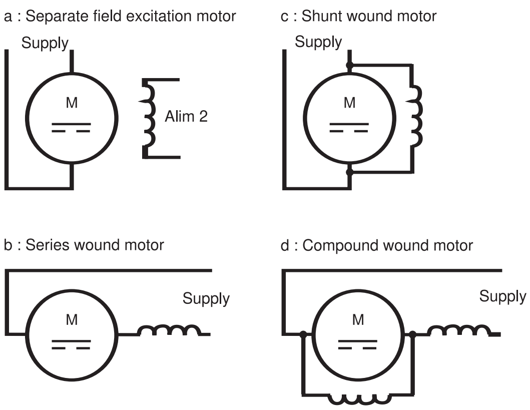
The collector is built into the armature. The brushes are immobile and rub against the collector to power the armature conductors.



↑ *Fig. 18* *Production of torque in a DC motor*



↑ *Fig. 19* *Torque/speed curves of a separate excitation motor*



↑ *Fig. 20* *Diagrams of direct current motor types*

Operating principle

When the inductor is powered, it creates a magnetic field (excitation flux) in the air gap, directed by the radii of the armature. The magnetic field "enters" the armature on the north pole side of the inductor and "leaves" it on the south pole side.

When the armature is powered, its conductors located below one inductor pole (on the same side as the brushes) are crossed by currents in the same direction and so are subjected to a Lorentz law force. The conductors below the other pole are subjected to a force of the same strength and in the opposite direction. Both forces create a torque which rotates the motor armature *(⇨ Fig. 18)*.

When the motor armature is powered by a direct or rectified voltage U and the rotor is rotating, a counter-electromotive force E is produced. Its value is E = U – RI.

RI represents the drop in ohm voltage in the armature. The counter-electromotive force E is related to the speed and excitation by **E = k** ω ϕ

where:
- k is a constant of the motor itself,
- ω is the angular speed,
- ϕ, is the flux.

This relationship shows that, at constant excitation, the counter-electromotive force E, proportional to ω, is an image of the speed.

The torque is related to the inductor flux and the current in the armature by: **T = k** ϕ **I**

When the flux is reduced, the torque decreases.

There are two ways to increase the speed:
- increasing the counter-electromotive force E and thus the supply voltage: this is called "constant torque" operation,
- decreasing the excitation flux and hence the excitation current, and maintain a constant supply voltage: this is called "reduced flux" or constant power operation. This operation requires the torque to decrease as the speed increases *(⇨ Fig. 19)*.

Furthermore, for high constant power ratios, this operation requires motors to be specially adapted (mechanically and electrically) to overcome switching problems.

Operation of such devices (direct current motors) is reversible:
- if the load counters the rotation movement (resistant load), the device produces a torque and operates as a motor,
- if the load makes the device run (driving load) or counters slowdown (standstill phase of a load with a certain inertia), the device produces electrical power and works as a generator.

Types of direct current wound motors *(⇨ Fig. 20)*

- **a and c parallel excitation motor (separate or shunt)**

The coils, armature and inductor are connected in parallel or powered by two different sources of voltage to adapt to the features of the machine (e.g.: armature voltage of 400V and inductor voltage of 180V). Rotation is reversed by inverting one of the windings, usually by inverting the armature voltage because of the much lower time constants. Most bi-directional controllers for DC motors work this way.

- **b series excitation motor**

This has a similar structure to the shunt excitation motor. The inductor coil is connected in series with the armature coil, hence the name. Rotation is reversed by inverting the polarities of the armature or the inductor. This motor is mainly used for traction, in particular in trolleys powered by accumulator batteries. In locomotive traction, the older TGVs were driven by this sort of motor; the later ones use asynchronous motors.

- **series parallel motor (compound)**

This technology combines the benefits of the series and parallel excitation motors. It has two windings. One is parallel to the armature (shunt winding) or is a separate excitation winding. It is crossed by a current that is weak compared to the working current. The other is in series. The motor has an added flux under the combined effect of the ampere-turns of both windings. Otherwise, it has a subtracted flux, but this system is rarely used because it causes operating instability at high loads.

3.5 Operating asynchronous motors

Squirrel cage motors

Consequences of variation in voltage

- **Effects on the current**

Voltage increase has two effect. During the starting phase the inrush current will be higher than nominal and when the machine will be running, the absorbed current increases steeply and the machine is likely to overheat, even when operating at low load. This increase is due to the saturation of the machine.

- **Effect on speed**

When the voltage varies, the synchronous speed is not altered but, when a motor is loaded, an increase in voltage causes the slip to decrease slightly. In practical terms, this property cannot be used due to the saturation of the motor, the current increases steeply and the machine is likely to overheat. Likewise, if the supply voltage decreases, the slip increases and the absorbed current increases to provide the torque, which may also cause overheating.

Furthermore, as the maximum torque decreases with the square of the voltage, there is a likelihood of stalling if the voltage drops steeply.

Consequences of a variation in frequency

- **Effect on the torque**

As in any electrical machine, the torque of an asynchronous motor is of the type: **T = K I** ϕ.

(K = constant factor dependent on the machine) .

In the equivalent diagram as shown *(⇨ Fig. 21)*, the coil L produces the flux and Io is the magnetising current. Note that the equivalent schema of an asynchronous motor is the same as that of a transformer and both devices are characterised by the same equation.

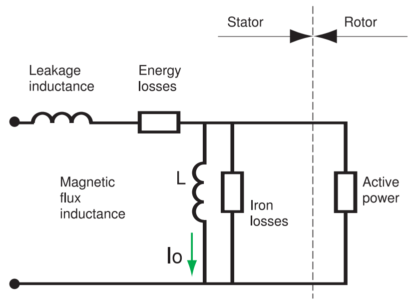


Fig. 21 *Equivalent diagram of an asynchronous motor*

In an initial approximation, forgetting the resistance and considering the magnetising inductance only (i.e. for frequencies of a few Hertz) the Io current is expressed as: **Io = U / 2π L f** and the flux expressed as:
ϕ **= k Io**.

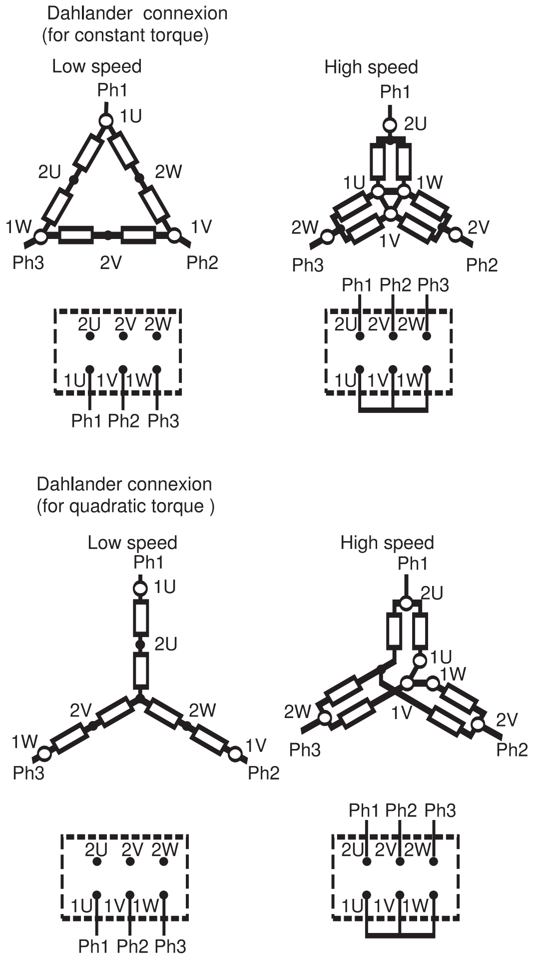
The machine torque is therefore expressed as:
T = K k Io I. Io and **I** are the rated currents the motor is sized for.

To keep within the limits, Io must be maintained at its rated value, which can only be the case if the U/f ratio remains constant.

Consequently, the torque and rated currents can be obtained as long as the supply voltage U can be adjusted to the frequency.

When this is not possible, the frequency can still be increased, but the Io current decreases and so does the working torque since it is not possible to exceed the machine's rated current continuously without running the risk of overheating it.

To operate with a constant torque at any speed the U/F ratio must be kept constant. This is what a frequency converter does.



↑ *Fig. 22* *Types of Dahlander connections*

- **Effect on speed**

The rotation speed of an asynchronous motor is proportional to the frequency of the supply voltage. This property is often used to operate specially designed machines at high speed, e.g. with a power supply at 400Hz (grinders, laboratory or surgical devices, etc.). Speed can also be varied by adjusting the frequency, for example from 6 to 50Hz (conveyor rollers, hoisting equipments, etc.).

□ Speed control in 3-phase asynchronous motors

For a long time, there were not many ways of controlling the speed of asynchronous motors. Squirrel cage motors mostly had to be used at their rated RPM.

Set speeds could practically only be obtained by motors with pole changing or separate stator windings, which are still widely in use.

With frequency converters i.e. AC drives, squirrel cage motors are now often speed-controlled, so can be used for purposes hitherto confined to direct current motors.

□ Pole-changing motors

As we have already seen, the speed of a squirrel cage motor depends on the mains supply frequency and the number of pairs of poles. So a motor with two or more speeds can be made by combining windings in the stator to correspond to different numbers of poles.

This type of motor can only have1/2 speed ratios (4 and 8 poles, 6 and 12 poles, etc.). It has six terminals (⇨ *Fig.22*).

For one of these speeds, the mains supply is connected to the three corresponding terminals. For the other, these terminals are connected to each other and the mains is connected to the remaining three.

Mostly, for both high and low speed, the motor is started direct on line involving no special device (direct starting).

In some cases, if the operating conditions require it and the motor allows it, the starting device automatically moves into low speed before changing to high speed or before stopping.

Depending on the currents absorbed by the Low Speed (LS) or High Speed (HS) changes, both speeds can be protected by a single thermal relay or by two relays (one for each speed).

Such motors usually have low efficiency and a fairly low power factor.

□ Separate stator winding motors

These motors, with two electrically separate stator windings, can produce two speeds in any ratio. However, their electrical characteristics are often affected by the fact that the low speed windings have to support the mechanical and electrical stress of high speed operation. So motors in low speed mode sometimes absorb more current than they do in high speed mode.

Three or four speed motors can be made by changing the poles on one or both of the stator windings. This solution requires additional connectors on the coils.

■ Slip-ring motors

□ Rotor resistance

The resistor externally inserted into the rotor circuit in this kind of motor defines:

- its starting torque,
- its speed.

A resistor permanently connected to the terminals of a slip-ring motor lowers its speed and the higher its value, the more the speed drops. This is a simple solution for speed variation.

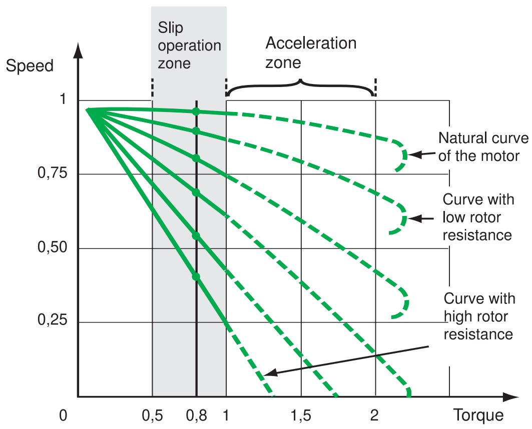


Fig. 23 Torque speed characteristics of a slip ring motor

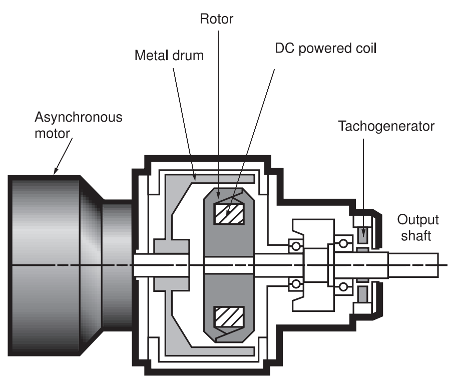


Fig. 24 Cross section of an eddy current drive

Slip-ring speed control

Slip-ring rotor resistors can be short-circuited in several steps to adjust speed discontinuously or accelerate gradually and fully start the motor. They have to support the entire duration of operation, especially when they are intended for speed control. This implies they can be bulky and costly.
This very simple process is used less and less because it has two major drawbacks:

- at low speed, a great deal of power from the mains supply is dissipated and lost in the resistors,
- the speed obtained is not independent of the load but varies with the load torque the machine exerts on the motor shaft (⇨ Fig. 23).

For any one resistor, the slip is proportional to the torque. For instance, the drop in speed caused by a resistor can be 50% at full load and only 25% at half load, whereas at no load, the speed hardly changes and is closed to the synchronous speed minus the slip.

If the machine is constantly monitored by an operator, this one can change the resistor value as required to set the speed in a certain area for fairly high loas, but adjustment is practically impossible at no load condition.
To reach a point of “low speed at low torque”, it inserts a very high resistance and then the slightest variation in the load torque changes the speed from zero to nearly 100%. This is too unstable.

Adjustment can also be impossible for machines with specific variation of the load torque relevant to the speed.

Example of slip ring operation. For a variable load exerting a load torque of 0.8 Cn, different speeds can be obtained as represented by the sign • in the diagram (⇨ Fig. 23).

For the same torque, the speed decreases as the rotor resistance increases.

Other speed control systems

Variable voltage regulator

This device is only used in low-powered asynchronous motors. It requires a resistant squirrel cage motor.

The speed is controlled by increasing the motor slip once the voltage drops.

Its use was fairly widespread in cooling systems, pumps and compressors, uses for which its torque availability gives satisfactory results. It is gradually giving way to more cost-effective frequency converters.

Other electromechanical systems

The other electromechanical speed control systems mentioned below are less used now that electronic speed controllers are in common use.

- **AC squirrel cage motors (Schrage)**

These are special motors where the speed is controlled by varying the position of the brushes on the collector in relation to the neutral.

- **Eddy current drives**

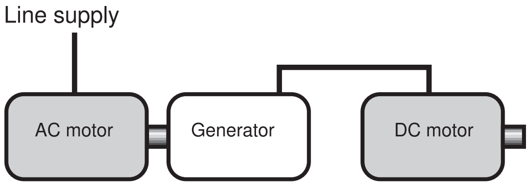
This consists of a drum connected directly to an asynchronous motor running at constant speed and a rotor with a coil feeded with direct current (⇨ Fig.24).

The movement is transmitted to the output shaft by electromagnetic coupling. The slip of the unit can be adjusted by adjusting coil excitation.

A built-in tacho-generator is used to control velocity with precision.

A ventilation system is used to evacuate the losses due to the sleep. This was a principle widely used in hoisting apparatus, cranes in particular.

Its structure makes it a robust system with no wearing parts that can be used for occasional purposes and up to a power of 100kW.



↑ *Fig. 25* *Ward Leonard arrangement*

- **Ward Leonard motor generator set**

This device, once very widespread, is the forerunner of DC motor speed controllers. It has a motor and a DC generator which feeds a DC motor *(⇨ Fig. 25)*.

The speed is controlled by regulating the excitation of the generator. A very small current is used to control powers of several hundred kW in all the torque and speed quadrants. This type of controller was used in rolling mills and pithead lifts.

This was the most efficient speed control system before it was made obsolete by the semiconductor.

□ **Mechanical and hydraulic speed controllers**

Mechanical and hydraulic speed controllers are still in use.

Many mechanical speed control systems have been designed (pulleys/belts, bearings, cones, etc.). The drawbacks of these controllers are that they require careful maintenance and do not lend themselves easily to servocontrol. They are now seriously rivalled by frequency converters.

Hydraulic speed controllers are still widely used for specific purposes.

They have substantial power weight ratios and a capacity to develop continuous high torques at zero speed. In industry, they are mostly used in power-assisted systems.

As this type of speed controller is not relevant to this guide, we shall not describe it in detail.

3.6 Electric motor comparison

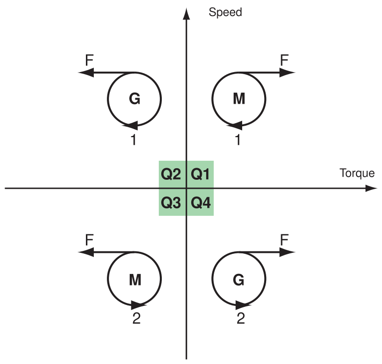
The table *(⇨ Fig. 26)* gives a brief summary of all the types of electric motor available, their main feature and fields of use.

We should point out the place held by 3-phase squirrel cage motors where the description "standard" is all the more relevant since the development of electronic speed control devices has fitted them perfectly to fit closely to the application.

Type of motor	**Asynchronous squirrel cage**		**Asynchronous slip-ring**	**Synchronous wound rotor**	**Rare earth rotor**	**Stepper**	**Direct current**
	3 phases	**Single-phase**					
Cost of motor	Low	Low	High	High	High	Low	High
Sealed motor	Standard	Possible	Option, expensive	Option, expensive	Standard	Standard	Possible Very expensive
Starting direct on line	Easy	Easy	Special starting device	Impossible after a few kW	Not designed for	Not designed for	Not designes for
Speed control	Easy	Very unusual	Possible	Frequent	Always	Always	Always
Cost of speed control solution	Increasingly cost-effective	Very cost-effective	Cost-effective	Cost-effective	Fairly cost-effective	Very cost-effective	Very cost-effective
Speed control performance	High to very high	Very low	Average	High to very high	Very high	high	High to very high
Mode	Constant or variable speed	Mainly constant speed	Constant or variable speed	Constant or variable speed	Variable speed	Variable speed	Variable speed
Industrial use	Universal	For low powers	Decreasing	High powers at medium voltage	High-dynamic machine tools	Open loop positioning for low powers	Decreasing

↑ *Fig. 26* *Comparison of electric motors*

3.7 Types of loads



Rotation direction	Mode	Torque T	Speed S	Product TS	Quadrant
1 (clockwise)	Driver	yes	yes	yes	1
	Generator		yes		2
2 (anticlockwise)	Driver			yes	3
	Generator	yes			4

Fig. 27 *The four possible situations for a machine in a torque-speed diagram*

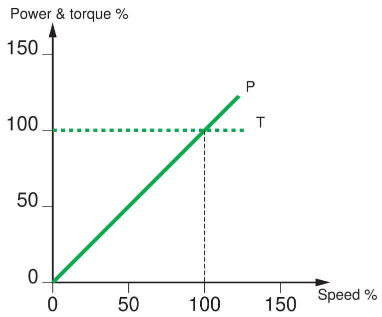
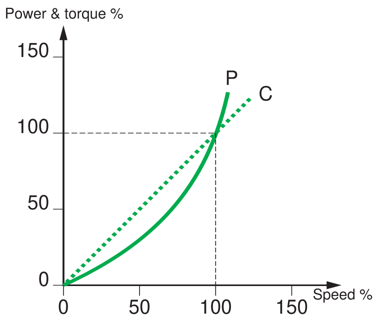


Fig. 28 *Constant torque operation curve*

a



b

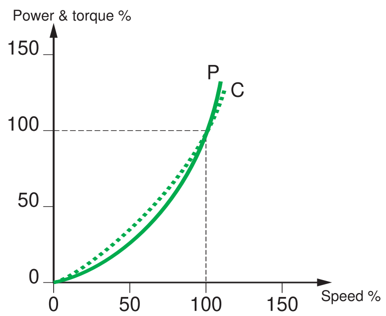


Fig. 29 a/b *Variable torque operation curve*

We can classify the loads in two families:
- the active loads which put moving a mobile or a fluid or which change its state like the gas state in the liquid state,
- the passive loads which do not get a driving force like lighting or the heating.

Active loads

This term covers all systems designed to set a mobile object or a fluid in motion.

The movement of a mobile object involves changing its speed or position, which implies applying a torque to overcome its resistance to movement so as to accelerate the inertia of the load. The speed of movement is directly related to on the torque applied.

Operating quadrants

The *figure 27* illustrates the four possible situations in the torque-speed diagram of a machine.

Note that when a machine works as a generator it must have a driving force. This state is used in particular for braking. The kinetic energy in the shaft is either transferred to the power system or dissipated in a resistor or, for low power, in machine losses.

Types of operation

• Constant torque operation

Operation is said to be constant torque when the charge's characteristics in the steady state are such that the torque required is more or less the same whatever the speed (⇨ *Fig. 28*).

This is the operating mode of machines like conveyors, crushers or hoists. For this kind of use, the starter device must be able to provide a high starting torque (1.5 times or more the nominal rate) to overcome static friction and accelerate the machine (inertia).

• Operation with torque increasing with speed

The characteristics of the charge imply that the torque required increases with the speed. This particularly applies to helical positive displacement pumps where the torque increases linearly with the speed (⇨ *Fig. 29a*) or centrifugal machines (pumps and fans) where the torque varies with the speed squared (⇨ *Fig. 29b*).

The power of displacement pumps varies with the speed squared.

The power of centrifugal machines varies with the speed cubed.

A starter for this type of use will have a lower starting torque (1.2 times the motor's nominal torque is usually enough).

3

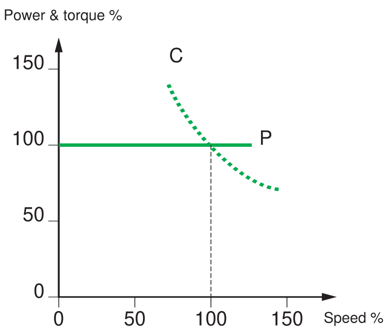


Fig. 30 *Decreasing torque operation*

• **Operation with torque decreasing with speed**

For some machines, the torque required decreases as the speed increases. This particularly applies to constant-power operation when the motor provides a torque that is inversely proportional to the angular speed (⇨ *Fig.30*).

This is so, for example, with a winder, where the angular speed needs to drop as the diameter of the winder increases with the build-up of material. It also applies to spindle motors on machine tools.

The constant-power operating range limited by its very nature: at low speed by the available current from the speed controller and at high speed by the torque the motor can provide. The driving torque on asynchronous motors and the switching capacity of DC motors should therefore be checked carefully.

The table (⇨ *Fig.31*) gives a list of common machines with their torque law depending on speed.

Type of machine	Torque law depending on speed
Conveyor	Constant
Rotary press	Constant
Helical displacement pump	Torque increasing linearly with speed
Metering pump	Constant
Centrifugal pump	Torque increasing with the speed squared
Fans and blowers	Torque increasing with the speed squared
Screw compressor	Constant
Scroll compressor	Constant
Piston compressor	Constant
Cement kiln	Constant
Extruding machine	Constant or decreasing linearly with speed
Mechanical press	Constant
Winders, unwinders	Constant or decreasing linearly with speed
Pulpers	Constant
Sectional machine	Constant
Crusher	Constant
Mixer	Torque increasing linearly with speed
Kneader, calender	Constant or decreasing linearly with speed
Centrifuge	Torque increasing with the speed squared
Machine tool spindle	Constant or decreasing linearly with speed
Hoist	Constant

Fig. 31 *Torque characteristic per machine*

When a machine starts, it often happens that the motor has to overcome a transitory torque, such as in a crusher when it starts with a full hopper. There can also be dry friction which disappears when a machine is running or a machine starting from a cold stage may needs a higher torque than in normal operation when warm.

Passive loads

There are two types of passive charge used in industry:
- heating,
- lighting.

3

Heating

Heating is a costly item for industrial premises. To keep these costs down, heat loss must be reduced; this is a factor which depends on building design and is beyond the scope of this guide.

Every building is a specific case and we cannot allow ourselves to give vague or irrelevant answers.

That said, proper management of the building can provide both comfort and considerable savings. For further information, please see the Schneider Electric *Electrical Installation Guide* or the *Cahier Technique 206* available from the Schneider Electric website.

If necessary, the best solution may be found by asking the advice of the electrical equipment supplier's experts.

Lighting

• Incandescent lighting

Incandescent lighting (trademarked by Thomas Edison in 1879) was an absolute revolution and, for many years afterwards, lighting was based on devices with a filament heated to a high temperature to radiate visible light. This type of lighting is still the most widely used but has two major disadvantages:

- extremely low efficiency, since most of the electricity is lost in heat consumption,
- the lighting device has a lifetime of a few thousand hours and has to be regularly changed. Improvements have increased this lifetime (by the use of rare gases, such as krypton, or halogen).

Some countries (Scandinavian ones in particular) plan to ban this type of lighting eventually.

• Fluorescent lighting

This family includes fluorescent tubes and fluocompact lamps.
The technology used is usually “low-pressure mercury”.

Fluorescent tubes

These were introduced in 1938. In these tubes, an electric discharge makes electrons collide with mercury vapour, which excites the mercury atoms and results in ultraviolet radiation.

The fluorescent matter lining the inside of the tube transforms the radiation into visible light.

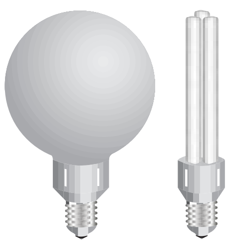
Fluorescent tubes dissipate less heat and last longer than incandescent lamps but require the use of two devices: one to start them and one called a ballast to control the current of the arc once they are switched on.

The ballast is usually a current limiting reactor connected in series with the arc.

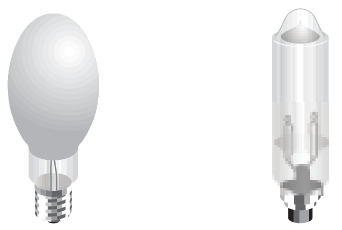
Fluocompact lamps *(⇨ Fig.32)*

These work to the same principle as a fluorescent tube. The starter and ballast functions are performed by an electronic circuit in the lamp, which enables the tubes to be smaller and to be folded.

Fluocompact lamps were developed as an alternative to incandescent lamps: they save a significant amount of power (15W instead of 75W for the same brightness) and last much longer (8000 hours on average and up to 20,000 for some).



↑ *Fig. 32* *Fluo compact lamps*



↑ *Fig. 33* *Discharge lamps*

Discharge lamps *(⇨ Fig.33)*
Light is produced by an electric discharge created by two electrodes within a gas in a quartz bulb. Such lamps all require a ballast, usually a current limiting reactor, to control the current in the arc.

The emission range depends on the gas composition and is improved by increasing the pressure. Several technologies have been developed for different functions.

Low-pressure sodium vapour lamps
These have the best lighting capacity but they have a very poor colour rendition because they radiate a monochrome orange light.

Uses: motorway lighting, tunnels.

High-pressure sodium vapour lamps

These emit a white light tinged with orange.

Uses: urban lighting, monuments.

☐ High-pressure mercury vapour lamps

The discharge is produced in a quartz or ceramic bulb at pressures exceeding 100kPa. The lamps are known as fluorescent bulbs and are characterised by the bluish white light they emit.

Uses: car parks, supermarkets, warehouses.

• **Metal halide lamps**
This is the most recent technology. The lamps emit a colour with a wide spectrum.

The tube is in ceramic to enhance lighting capacity and colour stability.

Uses: stadiums, shops, spotlighting.

• **LED (Light Emitting Diodes))**
This is one of the most promising technologies. LEDs emit light by means of an electric current through a semiconductor.

LEDs are used for many purposes but the recent development of blue or white diodes with a high lighting capacity opens up new avenues, in particular for signage (traffic lights, safety displays or emergency lighting) and motor vehicle lighting.

A LED has an average current of 20mA, with a voltage drop of 1.7 to 4.6 depending on the colour. Such properties are suited to very low voltage power supply, for batteries in particular.

Mains power requires the use of a transformer, which is economically perfectly feasible.

The advantage of LEDs is their low power consumption which results in a very low operating temperature and an almost unlimited lifetime. In the near future, it will be possible to incorporate such a lighting into buildings at the construction stage.

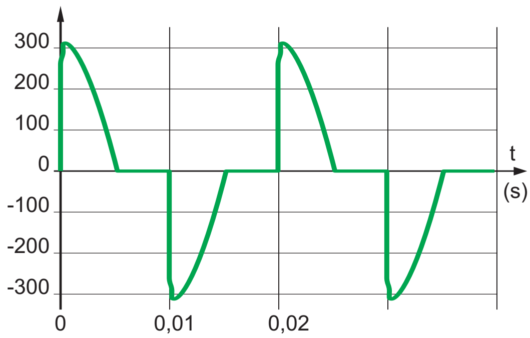
However, a basic diode has a very low lighting capacity. Powerful lighting therefore requires a great many units to be connected in a series.

As LEDs have no thermal inertia, they can be used for innovating purposes such as simultaneous transmission of light and data. To do this, the power supply is modulated with high frequency. The human eye cannot detect this modulation but a receiver with the right interface can detect the signals and use them.

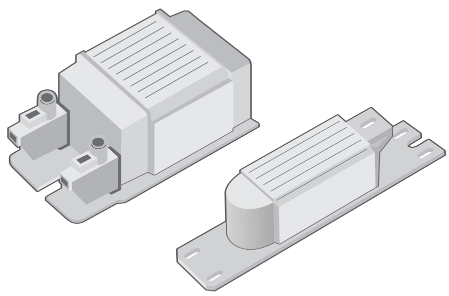
☐ Powering incandescent lamps

• **Constraints of direct powering**
The resistance of the filament varies widely due to the very high temperatures (up to 2500°C) it can reach during operation.

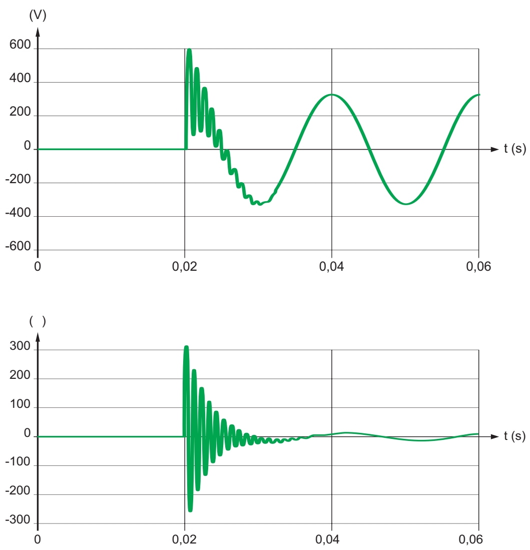
When cold, resistance is low, resulting in a power inrush current for a few to several dozen milliseconds when the lamp is switched on and which can be 10 to 15 times that of the nominal current.



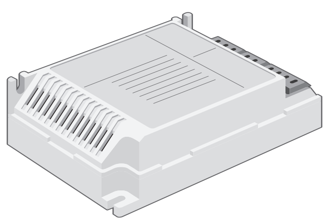
↑ Fig. 34 *Current waveform*



↑ Fig. 35 *Magnetic ballast*



↑ Fig. 36 *Voltage and current waveforms*



↑ Fig. 37 *Electronic ballast package*

This constraint applies equally to ordinary and halogen lamps. It requires reducing the maximum number of lamps that can be powered by the same device such as a remote control, modular contactor or relay on ready-made circuits.

- **Light dimming**

This can be achieved by varying the RMS voltage powering the lamp.

Voltage is usually adjusted by a triac used to vary the triggering angle in the mains voltage cycle.

The waveform of the voltage applied to the lamp is illustrated (⇨ Fig. 34).

Gradual powering of the lamp also reduces, or even eliminates, the power surge when it is switched on.

Note that light dimming:
- alters the colour temperature,
- shortens the life of halogen lamps when low voltage is maintained for long periods. The filament is not regenerated so efficiently at low temperature.

Some halogen lamps are powered at low voltage through a transformer. Magnetisation in a transformer can produce power surges 50 to 75 times greater than the nominal current for a few milliseconds.

Suppliers also offer static converters which do away with this disadvantage.

- **Powering fluorescent lamps and discharge lamps**

Fluorescent tubes and discharge lamps require control of arc intensity. This function is performed by a ballast device inside the bulb itself.

The magnetic ballast (i.e. limiting current reactor (⇨ Fig.35) is commonly used in domestic appliances.

A magnetic ballast works in conjunction with the starter device. It has two functions: to heat the electrodes in the tube and to generate a power surge to trigger the tube.

The power surge is induced by triggering a contact (controlled by a bimetal switch) which breaks the current in the magnetic ballast.

When the starter is working (for about 1 sec.), the current absorbed by the light is about twice the nominal current.

As the current absorbed by the tube and ballast together is mainly inductive, the power factor is very low (0.4-0.5 on average). In fixtures with a large number of tubes, a capacitor must be used to improve the power factor.

This capacitor is usually applied to each light appliance.

Capacitors are sized to ensure that the overall power factor exceeds 0.85.

In the most common type, the parallel capacitor, the average active power is 1µF for 10W for all types of lamp.

The parallel capacitor layout creates stress when the lamp is switched on.

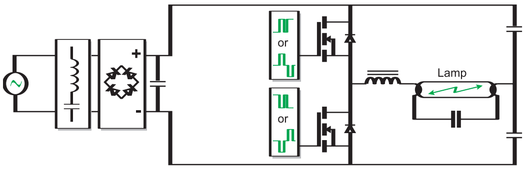
As the capacitor is initially discharged, switching on creates causes a power surge (⇨ Fig.36).

There is also a power surge due to oscillation in the power inductor/capacitor circuit.

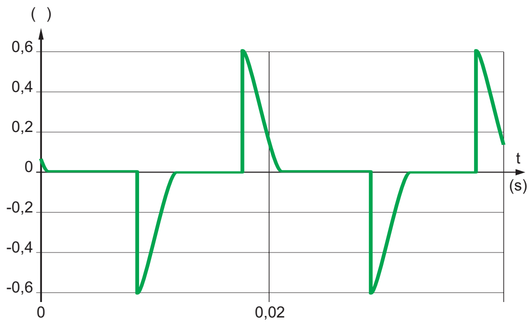
The electronic ballast (⇨ Fig. 37), first introduced in the 1980s, does away with these disadvantages.

The electronic ballast works by powering the lamp arc by an electronic device generating a rectangular alternating voltage.

There are low frequency or hybrid devices, with frequency ranging from 50 to 500Hz, and high frequency devices with frequency ranging from 20 to 60kHz. The arc is powered by high frequency voltage which completely eliminates flickering and strobe effects.



↑ *Fig. 38* *Electronic ballast schematics*



↑ *Fig. 39* *Current waveform of an electronic ballast*

The electronic ballast is totally silent. When a discharge lamp is heating up, it supplies it with increasing voltage while maintaining a virtually constant current. At continuous rating, it regulates the voltage applied to the lamp independently of fluctuations in the mains voltage.

As the arc is powered in optimal voltage conditions, 5-10% of power is saved and the lifetime of the lamp is increased. Furthermore, the output of an electronic ballast can exceed 93%, whereas that of a magnetic device is on average only 85%. The power factor is high (> 0.9).

An electronic ballast does however have some constraints with regard to the layout used *(⇨ Fig. 38)*, since a diode bridge combined with capacitors leads to a power surge when the device is switched on. In operation, the absorbed current is high in third harmonic *(⇨ Fig. 39)*, resulting in a poor power factor of around 55%.

The third harmonic overloads in the neutral conductor. For more information, see *Cahier Technique 202: The singularities of the third harmonic*.

Electronic ballasts usually have capacitors between the power conductors and the earth. These anti-interference capacitors induce a constant leakage current of about 0.5-1mA per ballast.

This limits the number of ballasts that can be powered when a residual current device (RCD) is installed (*see the Cahier Technique 114 Residual current device in LV*).

3.8 Valves and electric jacks

Forward

To complete the view of industrial loads that can be linked to automation systems, we should include a brief description of some commonly used devices: electrically-controlled screwjacks and valves.
Processes require loads to be positioned and moved. This function is ensured by pneumatic and hydraulic screwjacks, but can also be controlled by electromechanical ones. These can be built into motor starter units or linked to regulating devices for, e.g. positioning control. The following pages give short description of these positioning devices.
There is a very large market in valves to control fluid flow. These are used to:
- arrest fluid flow (stop valves),
- change the fluid circuit (3-channel valves),
- blend products (mixer valves),
- control flow (regulation valves).

Fluids can be liquids or gases (ventilation or chemical industry).

Electric scewjacks

Linearly driven applications require heavy-duty electric screwjacks that are powerful, fast, long-lived and reliable.

Manufacturers offer wide ranges of electric screwjacks for practically all requirements.

Structure of an electric screwjack

Electric screwjacks *(⇨ Fig.40)* comprise a control shaft or driving member, a guide unit and an electric motor.

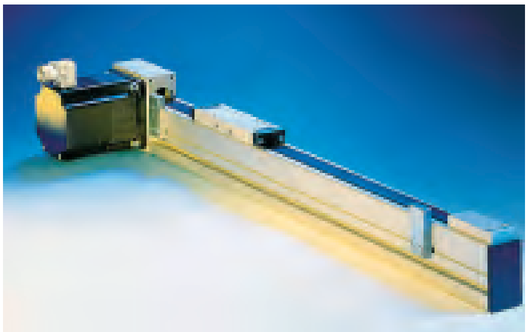
The photo shows an electric screwjack for linear movement.

The movement of the driving member can be linear, for travel, or rotational.

For linear movement, a screw nut system makes the driving member travel in a line.

Two of the most common systems are the ball screw and the acme screw.

The acme screw is made of rolled steel and the nut is made of plastic.



↑ *Fig. 40* *Electric screwjacks*

↑ *Fig. 41* *High performance electric screwjack*

This is a fairly cost-effective design with useful properties: plastic and metal can work together well without catching.

The acme screw works quietly, so it is suitable for offices, hospitals, etc.

Another of its assets is its high friction coefficient. This design is particularly well suited to screwjacks used in applications where they must be self-locking, i.e. with no recoil against the mass of the load. For instance, when a screwjack is used to adjust the height of a table, one with an acme screw enables the table to withstand heavy loads without altering its vertical position. This means that no brake or other locking mechanism is required to maintain the load in place when it is idle.

The ball screw system is used for high performance purposes *(⇨ Fig.41)*.

The ball screws in the screwjack are made of steel and have a row of ball bearings in a closed system between the nut and the screw.

This design gives a very low friction coefficient between the nut and the screw due to the rolling contact between the ball bearings, nut and tracks.

Wear is low compared to an acme screw, so the ball screw has a lifetime 10 times longer in identical operating conditions. This lifetime also implies that a ball screw can withstand heavy loads and long operating cycles.

Its low friction coefficient makes the ball screw especially efficient because it does not overheat.

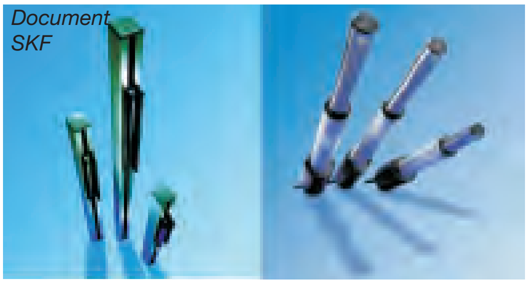
The ball screw is therefore highly suited for situations requiring lengthy operation at high speed.

A screwjack with a ball screw system has very little play, so its precision is significantly better in applications where position and precision are crucial.

Product family

Electric screwjacks can be made in many different shapes and sizes to fit easily into machines. Manufacturers also offer control units to make it easier to operate them.

The photo *(⇨ Fig.42)* gives a view of some products offered by one manufacturer (SKF).



↑ *Fig. 42* *Electrical screwjacks from SKF*

Selection guide

Choosing the right electric screwjack often requires detailed knowledge of the application and some calculation.

However, manufacturers' catalogues can help in making the initial choice of screwjacks meeting the basic criteria such as load and speed.

Screwjack drives and parts

Drives offered by manufacturers.
Electric screwjacks can be driven by:
- direct current motors,
- asynchronous alternating motors,
- brushless synchronous motors,
- stepper motors.

Direct current motors are usually low voltage (12 or 24 volts) for average forces (approx. 4000N) and medium performance (approx. 50mm/s). These screwjacks are used on mobile standalone battery-operated devices.

An asynchronous motor drive considerably increases performance up to 50,000N and 80mm/s. These screwjacks are mostly fitted to immobile machines.

Brushless drives are used for high dynamic performance (approx. 750mm/s) for forces up to about 30,000N.

Stepper motor drives are used for precision positioning of the load without recoil.

Parts and variants

• **Built-in controller**
Some electric screwjacks have a built-in control device. This is especially the case in some types of screwjack with a brushless motor drive. These include a speed controller which can be connected to the automation system by a field bus.

• **Potentiometer**
The potentiometer is a movement sensor. This device is used to ascertain the position of a moving part and align it with precision.

• **Thermal protection device**
This protects drives and control units from overheating.

• **Encoder**
This is a sensor which, when it is connected to a control unit, is used to give the position of the screwjack.

• **Stress limiters**
Some types of screwjack are fitted with a mechanical safety device similar to a friction clutch to protect the motor and the reduction unit from damage.

• **Limit switches**
These are switches which limit movement in a given direction in mechanical devices by opening and closing an electrical contact. Limit switches comes in all shapes and sizes and can be fitted on the inside or outside of the screwjack.

These safety devices are part of the control system and it is important to be aware of them when using screwjacks in an automation system or any other system.

• **Mechanical jamming control**
This safety device makes the screwjack to stop in case of an excessive resisting force. It is provided to protect persons from injuries.

• **Electrical jamming control**
This is a safety option on some electric screwjacks.

It cuts the power to the motor when external stress is applied in the opposite direction to screwjack movement.

Valves

Valve operating systems do not enter into the scope of this guide. That said, as valves can be part of industrial control systems such as regulation loops or speed controllers, it is useful to have some idea of their structure and what happens when they work.

Valve structure

A valve *(⇨ Fig.43)* consists of a body and a throttle which presses against a seat. Fluid movement is controlled by an operating rod. This rod is actuated by electric or pneumatic devices.

Many valves are pneumatically controlled, others are electrically controlled (solenoid valves).

There are many different valve designs (butterfly, spherical, diaphragm, etc.) for different types of use, fluid and progression rates (output in relation to the position of the throttle or the control signal in regulation valves).

The throttle usually has a specific shape to prevent or mitigate any unwanted effects such as water hammer or cavitation.

• **Water hammer**
This can occur in hydraulic pipes when the valve is closed. The flow through the pipe is suddenly stopped and causes this phenomenon known as water hammer.

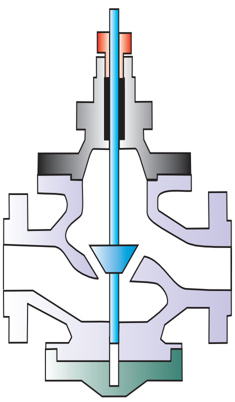
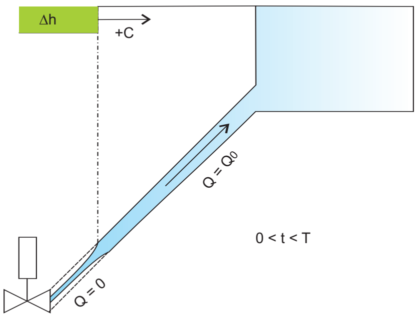
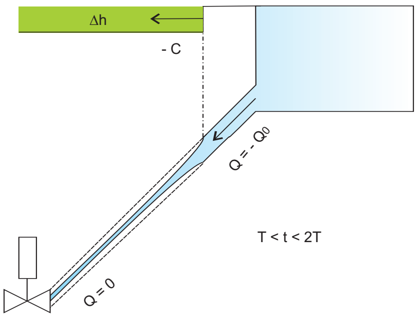


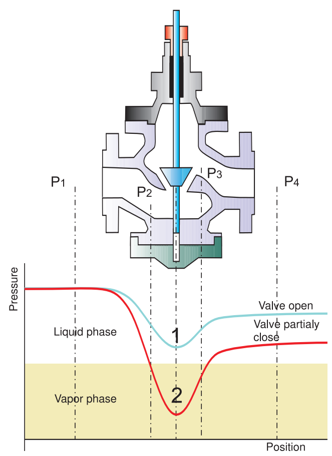
Fig. 43 Cross viexw of a valve



↑ *Fig. 44a* *Water hammer (start)*



↑ *Fig. 44b* *Water hammer*



↑ *Fig. 45* *Cavitation phenomenul*

As an example *(⇨ fig. 44a et 44b)*), here is a description of a pumping station feeding a reservoir above the feed pump.

When the emptying valve is closed, the water drained from the reservoir via the pump below the fluid column tends to pursue its movement while there is no more output from the pump.

This movement causes elastic deformation of the pipe which contracts at a point near the valve.

This phenomenon makes the mass of fluid temporarily available and maintains it in movement.

Depression occurs and spreads throughout the pipe at the speed of elastic waves C until the entire pipe is affected by it, i.e. after a time T=L/c, where L is the length of the pipe between the valve and the outlet.

The result is that the pressure where the pipe goes into the reservoir is lower than the pressure in the reservoir and causes backflow. The wave spreads from the reservoir to the pumping station and reaches the valve throttle after a time 2T from the start of the phenomenon.

The fluid column continues its descent and hits the closed valve again, causing the pipe to swell and reversing the movement of the fluid.

Water hammer would occur indefinitely if the effects of load loss, depression and overpressure are not gradually dampened.

To overcome this potentially destructive phenomenon, valve closing can be controlled by a system based on a slow closing law to keep overpressure and depression within reasonable limits.

Another procedure involves gradually slackening the speed of the feed pump to enable the valve to close the pipe.

In the case of pumps running at constant speed, the most suitable device is a soft start device such as Altistart by Telemecanique or Altivar for speed-controlled pumps.

• **Cavitation**

Closing a valve results in restricting the section available for fluid flow *(⇨ Fig.45)*. Applying the Bernoulli theorem, restricting the flow section left by the valve accelerates the flow and lowers static pressure at that point.

The amount of static pressure drop depends on:
- the internal geometry of the valve,
- the amount of static pressure downstream of the valve.

The pressure when the valve is open is shown on *(⇨ curve 1)*.

Flow is restricted at the point of the closing valve throttle, causing a drop in pressure and accelerated flow (Venturi effect);

When the throttle closes, the Venturi effect increases and curve 1 is gradually deformed *(⇨ curve 2)*.

When the static pressure in the fluid vein reaches the value of the vapour tension at the flow temperature, vapour bubbles form in the immediate vicinity of the restricted flow.
When the static pressure rises again downstream of the valve (pressure P2), the vapour bubbles condense and implose.
Cavitation has the following undesirable effects:
- unacceptably loud noise, rather like pebbles rattling in the pipes,
- vibrations at high frequencies which loosen the valve nuts and other parts,
- rapid destruction of the throttle, seat and body by removal of metal particles. Surfaces subject to cavitation are grainy,
- the flow through the valve is related to valve opening.

Regulation valves are often required to operate for a long time in conditions where cavitation can occur and their lifetime will be seriously affected by it.

Ways of limiting or preventing cavitation do not enter into the scope of this guide.

4 chapter
AC motors starting and protection systems

Presentation :

- *AC motors starting and braking systems*
- *AC motors protection devices and failure analysis*
- *Protection devices selection guide*

4. AC motors starting and protection systems

Summary

4. AC motors starting and protection systems

This section is devoted to starting and braking systems and the protection of asynchronous motors of all types.

Motor protection is required to ensure the installations work properly and to protect machines and equipment's.

Technology, starting and speed control are mentioned briefly. Please refer to the relevant sections with detailed descriptions in this guide.

Personal protection is not discussed in this section. For information on this, please refer to specific works on the topic. Details of this important aspect can be found in the Electrical installation guide published by Schneider Electric.

4.1 Asynchronous motor starting systems

Introduction

When a motor is switched on, there is a high inrush current from the mains which may, especially if the power line section is inadequate, cause a drop in voltage likely to affect receptor operation. This drop may be severe enough to be noticeable in lighting equipment. To overcome this, some sector rules prohibit the use of motors with direct on-line starting systems beyond a given power. See pages K34 and K39 of the Distribution BT 1999/2000 catalogue and the tables of voltage drops permitted by standard NF C 15-100.

There are several starting systems which differ according to the motor and load specifications.

The choice is governed by electrical, mechanical and economic factors.

The kind of load driven is also important in the choice of starting system.

Main starting modes

Direct on-line starting

This is the simplest mode, where the stator is directly connected to the mains supply *(⇨ Fig. 1)*. The motor starts with its own characteristics.

When it is switched on, the motor behaves like a transformer with its secondary, formed by the very low resistance rotor cage, in short circuit. There is a high induced current in the rotor which results in a current peak in the mains supply:
Current on starting = 5 to 8 rated Current.

The average starting torque is:
T on starting = 0.5 to 1.5 rated T.

In spite of its advantages (simple equipment, high starting torque, fast start, low cost), direct on-line starting is only suitable when:
- the power of the motor is low compared to that of the mains, which limits interference from inrush current,
- the machine to drive does not need to speed up gradually or has a damping device to limit the shock of starting,
- the starting torque can be high without affecting machine operation or the load that is driven.

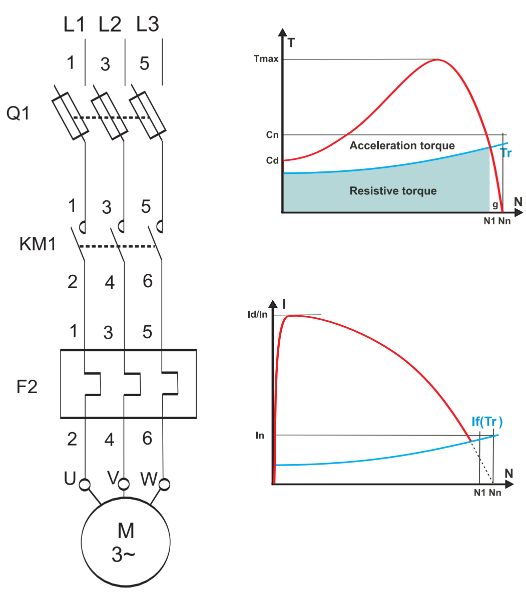


Fig. 1 Direct on-line starting

Schneider Electric

Star-delta starting

This starting system (⇨ *Fig. 2*) can only be used with a motor where both ends of its three stator windings are fitted to a terminal board.
Furthermore, the winding must be done so that the delta connection matches the mains voltage: e.g. a 380V 3-phase supply will need a motor with 380V delta and 660V star coiling.

The principle is to start the motor by connecting the star windings at mains voltage, which divides the motor's rated star voltage by √3 (in the example above, the mains voltage at 380V = 660V / √3).

The starting current peak (SC) is divided by 3:

- SC = 1.5 to 2.6 RC (RC rated Current).

A 380V / 660V motor star-connected at its rated voltage of 660V absorbs a current √3 times less than a delta connection at 380V. With the star connection at 380V, the current is divided by √3 again, so by a total of 3.

As the starting torque (ST) is proportional to the square of the supply voltage, it is also divided by 3:

ST = 0.2 to 0.5 RT (RT Rated Torque)

The motor speed stabilises when the motor and resistive torques balance out, usually at 75-85% of the rated speed. The windings are then delta-connected and the motor recovers its own characteristics. The change from star connection to delta connection is controlled by a timer. The delta contactor closes 30 to 50 milliseconds after the star contactor opens, which prevents short-circuiting between phases as the two contactors cannot close simultaneously.

The current through the windings is broken when the star contactor opens and is restored when the delta contactor closes. There is a brief but strong transient current peak during the shift to delta, due to the counter-electromotive force of the motor.

Star-delta starting is suitable for machines with a low resistive torque or which start with no load (e.g. wood-cutting machines). Variants may be required to limit the transient phenomena above a certain power level. One of these is a 1-2 second delay in the shift from star to delta.

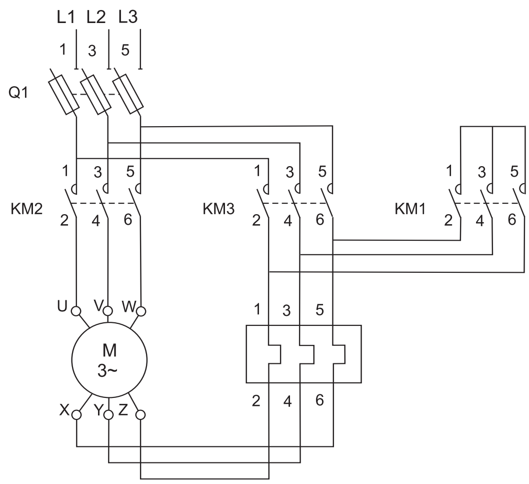
Such a delay weakens the counter-electromotive force and hence the transient current peak.

This can only be used if the machine has enough inertia to prevent too much speed reduction during the time delay.

Another system is 3-step starting: star-delta + resistance-delta.

There is still a break, but the resistor in series with the delta-connected windings for about three seconds lowers the transient current. This stops the current from breaking and so prevents the occurrence of transient phenomena.

Use of these variants implies additional equipment, which may result in a significant rise in the cost of the installation.



↑ *Fig. 2* *Star-delta starting*

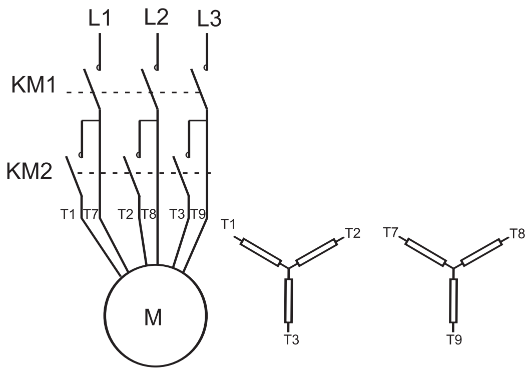


Fig. 3 Part winding starting

Part winding motor starting

This system (⇨ *Fig.3*), not widely used in Europe, is quite common in the North American market (voltage of 230/460, a ratio of 1:2). This type of motor has a stator winding divided into two parallel windings with six or twelve output terminals. It is equivalent to two “half motors” of equal power.

On starting, a single “half motor” is connected directly at full mains voltage strength, which divides the starting current and the torque approximately by two. The torque is however greater than it would be with a squirrel cage motor of equal power with star-delta starting.

At the end of the starting process, the second winding is connected to the mains. At this point, the current peak is low and brief, because the motor has not been cut off from the mains supply and only has a little slip.

Resistance stator starting

With this system (⇨ *Fig.4)*, the motor starts at reduced voltage because resistors are inserted in series with the windings. When the speed stabilises, the resistors are eliminated and the motor is connected directly to the mains. This process is usually controlled by a timer.

This starting method does not alter the connection of the motor windings so the ends of each winding do not need outputs on a terminal board.

The resistance value is calculated according to the maximum current peak on starting or the minimum starting torque required for the resistance torque of the machine to drive. The starting current and torque values are generally:

- SC = 4.5 RC
- ST = 0.75 RT

During the acceleration stage with the resistors, the voltage applied to the motor terminals is not constant but equals the mains voltage minus the voltage drop in the starting resistance.

The voltage drop is proportional to the current absorbed by the motor. As the current weakens with the acceleration of the motor, the same happens to the voltage drop in the resistance. The voltage applied to the motor terminals is therefore at its lowest on starting and then gradually increases.

As the torque is proportional to the square of the voltage at the motor terminals, it increases faster than in star-delta starting where the voltage remains constant throughout the star connection.

This starting system is therefore suited to machines with a resistive torque that increases with the speed, such as fans and centrifugal pumps.

It has the drawback of a rather high current peak on starting. This could be lowered by increasing the resistance value but that would cause the voltage to drop further at the motor terminals and thus a steep drop in the starting torque.

On the other hand, resistance is eliminated at the end of starting without any break in power supply to the motor, so there are no transient phenomena.

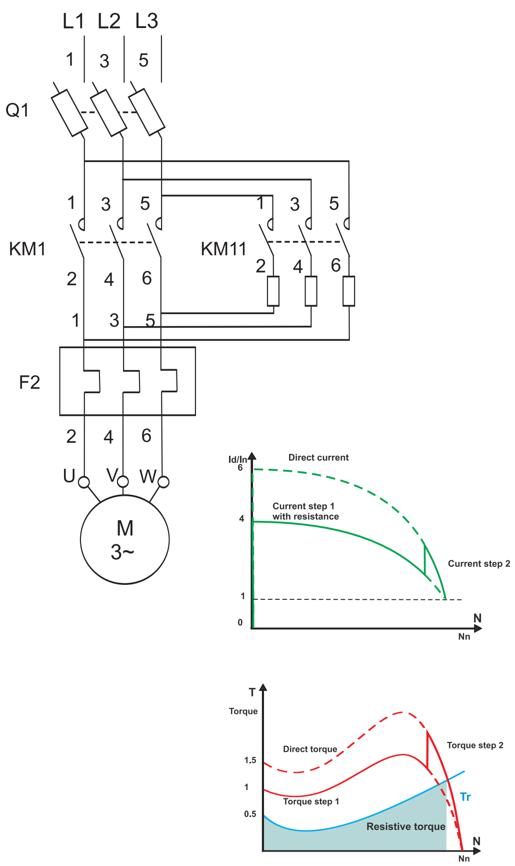
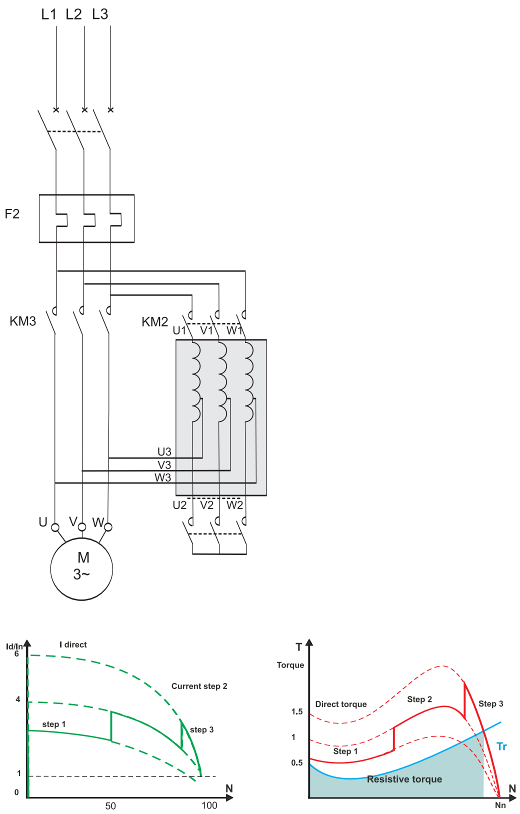
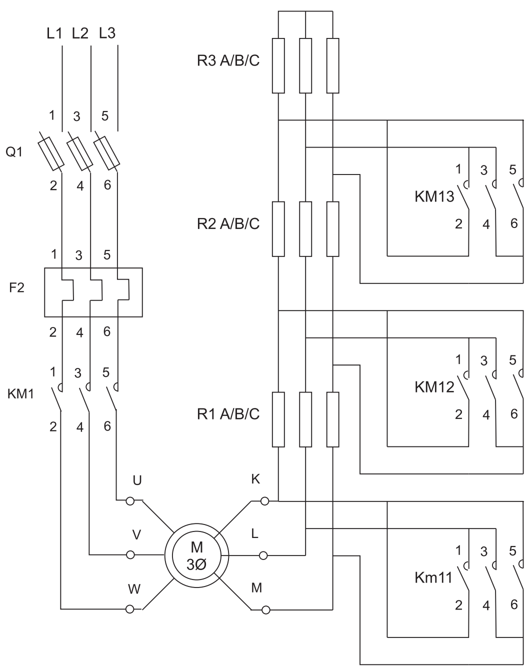


Fig. 4 Resistance stator starting



↑ Fig. 5 *Autotransformer starting*



↑ Fig. 6 *Slip ring motor starting*

☐ Autotransformer starting

The motor is powered at reduced voltage via an autotransformer which is bypassed when the starting process is completed *(⇨ Fig.5)*.

The starting process is in three steps:

- in the first place, the autotransformer is star-connected, then the motor is connected to the mains via part of the autotransformer windings. The process is run at a reduced voltage which depends on the transformation ratio. The autotransformer is usually tapped to select this ratio to find the most suitable voltage reduction value,
- the star connection is opened before going onto full voltage. The fraction of coil connected to the mains then acts as an inductance in series with the motor. This operation takes place when the speed balances out at the end of the first step,
- full voltage connection is made after the second step which usually only lasts a fraction of a second. The piece of autotransformer winding in series with the motor is short-circuited and the autotransformer is switched off.

The current and the starting torque vary in the same proportions. They are divided by (mains V/reduced V^2).

The values obtained are:
SC = 1.7 to 4 RC
ST = 0.5 to 0.85 RT

The starting process runs with no break in the current in the motor, so transient phenomena due to breaks do not occur.

However, if a number of precautions are not taken, similar transient phenomena can appear on full voltage connection because the value of the inductance in series with the motor is high compared to the motor's after the star arrangement is open. This leads to a steep drop in voltage which causes a high transient current peak on full voltage connection. To overcome this drawback, the magnetic circuit in the autotransformer has an air gap which helps to lower the inductance value. This value is calculated to prevent any voltage variation at the motor terminals when the star arrangement opens in the second step.

The air gap causes an increase in the magnetising current in the autotransformer. This current increases the inrush current in the mains supply when the autotransformer is energised.

This starting system is usually used in LV for motors powered at over 150kW. It does however make equipment rather expensive because of the high cost of the autotransformer.

☐ Slip ring motor starting

A slip ring motor cannot be started direct on-line with its rotor windings short-circuited, otherwise it would cause unacceptable current peaks. Resistors must therefore be inserted in the rotor circuit *(⇨ Fig.6)* and then gradually short-circuited, while the stator is powered at full mains voltage.

The resistance inserted in each phase is calculated to ascertain the torque-speed curve with strict accuracy. The result is that it has to be fully inserted on starting and that full speed is reached when it is completely short-circuited.

The current absorbed is more or less proportional to the torque supplied at the most only a little greater than the theoretical value.

For example, for a starting torque equal to 2 RT, the current peak is about 2 RC. This peak is thus much lower and the maximum starting torque much higher than with a squirrel cage motor, where the typical values are about 6 RC for 1.5 RT when directly connected to the mains supply. The slip ring motor, with rotor starting, is the best choice for all cases where current peaks need to be low and for machines which start on full load.

This kind of starting is extremely smooth, because it is easy to adjust the number and shape of the curves representing the successive steps to mechanical and electrical requirements (resistive torque, acceleration value, maximum current peak, etc.).

Soft starter starting/slackening

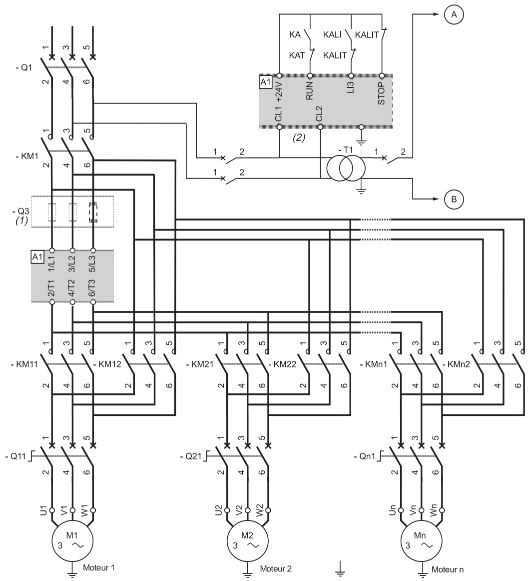
This is an effective starting system *(⇨ Fig. 7)* for starting and stopping a motor smoothly *(see the section on electronic speed controllers for more details)*.

It can be used for:
- current limitation,
- torque adjustment.

Control by current limitation sets a maximum current (3 to 4 x RC) during the starting stage and lowers torque performance. This control is especially suitable for “turbomachines” (centrifugal pumps, fans).

Control by torque adjustment optimises torque performance in the starting process and lowers mains inrush current. This is suited to constant torque machines.

This type of starter can have many different diagrams:
- one-way operation,
- two-way operation,
- device shunting at the end of the starting process,
- starting and slackening several motors in cascade *(⇨ Fig. 7)*,
- etc.



↑ Fig. 7 *Multiple motor starting with a soft starter*

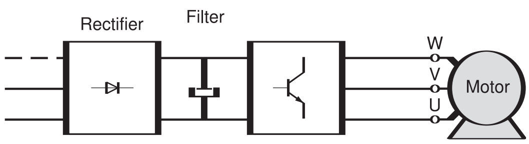
Frequency converter starting

This is an effective starting system *(⇨ Fig. 8)* to use whenever speed must be controlled and adjusted *(see the section on electronic speed control for more details)*.

Its purposes include:
- starting with high-inertia loads,
- starting with high loads on supplies with low short-circuit capacity,
- optimisation of electricity consumption adapted to the speed of "turbomachines".

This starting system can be used on all types of machines.

It is a solution primarily used to adjust motor speed, starting being a secondary purpose.



↑ Fig. 8 *Working diagram of a frequency converter*

4. AC motors starting and protection systems

4.1 Asynchronous motor starting systems

Summary table of 3-phase motor starting systems (⇨ Fig. 9)

	Direct on-line	Star-delta	Part windings	Resistors	Autotransformers	Slip ring motors	Soft starter	Frequency converter
Motor	Standard	Standard	6 windings	Standard	Standard	Specific	Standard	Standard
Cost	+	++	++	+++	+++	+++	+++	++++
Motor starting current	5 to 10 RC	2 to 3 RC	2 RC	Approx. 4.5 RC	1.7 to 4 RC	Approx. 2 RC	4 to 5 RC	RC
Voltage dip	High	High on connection change	Low	Low	Low; precautions to take in DOL connection	Low	Low	Low
Voltage and current harmonics	High	Moderate	Moderate	Moderate	Moderate	Low	High	High
Power factor	Low	Low	Moderate	Moderate	Low	Moderate	Low	High
Number of starts available	Restricted	2-3 times more than DOL	3-4 times more than DOL	3-4 times more than DOL	3-4 times more than DOL	2-3 times more than DOL	Limited	High
Available torque	Approx. 2.5 RT	0.2 to 0.5 RT	2 RT	RT	Approx. 0.5 RT	Approx. 2 RC	Approx. 0.5 RT	1.5 to 2 RT
Thermal stress	Very high	High	Moderate	High	Moderate	Moderate	Moderate	Low
Mechanical shocks	Très élevé	Moderate	Moderate	Moderate	Moderate	Low	Moderate	Low
Recommended type of load	Any	No-load	Ascending torque	Pumps and fans	Pumps and fans	Any	Pumps and fans	Any
High-inertia loads	Yes*	No	No	No	No	Yes	No	Yes

** This starting system requires the motor to be specifically sized.*

↑ Fig. 9 *Summary table*

Single-phase motor starting

A single-phase motor cannot start on its own, so there are different ways to run it.

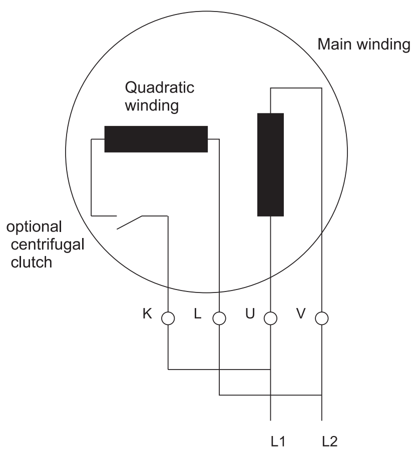
Auxiliary phase starting

In this type of motor (⇨ Fig. 10), the stator has two windings geometrically offset by 90°.

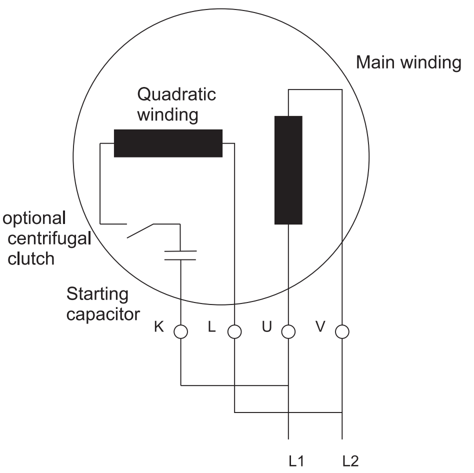
When it is switched on, because the coils are made differently, a current C1 crosses the main phase and a weaker current C2, noticeably shifted by $\pi/2$, circulates in the auxiliary phase. The fields which are generated are produced by two currents that are phase-shifted in relation to each other, so the resulting rotating field is strong enough to trigger no-load starting of the motor. When the motor has reached about 80% of its speed, the auxiliary phase can be cut off (centrifugal coupling) or kept running. The motor stator thus becomes a two-phase stator, either on starting or all the time.

The connections of a phase can be inverted to reverse the direction of rotation.

As the starting torque is low, it should be raised by increasing the offset between the two fields the coils produce.



↑ Fig. 10 *Single-phase motor with auxiliary phase*



↑ Fig. 11 *Single-phase motor with starting capacitor*

Auxiliary phase and resistance starting

A resistor in series with the auxiliary phase increases its impedance and the offset between C1 and C2.

Operation at the end of the starting process is the same as with the auxiliary phase on its own.

Auxiliary phase and inductance starting

This works in the same way as above, but the resistor is replaced by an inductance in series with the auxiliary phase to increase the offset between the two currents.

Auxiliary phase and capacitor starting

This is the most widespread device (⇨ Fig.11), where a capacitor is set in the auxiliary phase. For a permanent capacitor, the working value is about 8µF for a 200W motor. Starting purposes may require an extra capacitor of 16µF which is eliminated when the starting process is over.

As a capacitor produces a phase shift that is the opposite of an inductance one, during starting and operation, the motor works much like a two-phase one with a rotating field. The torque and power factor are high. The starting torque ST is more or less three times more than the rated torque RT and the maximum torque Tmax reaches 2 RT.

When starting is complete, it is best to maintain the phase-shift between the currents, though the value of the capacity can be reduced because the stator impedance has increased.

The diagram (⇨ Fig.11) represents a single-phase motor with a permanently-connected capacitor. Other arrangements exist, such as opening the phase-shift circuit by a centrifugal switch when a given speed is reached.

A 3-phase motor (230/400V) can be used with a 230V single-phase supply if it is fitted with a starting capacitor and an operating capacitor permanently connected. This operation lessens the working power (derating of about 0.7), the starting torque and the thermal reserve.

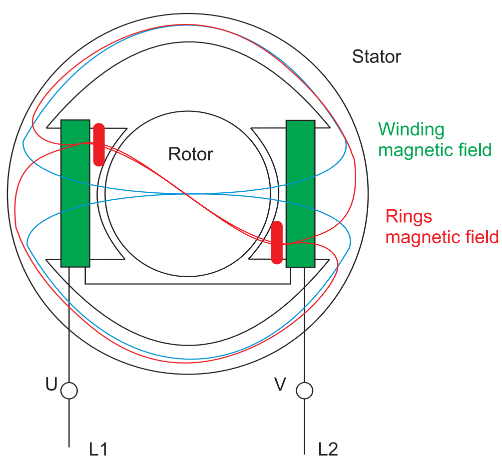
Only low-powered 4-pole motors of no more than 4kW are suitable for this system.

Manufacturers provide tables for selecting capacitors with the right values.

Shaded pole winding starting

This device (⇨ Fig.12) is used in very low-powered motors (around a hundred watts). The poles have notches with short-circuited conducting rings inserted in them. The induced current this produces distorts the rotating field and triggers the starting process.

Efficiency is low but adequate in this power range.



↑ Fig. 12 *Shaded pole winding motor*

4.2 Electrical braking of 3-phase asynchronous motors

Introduction

In a great many systems, motors are stopped simply by natural deceleration. The time this takes depends solely on the inertia and resistive torque of the machine the motor drives. However, the time often needs to be cut down and electrical braking is a simple and efficient solution. Compared to mechanical and hydraulic braking systems, it has the advantage of steadiness and does not require any wear parts.

Countercurrent braking: principle

The motor is isolated from the mains power while it is still running and then reconnected to it the other way round. This is a very efficient braking system with a torque, usually higher than the starting torque, which must be stopped early enough to prevent the motor starting in the opposite direction.

Several automatic devices are used to control stopping as soon as the speed is nearly zero:

- friction stop detectors, centrifugal stop detectors,
- chronometric devices,
- frequency measurement or rotor voltage relays (slip ring motors), etc.

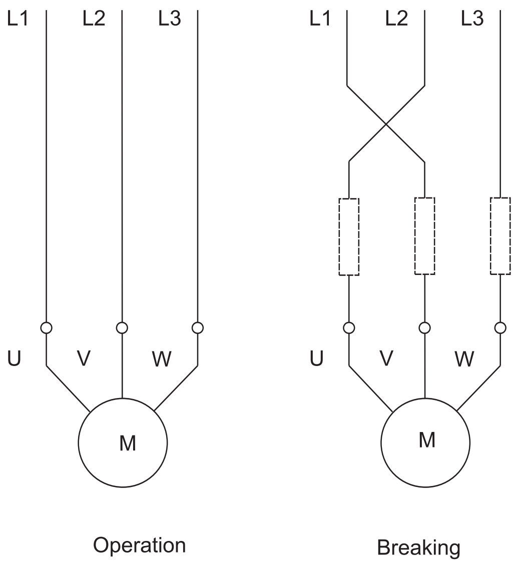
Squirrel cage motor

Before choosing this system *(⇨ Fig.13)*, it is crucial to ensure that the motor can withstand countercurrent braking with the duty required of it. Apart from mechanical stress, this process subjects the rotor to high thermal stress, since the energy released in every braking operation (slip energy from the mains and kinetic energy) is dissipated in the cage. Thermal stress in braking is three times more than in speed-gathering.

When braking, the current and torque peaks are noticeably higher than those produced by starting.

To brake smoothly, a resistor is often placed in series with each stator phase when switching to countercurrent. This reduces the torque and current, as in stator starting.

The drawbacks of countercurrent braking in squirrel cage motors are so great that this system is only used for some purposes with low-powered motors.



↑ *Fig. 13* *Principle of countercurrent braking*

Slip ring motor

To limit the current and torque peak, before the stator is switched to countercurrent, it is crucial to reinsert the rotor resistors used for starting, and often to add an extra braking section *(⇨ Fig.14)*.

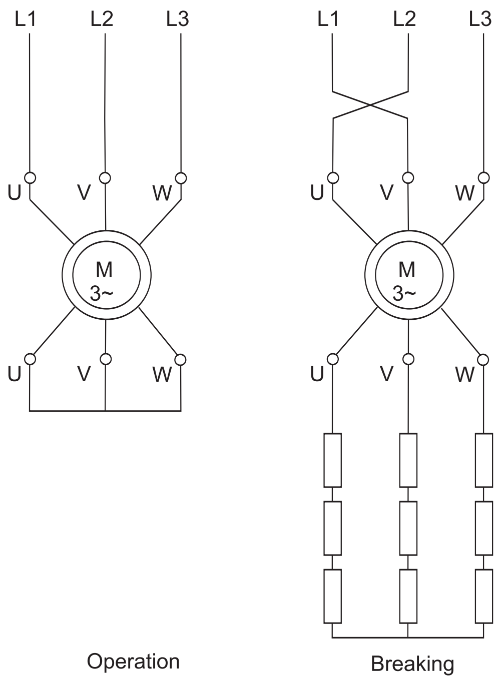
With the right rotor resistor, it is easy to adjust the braking torque to the requisite value.

When the current is switched, the rotor voltage is practically twice what it is when the rotor is at a standstill, which sometimes requires specific insulation precautions to be taken.

As with cage motors, a large amount of energy is released in the rotor circuit. It is completely dissipated (minus a few losses) in the resistors.

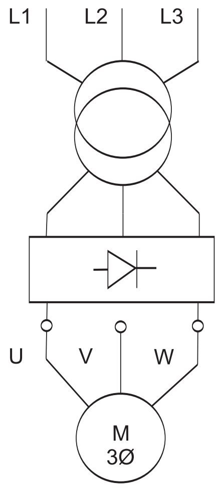
The motor can be brought to a standstill automatically by one of the above-mentioned devices, or by a voltage or frequency relay in the rotor circuit.

With this system, a driving load can be held at moderate speed. The characteristic is very unstable (wide variations in speed against small variations in torque).



↑ *Fig. 14* *Principle of countercurrent braking in an asynchronous slip ring machine*

4.2 Electrical braking of 3-phase asynchronous motors



↑ *Fig. 15* *Principle of direct current braking in an asynchronous machine*

Braking by injection of DC current

This braking system is used on slip ring and squirrel cage motors *(⇨ Fig.15)*. Compared to the countercurrent system, the price of the source of rectified current is offset by fewer resistors. With electronic speed controllers and starters, this braking option does not add to the cost.

The process involves isolating the stator from the mains and sending rectified current to it. The rectified current creates a fixed flux in the air gap of the motor. For the value of this flux to ensure adequate braking, the current must be about 1.3 times greater than the rated current. The surplus of thermal losses caused by this slight overcurrent is usually offset by a pause after braking.

As the value of the current is set by stator winding resistance alone, the voltage at the source of the rectified current is low. The source is usually provided by rectifiers or by speed controllers. These must be able to withstand transient voltage surges produced by the windings that have just been disconnected from the alternating supply (e.g. 380V RMS).

The movement of the rotor is a slip in relation to a field fixed in space (whereas the field spins in the opposite direction in the countercurrent system). The motor behaves like a synchronous generator discharging in the rotor. There are important differences in the characteristics obtained with a rectified current injection compared to a countercurrent system:

- less energy is dissipated in the rotor resistors or the cage. It is only equivalent to the mechanical energy given off by masses in movement. The only power taken from the mains is for stator energising,
- if the load is not a driving load, the motor does not start in the opposite direction,
- if the load is a driving load, the system brakes constantly and holds the load at low speed. This is slackening braking rather than braking to a standstill. The characteristic is much more stable than in countercurrent.

With slip ring motors, the speed-torque characteristics depend on the choice of resistors.

With squirrel cage motors, the system makes it easy to adjust the braking torque by acting on the energising direct current. However, the braking torque will be low when the motor runs at high speed.

To prevent superfluous overheating, there must be a device to cut off the current in the stator when braking is over.

Electronic braking

Electronic braking is achieved simply with a speed controller fitted with a braking resistor. The asynchronous motor then acts as a generator and the mechanical energy is dissipated in the baking resistor without increasing losses in the motor.

For more information, see the section on electronic speed control in *the motor starter units chapter*.

Braking by oversynchronous operation

This is where a motor's load drives it above its synchronous speed, making it act like an asynchronous generator and develop a braking torque. Apart from a few losses, the energy is recovered by the mains supply.
With a hoisting motor, this type of operation corresponds to the descent of the load at the rated speed. The braking torque exactly balances out the torque from the load and, instead of slackening the speed, runs the motor at constant speed.
On a slip ring motor, all or part of the rotor resistors must be short-circuited to prevent the motor being driven far above its rated speed, which would be mechanically hazardous.
This system has the ideal features for restraining a driving load:
- the speed is stable and practically independent of the driving torque,
- the energy is recovered and restored to the mains.

However, it only involves one speed, approximately that of the rated speed.

Oversynchronous braking systems are also used on multiple-speed motors to change from fast to slow speed.

Oversynchronous braking is easily achieved with an electronic speed controller, which automatically triggers the system when the frequency setting is lowered.

Other braking systems

Single-phase braking can still sometimes be found. This involves powering the motor between two mains phases and linking the unoccupied terminal to one of the other two connected to the mains. The braking torque is limited to 1/3 of the maximum motor torque. This system cannot brake the full load and must be backed by countercurrent braking. It is a system which causes much imbalance and high losses.

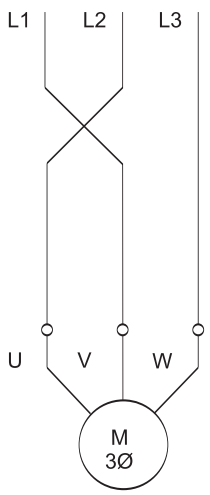
Another system is braking by eddy current slackening. This works on a principle similar to that used in industrial vehicles in addition to mechanical braking (electric speed reducers). The mechanical energy is dissipated in the speed reducer. Braking is controlled simply by an excitation winding. A drawback however is that inertia is greatly increased.

Reversing

3-phase asynchronous motors (⇨ *Fig.16*) are put into reverse by the simple expedient of crossing two windings to reverse the rotating field in the motor.

The motor is usually put into reverse when at a standstill. Otherwise, reversing the phases will give countercurrent braking (see the paragraph on the Slip ring motor). The other braking systems described above can also be used.

Single-phase motor reversing is another possibility if all the windings can be accessed.



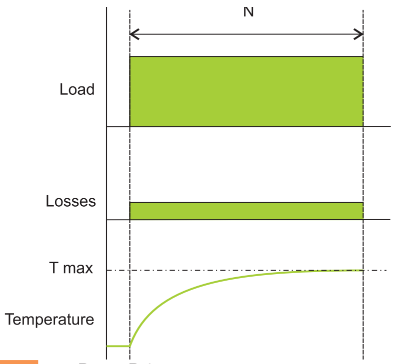
↑ *Fig. 16* *Principle of asynchronous motor reversing*

Types of duty

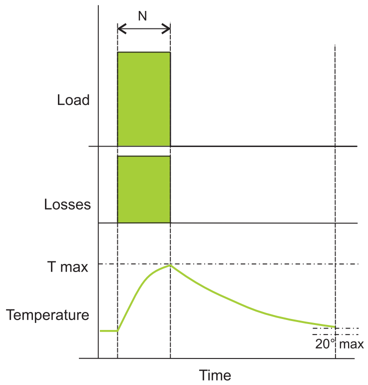
For an electrical motor, number of starting and braking per unit of time have a large incidence on the internal temperature. The IEC standard : Rotating electrical machines - Part 1: Rating and performance (IEC 60034-1:2004) gives the service factors which allow to calculate the heat generated ad size correctly a motor according to the operation. The following information is an overview of these service factors. Additional information will be found in the relevant IEC standard and the manufacturers' catalogues.

4. AC motors starting and protection systems

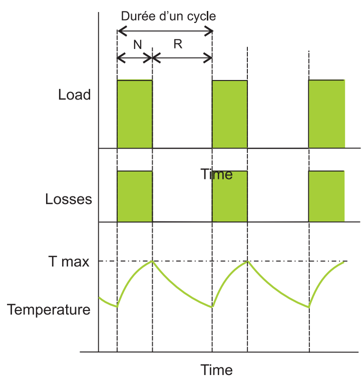
4.2 Electrical braking of 3-phase asynchronous motors



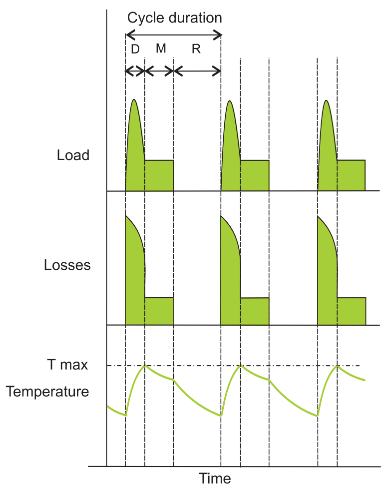
↑ *Fig. 17* *Duty D1*



↑ *Fig. 18* *Duty D2*



↑ *Fig. 19* *Duty D3*



↑ *Fig. 20* *Duty D4*

□ **Continuous duty - type D1** *(⇨ Fig.17)*

Constant-load operation lasting long enough to reach thermal equilibrium.

□ **Temporary duty – type D2** *(⇨ Fig.18)*

Constant-load operation for a given period of time, less than required to reach thermal equilibrium, followed by a pause to restore thermal equilibrium between the machine and the surrounding coolant at around 20° C.

□ **Periodic intermittent duty - type D3** *(⇨ Fig.19)*

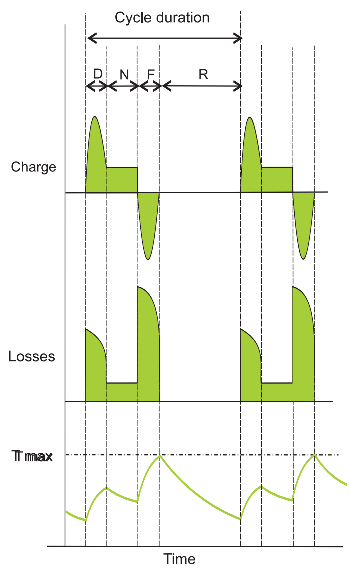
Series of identical cycles, each with a period of operation and a pause. The starting current in this type of duty is such that it has no significant effect on heating.

□ **Periodic intermittent duty with starting - type D4** *(⇨ Fig.20)*

Series of identical cycles, each with a significant starting period, a period of constant-load operation and a pause.

□ **Periodic intermittent duty with electrical braking - type D5** *(⇨ Fig.21)*

Series of duty cycles, each with a starting period, a period of constant-load operation, a period of electrical braking and a pause.



↑ *Fig. 21* *Duty D5*

4.2 Electrical braking of 3-phase asynchronous motors

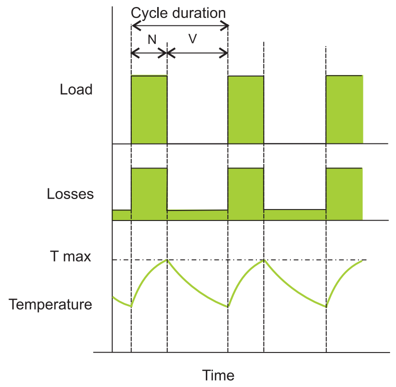


Fig. 22 *Duty D6*

Periodic continuous duty with intermittent load - type D6 *(⇨ Fig.22)*

Series of identical duty cycles, each with a period of constant-load operation and a period of no-load operation. There is no pause.

Periodic continuous duty with electrical braking - type D7 *(⇨ Fig.23)*

Series of identical duty cycles, each with a starting period, a period of constant-load operation and a period of electrical braking. There is no pause.

Periodic continuous duty with load-speed-linked changes - type D8 *(⇨ Fig.24)*

Series of identical duty cycles, each with a period of constant-load operation at a preset rotation speed, followed by one or more periods of constant-load operation at other speeds (e.g. by changing the number of poles). There is no pause.

Non-periodic load and speed variation duty - type D9 *(⇨ Fig.25)*

Duty where load and speed usually vary non-periodically within an allowed operating range. This duty often includes overloads which can be much higher than full load.

Separate constant-rate duty - type D10 *(⇨ Fig.26)*

Duty with at most four separate load values (or equivalent load values), each one applied long enough for the machine to reach thermal equilibrium. The minimum load in a load cycle can be zero (no-load operation or pause).

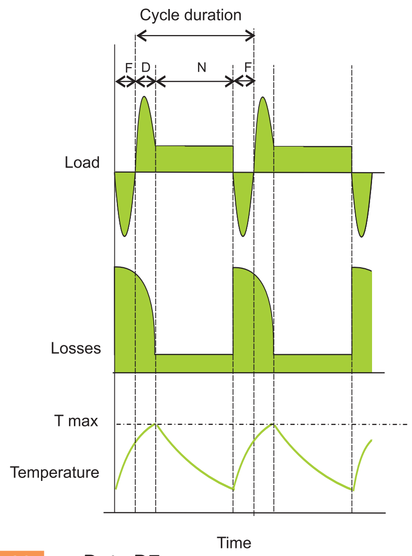


Fig. 23 *Duty D7*

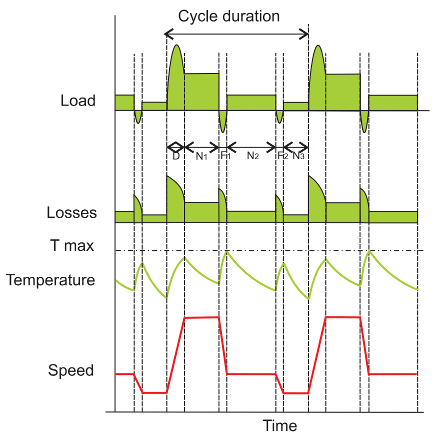


Fig. 24 *Service D8*

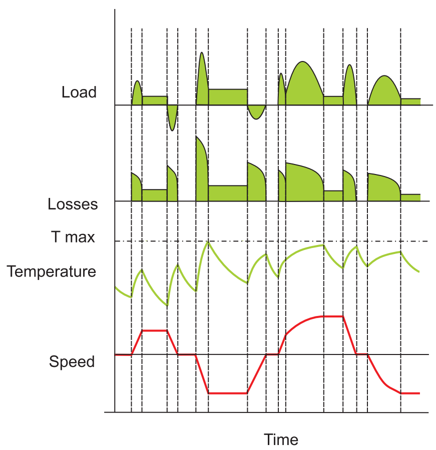


Fig. 25 *Duty D9*

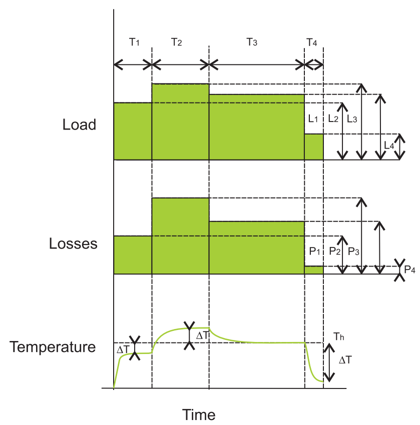


Fig. 26 *Duty D10*

4.3 Multifunction motor starter units

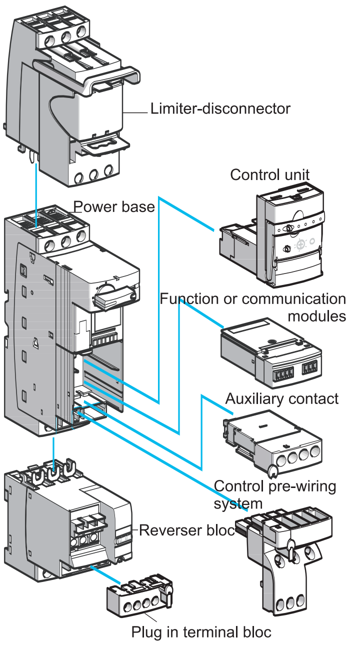


Fig. 27 Tesys U

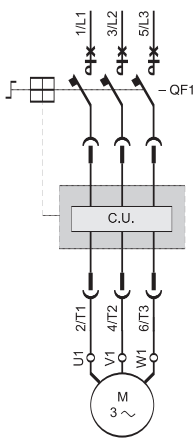


Fig. 28 Working diagram of Tesys U

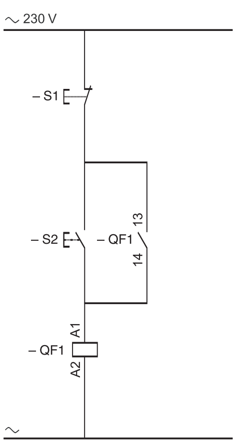


Fig. 29 3-wire control

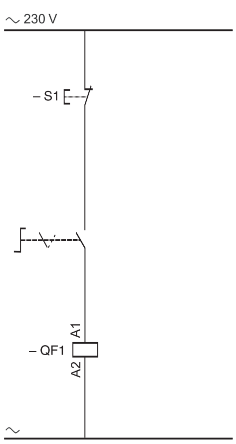


Fig. 30 2-wire control

With the changes in user requirements, motor starter units have made considerable progress over the last few years. The requirements include:

- smaller products for easier fitting and less bulky equipment,
- easy solutions to coordination problems,
- fewer component references,
- fast and easy wiring to cut down labour costs,
- automated functions at affordable prices,
- communication needs and field bus connections.

In 1983, the Telemecanique Integral range was the first answer to these demands. This was the first product to offer the following functions in a single package:

- isolation,
- switching,
- protection against overloads and short circuits with the performance of the best devices on the market, *(see the section on Motor protection for more details)*.

Twenty years later, the techniques have progressed and Schneider Electric now offers Tesys U. This product is a considerable advance for equipment building.

It ensures total coordination, meaning the device cannot fail to restart after a trip. Compared to a conventional solution, the number of references is divided by 10, savings in wiring are 60% and the space gain is 40%.

The illustration *(⇨ Fig.27)* shows Tesys U with some of its options.

Like Integral, it offers the major functions of motor starter units, and in addition has advanced dialogue and switching functions which can be used for outstandingly economical new diagrams. Tesys U has a “power base” with disconnection, switching and protection functions. It is this base element which performs the following basic function.

Forward operation

The diagram *(⇨ Fig.28)* shows how the product is built inside. The “power base” includes all the components required for disconnection, protection against short circuits and overload and power switching.

The “power base” is used to build the classic diagrams below with no additional components:

- 3-wire control *(⇨ Fig.29)*, Pulse control with latch,
- Or 2-wire control *(⇨ Fig.30)*, 2-position switch control.

Schneider Electric

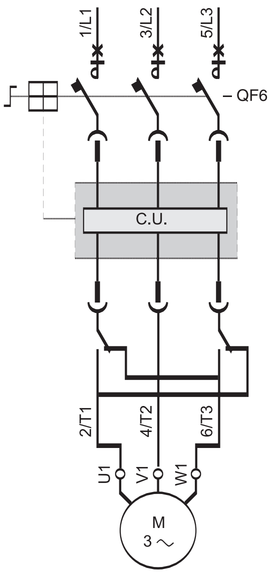


Fig. 31 Tesys U with reversing module (working principle)

Forward and reverse operation

The *figures 31 and 32* illustrate the power base and the reversing attachment which can be connected to the side of the product or connected directly to make a compact product.

The "power base" controls the Stop/Start, short-circuit break and thermal protection.

The reverser never switches in on-load mode, so there is no electrical wear.

There is no need for mechanical locks because the electromagnet is bistable and the reverser contact holder is inaccessible so its position cannot be changed.

Example of 3-wire control *(⇨ Fig.33)*: pulse control with latch and top and bottom limit switches.

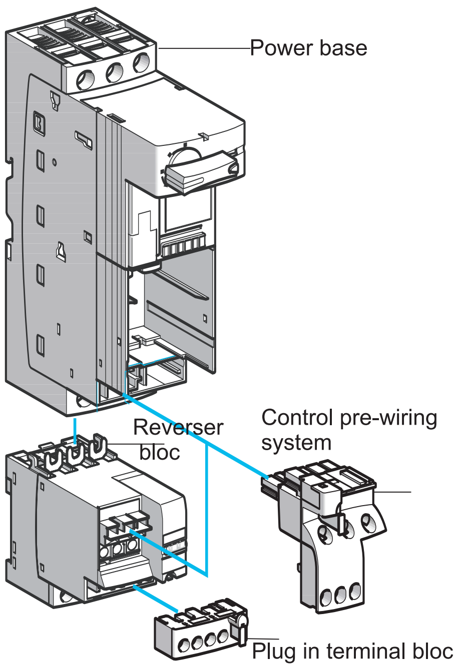


Fig. 32 Tesys U with reversing module

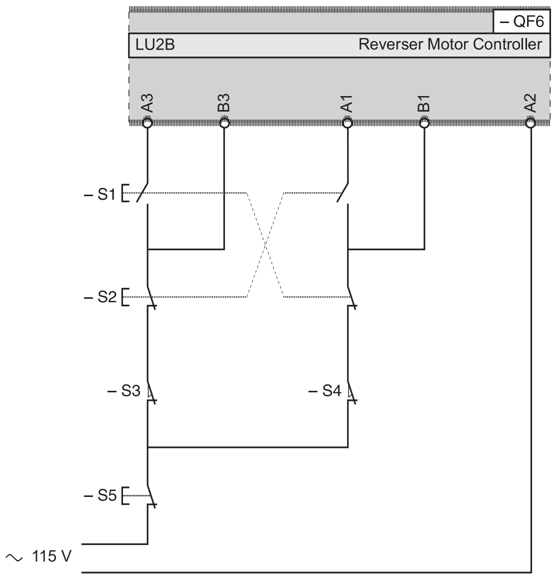


Fig. 33 Example of Tesys U used with reversing function

4.4 Motors protection

Every electric motor has operating limits. Overshooting these limits will eventually destroy it and the systems it drives, the immediate effect being operating shutdown and losses.

This type of receiver, which transforms electrical energy into mechanical energy, can be the seat of electrical or mechanical incidents.

- **Electrical**
  - power surges, voltage drops, unbalance and phase losses causing variations in the absorbed current,
  - short circuits where the current can reach levels that can destroy the receiver.
- **Mechanical**
  - rotor stalling, momentary or prolonged overloads increasing the current absorbed by the motor and dangerously heating its windings.

The cost of these incidents can be high. It includes production loss, loss of raw materials, repair of the production equipment, non-quality production and delivery delays. The economic necessity for businesses to be more competitive implies reducing the costs of discontinuous output and non-quality.

These incidents can also have a serious impact on the safety of people in direct or indirect contact with the motor.

Protection is necessary to overcome these incidents, or at least mitigate their impact and prevent them from causing damage to equipment and disturbing the power supply. It isolates the equipment from the mains power by means of a breaking device which detects and measures electrical variations (voltage, current, etc.).

- **Every starter motor unit should include**
  - protection against short circuits, to detect and break abnormal currents – usually 10 times greater than the rated current (RC) – as fast as possible,
  - protection against overloads to detect current increase up to about 10 RC and open the power circuit before the motor heats up, damaging the insulation.

These protections are ensured by special devices such as fuses, circuit breakers and overload relays or by integral devices with a range of protections.

Ground fault protection, which covers personal protection and fire safety, is not dealt with here because it is normally part of the electrical distribution in equipment, workshops or entire buildings.

4.5 Motor losses and heating

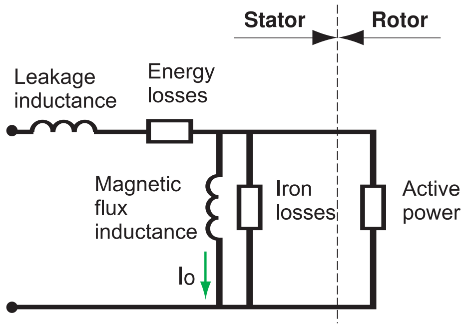


Fig. 34 *Equivalent diagram of an asynchronous motor*

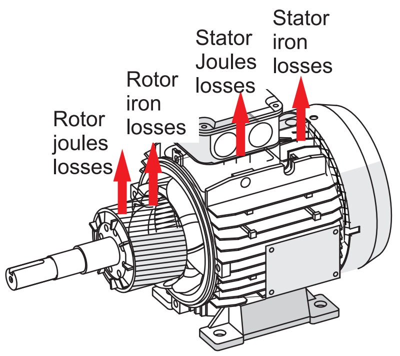


Fig. 35 *Losses in a AC motor*

	Δt	T max
Category B	80°K	125°C
Category F	105°K	155°C
Category H	125°K	180°C

Fig. 36 *Insulation classes*

Equivalent diagram of a motor

An asynchronous squirrel cage motor can be represented by the diagram (⇨ Fig.34).

Part of the electrical power supplied to the stator is transmitted to the shaft as drive power or active power.

The rest is transformed into heat in the motor (⇨ Fig. 35):
- "joule" or energy losses in the stator windings,
- "joule" or energy losses in the rotor due to the induced currents in it (see the section on motors),
- iron losses in the rotor and stator.

These losses depend on use and working conditions (*see the section on motor starting*) and lead to motor heating.

Faults due to the load or the power supply voltage or both are likely to cause dangerous overheating.

Insulation categories

Most industrial machines come into the F insulation category. See the table (⇨ Fig.36).

Category F permits heating (measured by the resistance variation method) up to 105°K and maximum temperatures at the hottest points of the machine are limited to 155°C (ref IEC 85 and IEC 34-1). For specific conditions, in particular at high temperature and high humidity, category H is more suitable.

Good quality machines are sized so that maximum heating is 80° in rated operating conditions (temperature of 40°C, altitude less than 1000m, rated voltage and frequency and rated load). Derating applies when exceeding these values.

For a category F, this results in a heating reserve of 25°K to cope with variations in the region of the rated operating conditions.

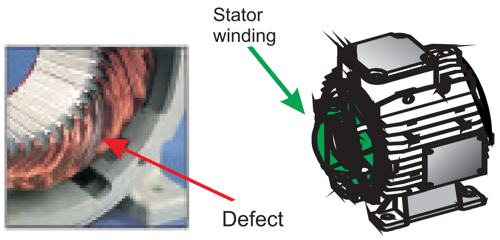
4.6 Causes of faults and their effects

There are two separate types of fault with electric motors: faults in the motor itself and faults with external causes.

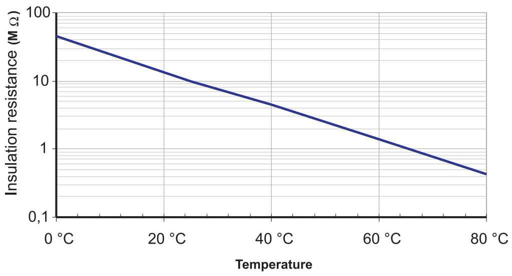
- **Faults in the motor**
  - phase to ground short circuit,
  - phase to phase short circuit,
  - internal winding short circuit,
  - overheating of windings,
  - broken bar in squirrel cage motors,
  - problems in windings,
  - etc.
- **Faults with external causes**

Their sources are located outside the electric motor but their effects can damage it.

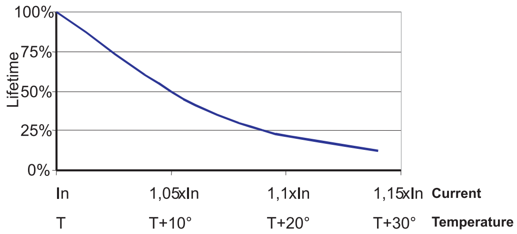
4.6 Causes of faults and their effects



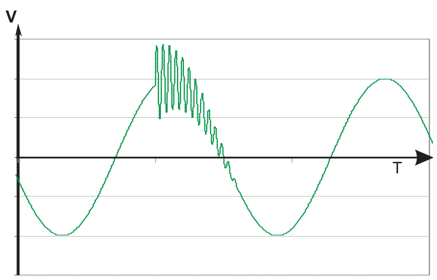
↑ Fig. 37 *Windings are the motor parts most vulnerable to electrical faults and operating incidents*



↑ Fig. 38 *Insulation resistance temperature*



↑ Fig. 39 *Lifetime of motor depending on operating*



↑ Fig. 40 *Example of a voltage surge*

□ **Dysfunction can be caused by**

- **the power supply**
  - power failure,
  - inverted or unbalanced phases,
  - voltage drop,
  - voltage surge,
  - etc.
- **the motor's operating conditions**
  - overload states,
  - excessive number of starts or braking,
  - abnormal starting state,
  - too high a load inertia,
  - etc.
- **the motor's installation conditions**
  - misalignment,
  - unbalance,
  - stress on shaft,
  - etc.

■ Faults in the motor

Stator or rotor winding failure

The stator winding in an electric motor consists of copper conductors insulated by a varnish. A break in this insulation can cause a permanent short circuit between a phase and ground, between two or three phases or between windings in one phase *(⇨ Fig. 37)*. Its causes can be electrical (superficial discharge, voltage surges), thermal (overheating) or mechanical (vibration, electrodynamic stress on the conductors).

Insulation faults can also occur in the **rotor winding** with the same result: breakdown of the motor.

The commonest cause of failure in motor windings is overheating. The rise in temperature is due to an overload leading to a power surge in the windings.

The curve *(⇨ Fig. 38)*, which most electric motor manufacturers supply, shows how insulation resistance changes with the temperature: as the temperature rises, insulation resistance decreases. The lifetime of the windings, and hence the motor, is greatly shortened.

The curve *(⇨ Fig. 39)*, shows that an increase of 5% in the current, equivalent to a temperature rise of about +10°, halves the lifetime of the windings.

Protection against overload is thus mandatory to prevent overheating and reduce the risk of motor failure due to a break in winding insulation.

■ Faults with external causes

Related to the motor power supply

□ **Voltage surges**

Any voltage input to plant with a peak value exceeding the limits defined by a standard or specification is a voltage surge *(cf Cahiers Techniques Schneider-Electric 151 and 179)*.

Temporary or permanent excess voltage *(⇨ Fig. 40)* can have different origins:
- atmospheric (lightning),
- electrostatic discharge,
- operation of receivers connected to the same power supply,
- etc.

4.6 Causes of faults and their effects

The main characteristics are described in the table (⇨ *Fig. 41*).

Type of surge	Duration	Raising time - frequency	Damping
Atmospheric	Very short (1 à 10µs)	Very high (1000 kV/µs)	Strong
Electrostatic discharge	Very short (ns)	High (10 MHz)	Very strong
Operation	Short (1ms)	Medium (1 to 200 kHz)	Medium
Industrial frequency	Long (>1s)	Mains frequency	Nil

Fig. 41 *Characteristics of the types of voltage surge*

These disturbances, which come on top of mains voltage, can apply in two ways:
- regular mode, between active conductors and the ground,
- differential mode, between active conductors.

In most cases, voltage surges result in dielectric breakdown of the motor windings which destroys the motor.

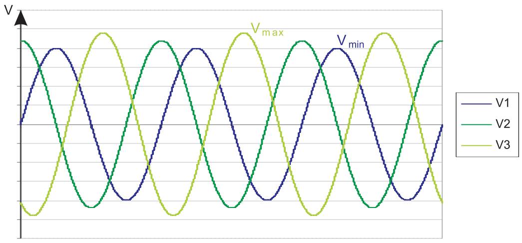


Fig. 42 *3 phase unbalanced voltages*

Unbalanced phases

A 3-phase system is unbalanced when the three voltages are of unequal amplitude and/or are not phase-shifted by 120° in relation to each other.

Unbalance (⇨ *Fig. 42*) can be due to phase opening (dissymmetry fault), single-phase loads in the motor's immediate vicinity or the source itself.

Unbalance can be approximated by the following equation:

$$\text{Unbalance}(\%) = 100 \times \text{MAX}\left(\frac{Vmax - Vmoy}{Vmoy}, \frac{Vmoy - Vmin}{Vmoy}\right)$$

where:
Vmax is the highest voltage,

Vmin is the lowest voltage,

$$Vmoy = \frac{(V1 + V2 + V3)}{3}$$

The result of unbalance in the voltage power supply is an increase of current for the same torque, invert component, thereby overheating the motor (⇨ *Fig.43*).

The IEC 60034-26 standard has a derating chart for voltage unbalance (⇨ *Fig. 44*) which should be applied when the phenomenon is detected or likely in the motor power supply. This derating factor is used to oversize a motor to take into account the unbalance or to lower the operating current of a motor in relation to its rated current.

Unbalance value (%)	0	2	3,5	5
Stator current (A)	In	1,01 x In	1,04 x In	1,075 x In
Loss increase (%)	0	4	12,5	25
Heating (%)	100	105	114	128

Fig. 43 *Effect of voltage unbalance on motor operating characteristics*

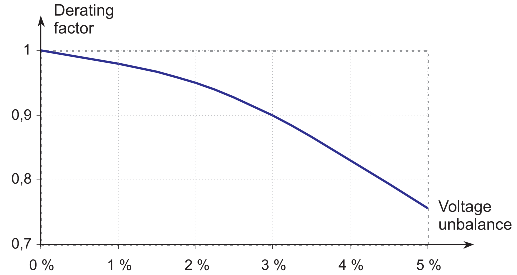
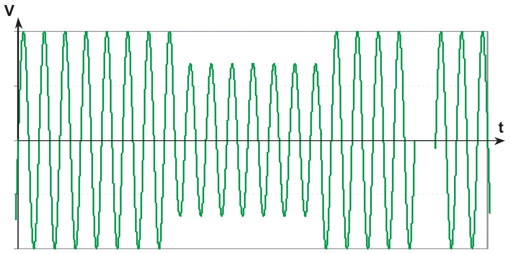


Fig. 44 *Motor derating according to unbalanced voltage in its power supply*

4.6 Causes of faults and their effects



↑ *Fig. 45* *Example of a voltage drop and a short voltage break*

Voltage drops and breaks

A voltage drop *(⇨ Fig. 45)* is a sudden loss of voltage at a point in the power supply.

Voltage drops (EN50160 standard) are limited to 1 to 90% of nominal voltage for half a cycle at 50 Hz i.e. 10 ms to 1 minute.

According to the same standards, a short break is when the voltage falls below 90% of nominal voltage for less then 3 minutes. A long brake is when the duration exceeds 3 minutes.

A micro drop or brake is one that lasts about a millisecond.

Voltage variations can be caused by random external phenomena (faults in the mains supply or an accidental short circuit) or phenomena related to the plant itself (connection of heavy loads such as big motors or transformers). They can have a radical effect on the motor itself.

- **Effects on asynchronous motors**

When the voltage drops, the torque in an asynchronous motor (proportional to the square of the voltage) drops suddenly and causes a speed reduction which depends on the amplitude and duration of the drop, the inertia of rotating masses and the torque-speed characteristic of the driven load. If the torque developed by the motor drops below the resistant torque, the motor stops (stalls). After a break, voltage restoration causes a re-acceleration inrush current which can be close to the starting current.

When the plant has a lot of motors, simultaneous re-acceleration can cause a voltage drop in the upstream power supply impedances. This prolongs the drop and can hamper re-acceleration (lengthy restarting with overheating) or prevent it (driving torque below the resistant torque).

Rapidly repowering (~150ms) a slowing down asynchronous motor without taking precautions can lead to an phase opposition between the source and the residual voltage maintained by the asynchronous motor. In this event, the first peak in current can be three times the starting current (15 to 20 Rated Current) (*cf. Cahier Technique Schneider Electric* n°161).

These voltage surges and resulting drop can have a number of effects on a motor:
- further heating and electrodynamic stress in the windings likely to break insulation,
- inching with abnormal mechanical stress on couplings or premature wear or breakage.

They can also affect other parts such as contactors (contact wear or welding), cause overall protection devices to cut in bringing the manufacturing chain or workshop to a standstill.

- **Effects on synchronous motors**

The effects are more or less the same as for asynchronous motors, though synchronous motors can, due to their greater general inertia and the lower impact of voltage on the torque, sustain greater voltage drops (about 50% more) without stalling.

When it stalls, the motor stops and the starting process must be run again, which can be complex and time consuming.

4.6 Causes of faults and their effects

- **Effects on speed-controlled motors**

The problems caused by voltage drops in speed controllers are:
- inability to supply enough voltage to the motor (loss of torque, slow down),
- dysfunction of mains-powered control circuits,
- possible overcurrent on voltage restoration due to the smoothing capacitors built into the drive,
- overcurrent and unbalanced current in the mains supply when voltage drops on a single phase.

Speed controllers usually fault when the voltage drop exceeds 15%.

Harmonics

Harmonics can be harmful to AC motors.

Non-linear loads connected to the mains supply causes a non sinusoidal currant and voltage distortion.

This voltage can be broken down into a sum of sinusoids:

$$y(t) = Y_0 + \sum_{h=1}^{\infty} Y_h . \sin(h.\omega.t + \varphi_h)$$

where :

Y_0 : continuous component

h : harmonic rank

ω : pulse (2.π.f)

Y_h : amplitude of harmonic rank h

Y_1 : fundament component

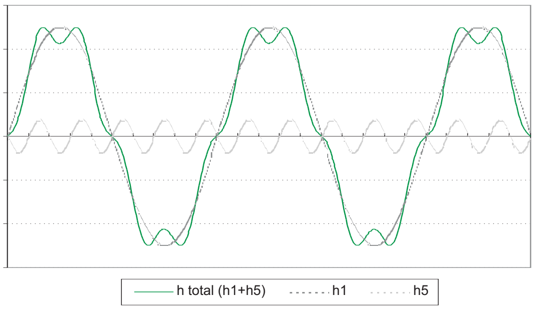


Fig. 46 Voltage with rank 5 harmonic

Signal distortion is measured by the rate of Total Harmonic Distortion (THD):

$$\text{DHT}(\%) = 100 \text{ x} \sqrt{\sum_{h=2}^{\infty} \left(\frac{Y_h}{Y_1}\right)^2}$$

Harmonic distortion (⇨ Fig. 46) is a form of pollution in the electricity network likely to cause problems at rates over 5%.

Electronic power devices (speed controller, UPS, etc.) are the main sources that create harmonics into the power supply. As the motor is not perfect either, it can be the source of rank 3 harmonics.

Harmonics in motors increase losses by eddy currents and cause further heating. They can also give rise to pulse torque's (vibrations, mechanical fatigue) and noise pollution and restrict the use of motors on full load (*cf. Cahiers Techniques Schneider-Electric* n° 199).

4.6 Causes of faults and their effects

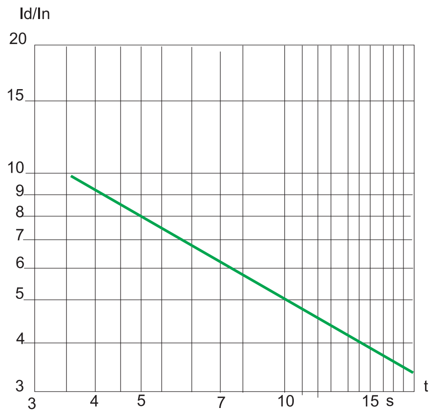


Fig. 47 Starting time based on the ratio of starting current to rated current

Faults with external causes related to motor operation

Motor starting: too long and/or too frequent

A motor's starting phase is the duration required for it to reach its nominal rotating speed (⇨ Fig. 47).

The starting time (t_s) depends on the resistant torque (T_r) and the driving torque (C_m).

$$t_D(s) = \frac{\pi}{30} . J . \frac{N}{C_m - C_r}$$ where

J: moment of global inertia of the masses in movement,

N(*rotation.s*$^{-1}$): rotor rotation speed.

Given its intrinsic characteristics, a motor can only sustain a limited number of starts, usually specified by the manufacturer (number of starts per hour).

Likewise, a motor has a starting time based on its starting current (⇨ Fig. 47).

Rotor locks

Motor locks from mechanical causes lead to an overcurrent approximately the same as the starting current. But the heating that results is much greater because rotor losses stay at their maximum value throughout the lock and cooling stops as it is usually linked to rotor rotation. Rotor temperatures can raise to 350°C.

Overload (slow motor overload)

Slow Motor overload is caused by an increase in the resistant torque or a drop in mains voltage (>10% of Nominal Voltage). The increase in current consumption causes heating which shortens the lifetime of the motor and can be fatal to it in the short or long run.

Summary

The summary in the table in *figure 48* shows the possible causes of each type of fault, the probable effects and inevitable outcome if no protection is provided.

In any event, motors always require two protections:
- protection against short circuits,
- protection against overload (overheating).

Faults	Causes	Effects	Effects on the motor
Short circuit	• Phase-to-phase, phase-to-ground , winding to winding	• Current surge • Electrodynamic stress on conductors	• Windings destroyed
Voltage surge	• Lightning • Electrostatic discharge • Disconnection of a load	• Dielectric breakdown in windings	• Windings destroyed by loss of insulation
Unbalanced voltage	• Phase opening • Single-phase load upstream of motor	• Decrease of the available torque • Increased losses	• Overheating(*)
Voltage drop and dip	• Instability in mains voltage • Connection of high loads	• Decrease of the available torque • Increased losses	• Overheating(*)
Harmonics	• Mains supply pollution by non linear loads	• Decrease of the available torque • Increased losses	• Overheating(*)
Starting too long	• Too high a resistant torque • Voltage drop	• Increase in starting time	• Overheating(*)
Locking	• Mechanical problem	• Overcurrent	• Overheating(*)
Overload	• Increase in resistant torque • Voltage drop	• Higher current consumption	• Overheating (*)

(*) And in the short or long run, depending on the seriousness and/or frequency of the fault, the windings short-circuit and are destroyed.

Fig.48 Summary of possible faults in a motor with their causes and effects

4.7 Protection functions

Protection against short circuits

Overview

A short circuit is a direct contact between two points of different electric potential:

- *alternating current*: phase-to-phase contact, phase-to-neutral contact, phase-to-ground contact or contact between windings in a phase,
- *direct current*: contact between two poles or between the ground and the pole insulated from it.

This can have a number of causes: damage to the varnish insulating the conductors, loose, broken or stripped wires or cables, metal foreign bodies, conducting deposits (dust, moisture, etc.), seepage of water or other conducting fluids, wrong wiring in assembly or maintenance.

A short circuit results in a sudden surge of current which can reach several hundred times the working current within milliseconds. A short circuit can have devastating effects and severely damage equipment. It is typified by two phenomena.

• A thermal phenomenon

A thermal phenomenon corresponding to the energy released into the electrical circuit crossed by the short circuit current I for at time t based on the formula I^2t and expressed as A^2s. This thermal effect can cause:

- melting of the conductor contacts,
- destruction of the thermal elements in a bimetal relay if coordination is type 1,
- generation of electrical arcs,
- calcination of insulating material,
- fire in the equipment.

• An electrodynamic phenomenon

An electrodynamic phenomenon between conductors producing intensive mechanical stress as the current crosses and causing:

- distortion of conductors forming the motor windings,
- breakage of the conductors' insulating supports,
- repulsion of the contacts (inside the contactors) likely to melt and weld them.

These results are dangerous to property and people. It is therefore imperative to guard against short circuits with protection devices that can detect faults and interrupt the short circuit rapidly, before the current reaches its maximum value.

Two protection devices are commonly used for this:

- fuses, which break the circuit by melting and must be replaced afterwards,
- magnetic circuit breakers which automatically break the circuit and only require to be reset.

Short-circuit protection can also be built into multifunction devices such as motor starter protection and contactor breakers.

4. AC motors starting and protection systems

4.7 Protection functions

Break capacity (BC)	φ Cos	Closing capacity (CC)
4.5kA < BC < 6kA	0.7	1.5 BC
6kA < BC < 10kA	0.5	1.7 BC
10kA < BC < 20kA	0.3	2 BC
20kA < BC < 50kA	0.25	2.1 BC
50kA < BC	0.2	2.2 BC

↑ *Fig. 49* *Break and closing capacities for circuit breakers by the IEC 60947-2 standard*

□ Definitions and characteristics

The main characteristics of short-circuit protection devices are:

- breaking capacity: the highest value in the estimated short-circuit current that a protection device can break at a given voltage,
- closing capacity: the highest value a protection device can reach at its rated voltage in specified conditions. The closing value is k times the break capacity as shown in the table *(⇨ Fig. 49)*.

□ Fuses

Fuses perform phase-by-phase (single pole) protection with a high break capacity at low volume. They limit I^2t and electrodynamic stress ($I_{crête}$).

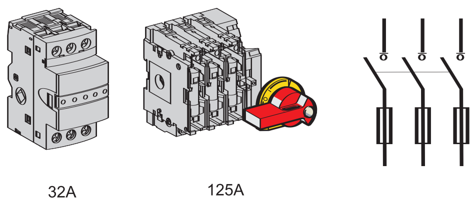
They are mounted:

- on special supports called fuseholders,
- or on isolators in the place of sockets and links *(⇨ Fig. 50)*.

Note that trip indicator fuse cartridges can be wired to an all-pole switching device (usually the motor control contactor) to prevent single-phase operation when they melt.

The fuses used for motor protection are specific in that they let through the overcurrents due to the magnetising current when motors are switched on. They are not suitable for protection against overload (unlike gG fuses) so an overload relay must be added to the motor power supply circuit.

In general, their size should be just above the full load current of the motor.



↑ *Fig. 50* *Fuse holder switch*

□ Magnetic circuit breakers

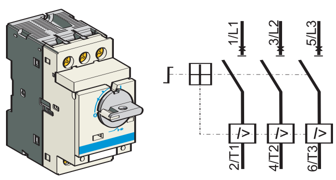
These circuit breakers protect plant from short circuits within the limits of their breaking capacity and by means of magnetic triggers (one per phase) *(⇨ Fig. 51)*.

Magnetic circuit breaking is all-pole from the outset: one magnetic trigger will simultaneously open all the poles.
For low short-circuit currents, circuit breakers work faster than fuses.
This protection complies with the IEC 60947-2 standard.
To break a short-circuit current properly, there are three imperatives:

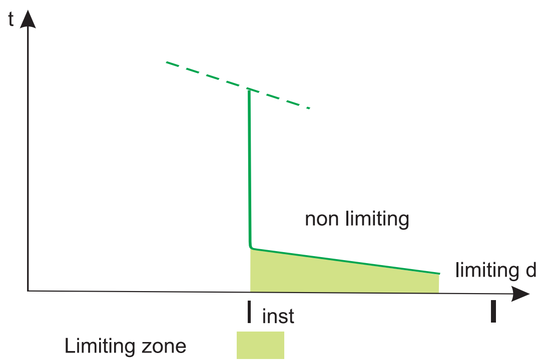
- early detection of the faulty current,
- rapid separation of the contacts,
- breakage of the short-circuit current.

Most magnetic circuit breakers for motor protection are current-limiting devices and so contribute to coordination *(⇨ Fig.52)*. Their very short cut-off time breaks the short-circuit current before it reaches its maximum amplitude.

This limits the thermal and electrodynamic effects and improves the protection of wiring and equipment.



↑ *Fig. 51* *GV2-L magnetic circuit breaker (Telemecanique) and its graphic symbol*



↑ *Fig. 52* *Curves of magnetic circuit breaker tripping*

Protection against overload

Overview

Overload is the commonest fault in motors. It is revealed by an increase in the current absorbed by the motor and by thermal effects. The insulation category sets normal motor heating at an ambient temperature of 40°C. Any overshoot of this operating limit leads to a reduction in lifetime by premature ageing of the insulating material.
It should however be noted that overloads leading to overheating will not have any immediately detrimental effects if they are short and infrequent. They do not necessarily involve stopping the motor but it is important to restore normal conditions very quickly.
The importance of proper protection against overload is easy to understand:
- It preserves the lifetime of motors by preventing them from working in overheating conditions.
- It ensures operating continuity by:
- preventing motors from stopping abruptly,
- after tripping, enabling restart in the best conditions of safety for people and equipment.

Actual operating conditions (temperature, altitude and standard duty) are requisite for determining a motor's operating values (power, current) and choosing adequate protection against overload (⇨ Fig.53). Operating values are given by the motor manufacturer.

Altitude m	Ambient temperature 30°C	35°C	40°C	45°C	50°C	55°C	60°C
1000	1.07	1.04	1.00	0.96	0.92	0.87	0.82
1500	1.04	1.01	0.97	0.93	0.89	0.84	0.79
2000	1.01	0.98	0.94	0.90	0.86	0.82	0.77
2500	097	0.95	0.91	0.87	0.84	0.79	0.75
3000	0.93	0.91	0.87	0.84	0.80	0.76	0.71
3500	0.89	0.86	0.83	0.80	0.76	0.72	0.68
4000	0.83	0.81	0.78	0.75	0.72	0.68	0.64

The values in the table above are for information only, as the derating of a motor depends on its size, insulation category, structure (self-cooling or fan-cooled, protection level – IP 23, IP 44, etc.) and varies with the manufacturer.

Note: The rated power value usually stamped on a motor's plate is set by the manufacturer for continuous duty D1 (steady state operation long enough to reach thermal balance).

There are other standard duties, such as temporary duty D2 and periodical intermittent duties D3, D4 and D5, for each of which the manufacturer sets a working power different from the rated power.

↑ Fig. 53 *Motor derating factors according to their operating conditions*

Depending on the level of protection required, overload protection can be provided by relays:
- overload, thermal (bimetal) or electronic relays, which provide minimum protection against:
  - overload, by controlling the current absorbed on each phase,
  - unbalanced or missing phase, by a differential device,
- positive temperature coefficient (PTC) thermistor probe relays,
- overtorque relays,
- multifunction relays.

Reminder: A protection relay does not break a circuit. It is designed to open a breaking device with the requisite breaking capacity for the faulty current, usually a contactor.

For this purpose, protection relays have a fault contact (NC) fitted in series with the contactor coil.

Overload relays (thermal or electronic)

- Overview

These relays protect motors against overload but must sustain the temporary overload of starting and only trip when starting lasts too long.

Depending on its use, motor starting can range from a few seconds (no-load starting, low resistant torque, etc.) to a few dozen seconds (high resistant torque, high inertia of the driven load, etc.).

Hence the necessity for relays adapted to the starting time. To meet this need, the IEC 60947-4-1 standard has several categories of overload relay each defined by its tripping time (⇨ Fig.54).

	Tripping time from: Cold to 1.05 x I_r	Warm to 1.2 x I_r	Warm to 1.5 x I_r	Cold to 7.2 x I_r	Lower tolerance (band E)
Classe					
10 A	> 2 h	< 2 h	< 2 min	2 s < tp < 10 s	-
10	> 2 h	< 2 h	< 4 min	4 s < tp < 10 s	5 s < tp < 10 s
20	> 2 h	< 2 h	< 8 min	6 s < tp < 20 s	10 s < tp < 20 s
30(*)	> 2 h	< 2 h	< 12 min	9 s < tp < 30 s	20 s < tp < 30 s

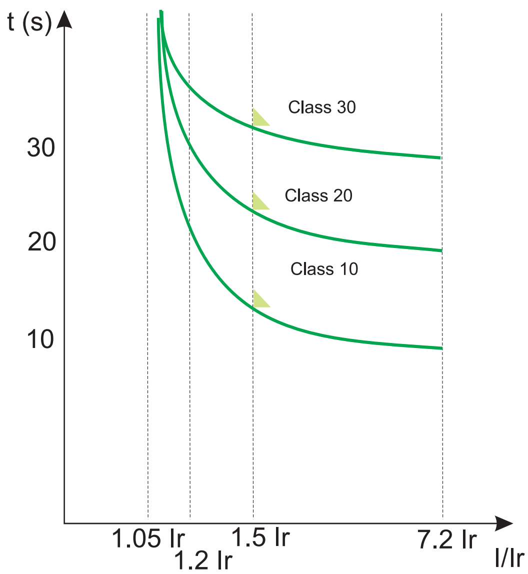
(*) category little used in Europe but widespread in the USA.
Cold : initial state with no previous load
Warm : thermal balance reached at Ir
Ir : overload relay current setting

↑ Fig. 54 *Main categories of overload relay tripping according to the IEC 60947-4-1 standard.*

The relay size should be chosen on the basis of the motor's rated current and the estimated starting time.

Limits of use are characterised by curves (⇨ Fig. 55) based on the time and value of the current setting (in multiples of Ir).

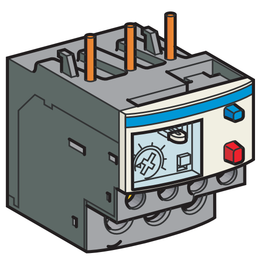
These relays have a thermal memory (apart from some electronic ones, indicated by their manufacturers) and can be connected:
- in series with the load,
- or, for high powers, to current transformers fitted in series with the load.



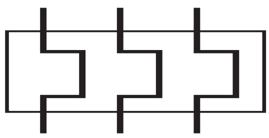
↑ Fig. 55 *Overload relay tripping curves*

Bimetal thermal overload relays (⇨ Fig. 56 and 57)

These are linked to a contactor to protect the motor, the power supply and the equipment against low prolonged overload. They are thus designed to enable the motor to start normally without tripping. However, they must be protected from strong over currents by a circuit breaker or fuses (see protection against short circuits).



↑ Fig. 56 *Bimetal thermal overload relays*



↑ *Fig. 57* *Thermal relay diagram*

The operating principle of a thermal overload relay is based on the distortion of its bimetal strips heated by the current that crosses them.

As the current crosses them, the strips distort and, depending on the setting, cause the relay contact to open suddenly.

The relay can only be reset when the bimetal strips have adequately cooled down.

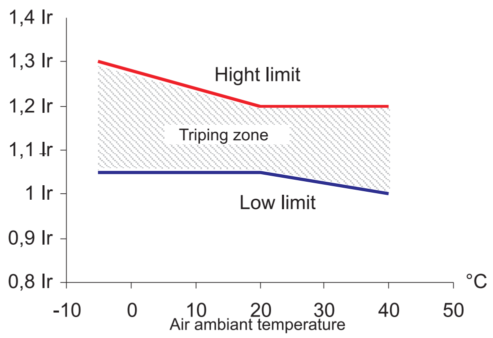
Thermal overload relays work with alternating and direct current and are usually:

- 3-pole,
- compensated, i.e. insensitive to ambient temperature variations (same tripping curve from 0°C to 40°C on a standard gauge *(⇨ Fig.58)*,
- graduated in “motor amperes”: current indicated on the motor plate displayed on the relay.

They can also respond to a loss of a phase: this is the differential. This feature prevents the motor from working in single-phase and complies with standards IEC 60947-4-1 and 60947-6-2 *(⇨ table Fig. 59)*.

Tripping time	Multiple of current setting value
> 2 h	2 poles : 1.0 Ir 1 pole : 0.9 Ir
> 2 h	2 poles : 1.15 Ir 1 pole : 0

↑ *Fig. 59* *Operating limit of a differential thermal overload relay (responding to loss of a phase).*



↑ *Fig. 58* *Operating limit of a differential thermal overload relay (responding to loss of a phase)*

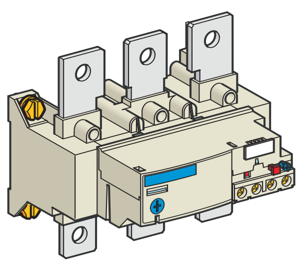
Widely used, this relay is very reliable and cost-effective. It is especially recommended if there is a risk of rotor locking. It does however have the disadvantages of imprecision with regard to the thermal status of the motor and sensitivity to the thermal conditions where it is installed (housing ventilation, etc.).

◻ Electronic overload relays *(⇨ Fig. 60)*

These relays have the advantages of electronic systems and build a more detailed thermal image of the motor. Using a template with the motor’s thermal time constants, the system continuously calculates the motor temperature based on the current crossing it and operating time. Protection is hence closer to the reality and can prevent inadvertent tripping. Electronic overload relays are less sensitive to the thermal conditions where they are installed.

Apart from the usual functions of overload relays (protection against motor overload, unbalance and lack of phase) electronic overload relays can include options such as:

- PTC probe temperature control,
- protection against locking and overtorques,
- protection against phase inversion,
- protection against insulation faults,
- protection against no-load operation,
- etc.



↑ *Fig. 60* *Electronic overload relay (LR9F - Telemecanique)*

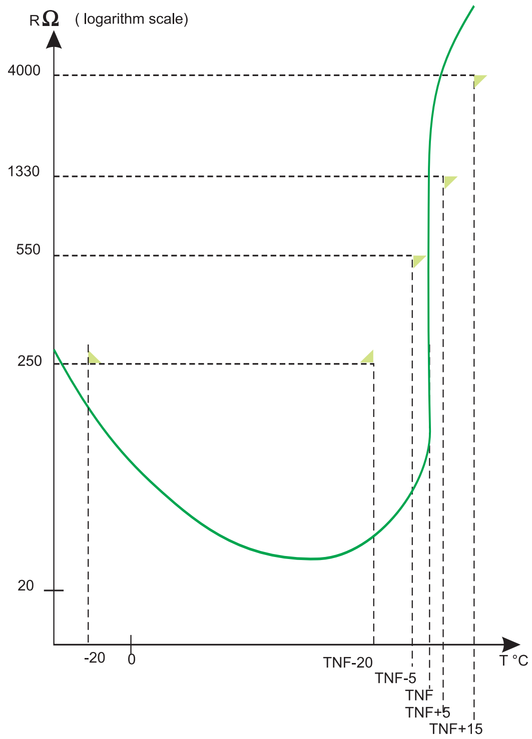


Fig. 61 PTC thermistor probe limits or "operating points"

Fig. 62 Electronic device (LT3 - Telemecanique) for three thermistor probes

Fig. 63 The overtorque relay (LR97D - Telemecanique

PTC thermistor probe relays

These protection relays control the actual temperature of the motor to be protected.

Probes are imbedded into the motor and because they are small, their thermal inertia is very low, ensuring a very short response time and hence a very accurate temperature reading.

They directly control the temperature of the stator windings so can be used to protect motors against: overload, increase in ambient temperature, ventilation circuit faults, too frequent starting processes, inching, etc.

They consist of:

- one or more Positive Temperature Coefficient (PTC) thermistor probes in the windings themselves or at any other point likely to heat (bearings, etc.).

These are static components with resistance that increases suddenly when the temperature reaches a threshold called the Nominal Operating Temperature (NOT) as shown by the curve (⇨ *Fig.61*).

- **An electronic device**

An electronic device powered by alternating and direct current for continuous control of the resistance of the probes linked to it. If the NOT is reached, the strong increase in resistance is detected by a threshold circuit which then orders a change in the status of the output contacts. Depending on the probes chosen, this protection mode can be used to:

- set off an alarm without stopping the machine (NOT of the probes lower than the maximum temperature set for the element to be protected),
- or order the machine to stop (the NOT has reached the maximum level) (⇨ *Fig.62*).

This protection system should be organised upfront because the probes have to be set in the windings when the motor is manufactured, though they can be included when new windings are fitted after an incident.

The choice of PTC probes depends on the insulation category and motor structure. It is usually made by the motor manufacturer or winding fitter who are the only ones with the requisite skills.

These two conditions mean that PTC probe protection really only applies to high-end equipment with expensive motors or processes.

Overtorque relays: extra protection (⇨ *Fig.63*)

In addition to thermal protection by relays or PTC probe, these ensure protection of the drive chain in the event of rotor locking, mechanical seizing or inching.

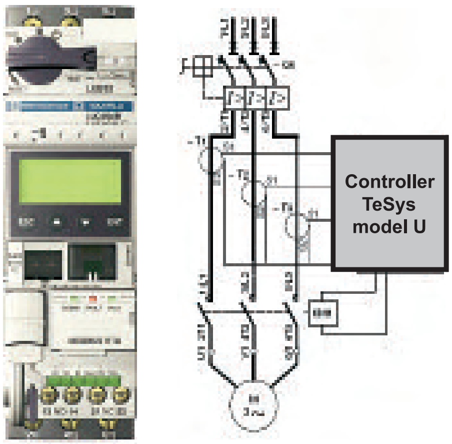
These, unlike most overload relays, have no thermal memory. They have a set operating time (adjustable current threshold and timing).

An overtorque relay can be used to protect motors against overload when their starting process is long or very frequent (e.g. inching).

Multifunction relays

- **Electromechanical or electronic relays**

Electromechanical or electronic relays protect the motor using the current flowing into the motor. The are perfectly suitable for regular operation. However, they are not able to take into consideration multiple potential problems due to voltage temperature or specific application. Furthermore user's requirements as maintenance or production management has become a major concern and electrical manufacturers has introduced to the market new products which can be tailored to the application and offer a global protection for the motor and the driven load.



↑ *Fig. 65* *Multifunction relay is separated from the motor starter*

- **Features**

These relays has been developed using the following technologies: voltage and current sensors, the latter's use ironless devices (Rogowsky sensors) which are fast and offer an outstanding linearity:

- an electronic combining numerical and analogic technologies, the result being a good capacity for treatment and data storage,
- use of field buses to exchange data to and from the PLC's and other devices,
- use of accurate motor modelisation algorithms,
- use of embedded programmes whose parameters can be defined.

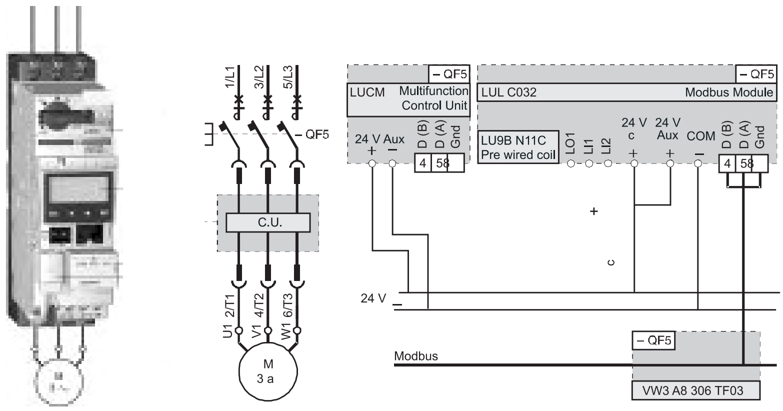
This new generation of product allow to reduce the costs from the design of the equipment, as PLC's programming are made simple, to the operation as maintenance cost and downtime are dramatically cut down.

The following is a brief description of the possible solutions and a basic selection guide.

Readers should consult Schneider Electric technical documentation which give more in depth information.

- **The whole product line can be broken down in three families**

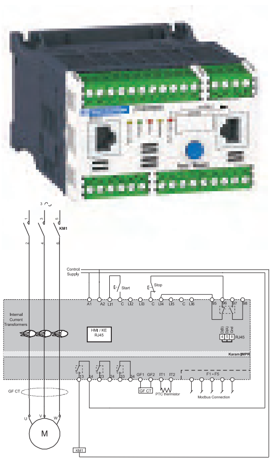
Solution 1: The multifunction relay is embed into the motor starter *(⇨Fig. 64)*. The benefit of this all in one solution is a very compact product with a limited number of connections.
The upper limit is 32 Amps.



↑ *Fig. 64* *Multifunction relay embed into the motor starter*

Solution 2: the multifunction relay is separated from the motor starter and uses the same components as the all in one solution *(⇨Fig. 65)*.
The benefit is a possible connection to any motor starter.

Solution 3: the multifunction relay is segregated from the motor starter and offer multiple inputs / outputs.
It is the most versatile solution. *(⇨Fig. 66)*



↑ *Fig. 66* *Multifunction relay with multiple I/O*

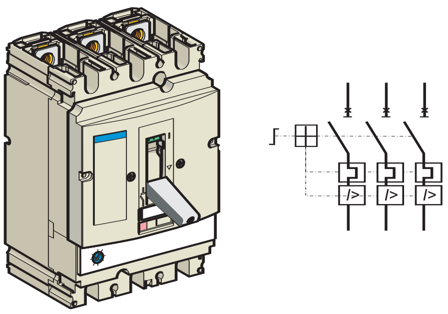
Protection relay selection guide

Main functions are given in the table bellow *(⇨Fig. 67)*. More in depth information can be found in the manufacturer data sheets.

4.7 Protection functions

Type of relays	Overload relay (thermorelay or electronic relay)	PTC probe relay	Overtorque relay	Muntifunction relay		
				Built in the starter	Outside the starter	Segregated motor monitor
Type of control						
Current						
Protection classes	10 et 20			5 to 20	5 to 20	5 to 30
Overcurrent	++		+++	+++	+++	+++
Ground fault						
Phase imbalance	++			++	++	+++
Mechanical locking during / after starting	+		++	++	++	+++
No load operation				module	module	+++
Votage and power supply						
Voltage imbalance						+++
Phase loss						+++
Phase inversion						+++
Undervoltage						+++
Overvoltage						+++
Power an power factor						+++
Temperature						
PTC probes				module	module	+++
PT100 probes				module	module	+++
Numerical functions						
Truth table				3 I/O	10 I/O	10 to 20 I/O
Timer						++
Starting mode						
Direct on line				+++	+++	+++
Reversing				+++	+++	+++
Star delta				+++	+++	+++
Part winding - two speed motors					+++	+++
Operation / maintenance						
Diagnostics				+	+	+++
Log				module	module	+++
Links / communication						
Local display	+			module	module	+++
Remote display (communication bus)				module	module	+++
Remote control (communication bus)				module	module	+++

↑ *Fig. 67* *Motor protection table*



↑ *Fig. 68* *Motor circuit breaker (GV7 - Telemecanique) and its graphic symbol*

Motor circuit breakers

Overview

This device is a thermal and a magnetic circuit breaker in the same package which protects a motor against short circuits and overload by rapidly opening the faulty circuit. It is a combination of a magnetic circuit breaker and overload relays It complies with the IEC 60947-2 and 60947-4-1 standards *(⇨ Fig. 68)*.

In these circuit breakers, the magnetic devices (protection against short circuits) have a non-adjustable threshold, usually about 10 times the maximum current setting of thermal release units.

The thermal elements (protection against overload) are compensated for fluctuations of the ambient temperature. The thermal protection threshold can be adjusted on the front of the unit. Its value must correspond to the rated current of the motor to be protected.

In all these circuit breakers, coordination (type II) between the thermal elements and short-circuit protection is built into the device.

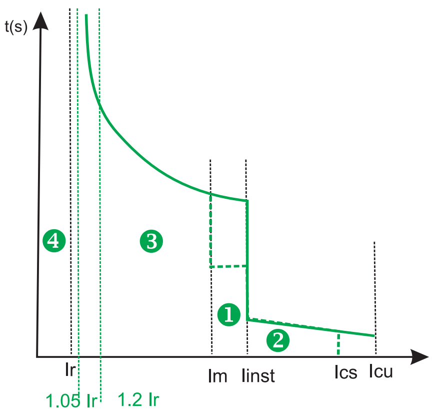
Moreover, in the open position, the insulation distance (between contacts) in most of these units is adequate to ensure isolation. They also have a padlocking device.

Tripping curves

A motor trip switch is characterised by its tripping curve, which represents the time it takes to trip based on the current (multiple of I_r).

This curve is divided into four zones *(⇨ Fig. 69)* :

- Ic normal operating zone ❶ . As long as $I < I_r$, there is no tripping,
- thermal overload zone ❷. Tripping is ensured by the “thermal” feature; the greater the overload, the less time it takes to trip. The standards refer to this as “inverse time”,
- strong high current zone ❸, monitored by the “instant magnetic” or “short-circuit” feature which works instantaneously (less than 5ms),
- and on some circuit breakers (electronic), an intermediate zone ❹ monitored by a “timed-delay magnetic” feature with a delay function (0 to 300ms). The standards refer to this as “definite time-lag”. This prevents accidental tripping at switch-on with magnetising peak currents.



↑ *Fig. 69* *Thermal magnetic circuit breaker operating zones*

Their limits are:

I_r: setting current for protection against overload; should correspond to the rated current value (I_n) of the motor to be protected,

I_m: tripping current of timed magnetic protection,

I_{inst}: tripping current of instant magnetic protection. This can range from 3 to 17 times Ir but is usually close to 10 I_r,

I_{cs}: service rated breaking capacity in short circuit,

I_{cu}: ultimate (maximum) breaking capacity in short circuit.

Conclusion

Motor protection is an essential function for ensuring the continuity of machine operation. The choice of protection device must be made with extreme care. The user would be wise to select devices that include electronic communication features to foresee and prevent any faults. These greatly improve the detection of abnormalities and the speed with which service is restored.

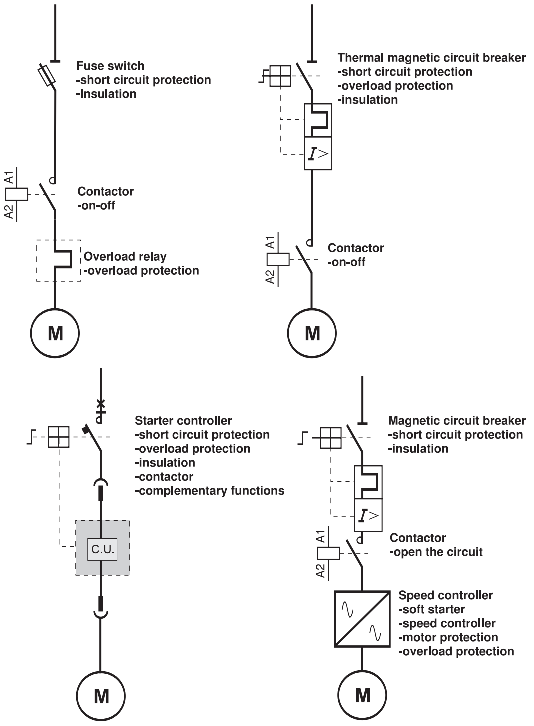
5 chapter
Motor starter units

Presentation:
- *Mandato functions to built a motor starter*
- *Selection table*

5 - Motor starter units Summary

5 - Motor starter units

5.1 Forward



↑ *Fig. 1* *The different functions and their combinations to build a motor starter*

A motor starter unit has four basic functions:
- isolating the load from mains,
- protection against short-circuits,
- protection against overload,
- commutation or control (start - stop).

Each motor starter unit can be enhanced with additional functions depending on its purpose. These can be:
- power: speed controller, soft starter, phase reversal, etc,
- checking: auxiliary contacts, time-delay, communication, etc.

According to the structure of a motor starter unit, the functions can be distributed in different ways *(⇨ Fig. 1)* shows the possible arrangements.

5.2 The basic functions of motor starter units

Isolating contacts

Isolating contacts are compulsory and must be fitted at the head of all circuits (cf. installation standards NF C15-100, IEC 60364-5-53), they are not compulsory but recommended for each motor starter unit. Their role is to insulate circuits safely from their energy source (mains power supply) to ensure the protection of goods and people if there is maintenance work, reparation work, or alterations to electric circuits downstream.

This isolating contact must comply with the specifications which stipulate:
- all-pole and simultaneous switching,
- proper insulation distances depending on the supply voltage,
- interlocking,
- a visible or apparent break,
- the “visible break” means that the opening of the poles is completely visible for an operator,
- the apparent break can be identified either by the position of the working gear, or by the position indicator which, according to the standards, can only indicate the “de-energised” position if the contacts are actually separated by an adequate distance as specified in the standards. Manufacturers offer a number of devices with these functions. Often one device can handle the functions of isolating contacts and protection against short-circuits (ex. fuse holder / disconnector device). For this, some basic machines must have a boosting device added, e.g. a connection support.

A disconnector is designed to insulate a circuit and does not have the capacity to break or close down, which is why it should always be a no-load manipulation. A switch not only has insulation capacities but can also complete, withstand, and break currents (standard IEC 947-3).

Protection

Protection against short-circuits

For this, it is necessary to detect the overcurrents following the short circuits (generally more than 10 times the rated current) and open the faulty circuit. It is filled with fuses or magnetic circuit breakers.

Protection against overload

For this it is necessary to detect the overcurrents following the overload ($I_r < I_{overload} < I_m$) and open the faulty circuit. It is filled with electromechanical or electronic devices (overload relay) linked to a breaking device (a circuit breaker or contactor) or built into the starters or electronic speed controllers. It also protects the motor line against thermal overload.

Protections for starters and electronic variable speed controllers

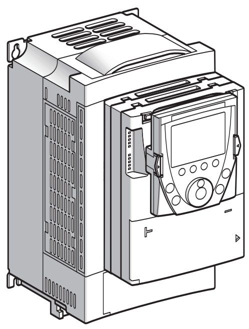
Direct starting on the asynchronous motor power supply is the most common solution, the most cost-effective and usually the most suitable for a large variety of machines. However, it does include constraints which can be impeding for certain applications, or even incompatible with what the machine is supposed to do (inrush on starting, mechanical jerks on starting, inability to control acceleration and deceleration, inability to vary speed, etc.).

Soft starters and electronic speed controllers *(⇨ Fig. 2)* can overcome these drawbacks, but the conventional protections previously described are not suitable with these products which modulate the electrical energy supplied to the motor.

Speed controllers and electronic starters therefore have built-in protections. Modern speed controllers ensure overall protection from motor overload and their own protection. Using the current measurement and information on the speed, a microprocessor calculates the motor's temperature increase and gives an alarm or trip signal in case of excessive overheating.

Furthermore, the information generated by the thermal protection built into the speed controller can be sent to a PLC or a supervisor by a field bus included in the more modern speed controllers and starters.

For more information, see the section in this guide on speed controllers.



↑ Fig. 2 *Speed controller (ATV71 - Telemecanique)*

Commutation or control

The control function

The word "control" means closing (making) and opening (breaking) an electrical circuit on-load. The control function can be ensured by a load break switch or by motor starting device, soft starters or speed controllers.
But a contactor is mostly used to carry out this function as it allows for remote control. With motors, this control device must allow for a large number of operations (electrical durability) and must comply with standards IEC 60947-4-1. These standards stipulate that, for this material, manufacturers must clarify the following points:

- **Control circuit:**
  - type of control current and its frequency, in the case of alternating current,
  - rated control circuit voltage (Uc) or supply voltage control (Us).
- **Power circuit:**
  - rated operational power (Ue): generally shown by voltage between phases. It determines the utilisation of the circuits which contribute to the making and breaking capacity, the type of service and the starting characteristics.

- rated operational current (Ie) or rated operational power: this characteristic is defined by the manufacturer based on the nominal operational conditions and especially taking into account the rated operational voltage and the conventional thermal current. In the case of equipment for direct control of one motor, the indication of the rated operational voltage can be replaced or completed by that of the assigned maximum available power.

This information can, in some cases, be completed by:
- the assigned service, mentioning the intermittent service class, if there is one. The classes define different operational cycles,
- the powers assigned to making and/or breaking. These are maximum current values, set by the manufacturer, that device can adequately make (closing) or break (opening) in specific conditions. The assigned powers of making and breaking are not necessarily specified by the manufacturer but standards require the minimum value for each utilisation category.

□ Control devices categories

The standards in the IEC 60947 series define the utilisation categories according to the purposes the control gear is designed for (⇨ Fig. 3). Each category is characterised by one or more operating conditions such as:
- currents,
- voltages,
- power factor or time constant,
- and if necessary, other operating conditions.

Type of current	Operating categories	Typical uses
Alternating current	**AC-1**	Non inductive or slightly inductive load, resistance furnace. Power distribution (lighting, generators, etc.).
	AC-2	Brush motor: starting, breaking. Heavy duty equipment (hoisting, handling, crusher, rolling-mill train, etc.).
	AC-3	Squirrel cage motor: starting, switching off running motors. Motor control (pumps, compressors, fans, machine-tools, conveyors, presses, etc.).
	AC-4	Squirrel cage motor: starting, plugging, inching. Heavy-duty equipment (hoisting, handling, crusher, rolling-mill train, etc.).
Direct current	**DC-1**	Non inductive or slightly inductive load, resistance furnace.
	DC-3	Shunt wound motor: starting, reversing, counter-current breaking, inching. Dynamic breaking for direct current motors.
	DC-5	Series wound motor: starting, reversing, counter-current breaking, inching. Dynamic breaking for direct current motors.

** Category AC-3 can be used for the inching or reversing, counter-current breaking for occasional operations of a limited length of time, such as for the assembly of a machine. The number of operations per limited length of time normally do not exceed five per minute and ten per 10 minutes.*

↑ *Fig. 3* *Contactor utilisation categories based on the purposes they are designed for, according to IEC 60947-1*

The following is also taken into consideration:
- circuit making and breaking conditions,
- type of load (squirrel cage motor, brush motor, resistor),
- conditions in which making and breaking take place (motor running, motor stalled, starting process, counter-current breaking, etc.).

□ Choosing a contactor

The utilisation categories defined in the standard allow for initial selection of a device that can meet the demands of the purpose the motor is designed for. However, there are certain constraints to take into consideration and which are not all defined by the standard. These are all the factors which have nothing to do with the purpose itself, such as climatic conditions (temperature, humidity), geographical setting (altitude, sault mist), etc.

In certain situations, the reliability of the equipment can also be a critical factor, especially if maintenance is difficult. The electrical life (durability of contacts) of the device (contactor) therefore becomes an important feature.

It is thus necessary to have detailed and accurate catalogues to ensure the product chosen complies with all these requirements.

5.3 An additional function: communication

■ Communication is now an almost mandatory function

In industrial production processes and systems, remote control is used to check and interrogate devices and control the machines on a production system.

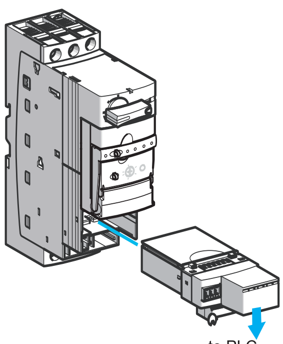
For such a communication between all the elements of a production system, the communication components or modules *(⇨ fig. 4)* are built into most units including protective devices such as multifunction relays or motor starters.

■ What communication provides

With communication modules such as AS-I, Modbus, Profibus, etc., besides the monitoring of the motor (stop-start remote control of the motor starter), the motor load (current measurement) and/or existing or former defects (log files) can be ascertained from a distance. Apart from being useful for integrating protection into the industrial automation process, communication can also contribute to the following services:

- early warnings to anticipate the appearance of a defect,
- create log files to record and identify a recurrent event,
- help with implementation,
- help with maintenance by identifying a loss of accuracy in the operating conditions.

It thus contributes to the progress of equipment management with a positive impact on economic results.



↑ *Fig. 4* *Starter controller with its communication module Modbus (Tesys U - Telemecanique)*

5.4 Motor starter units and coordination

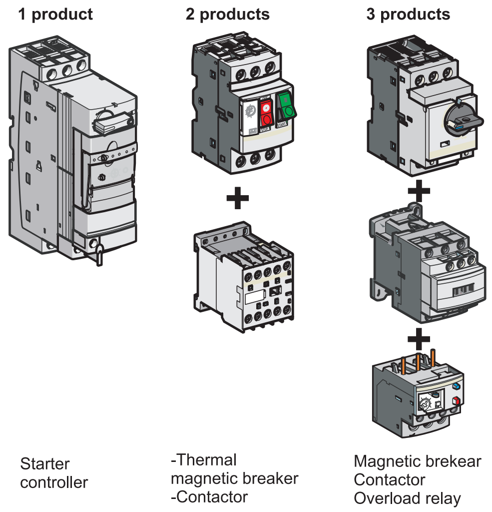


Fig. 5 *The three device combinations for making a motor starter unit*

Motor starter unit solutions

As explained at the beginning of this section, the main functions that a motor starter unit must provide (insulation, control and protection against short-circuits and overloads) can be fulfilled a range of products.

Three device combinations can be used (⇨ *fig. 5)* for a motor starter unit to adequately fulfil all these functions, but the devices must have compatible features.

- **"All-in-one" solution**

A single package includes the three functions and its overall performance is guaranteed by the manufacturer. For the user, from the engineering and design office to installation, it is simplest solution, easy to implement (little wiring) and immediate to choose (no special design necessary).

- **"2-device" solution**

Thermal magnetic circuit breaker + contactor.

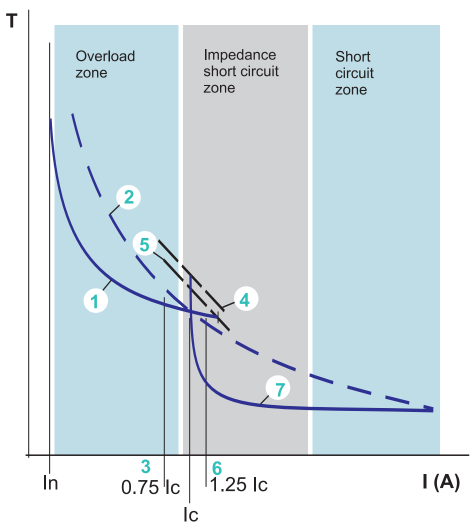
Compatibility of the features of both devices must be checked by the user.

- **"3-device" solution**

Magnetic circuit breaker + contactor + overload relay.

This covers a wide power range. The combination calls for a compatibility study to choose the devices and an installation study to see if they should be panel mounted or enclosed.

This work (compatibility, choice and installation) may not be straightforward for users as they must establish all the features of the devices and know how to compare them. This is why manufacturers first study and then offer the device combinations in their catalogues. Likewise, they try to find the most efficient combinations between protections. This is the notion of coordination.



1 trip curve overload relay
2 Fuse
3 trip of the overload relay alone
4 thermal limit of the breaker
5 Overload relay limit
6 Breaking current with SCPD (1) (1).
7 Magnetic tripping of the breaker

Fig. 6 *The basics of coordination*

Coordination between protections and control

It is coordination, the most efficient combination of the different protections (against short circuits and overloads) and the control device (contactor) which make up a motor starter unit.

Studied for a given power, it provides the best possible protection of the equipment controlled by this motor starter unit (⇨ *Fig. 6)*.

It has the double advantage of reducing equipment and maintenance costs as the different protections complement each other as exactly as possible, with no useless redundancy.

There are different types of coordination

Two types of coordination (type 1 and type 2) are defined by IEC 60947-4-1.

- **Type 1 coordination:** the commonest standard solution. It requires that in event of a short circuit, the contactor or the starter do not put people or installations in danger. It admits the necessity of repairs or part replacements before service restoration.
- **Type 2 coordination:** the high performance solution. It requires that in the event of a short circuit, the contactor or the starter do not put people or installations in danger and that it is able to work afterwards. It admits the risk of contact welding. In this case, the manufacturer must specify the measures to take for equipment maintenance.
- Some manufacturers offer : the highest performance solution, which is **“Total coordination”**.

This coordination requires that in the event of a short circuit, the contactor or the starter do not put people or installations in danger and that it is able to work afterwards. It does not admit the risk of contact welding and the starting of the motor starter unit must be immediate.

Control and protection switching gear (CPS)

CPS or “starter-controllers” are designed to fulfil control and protection functions simultaneously (overload and short circuit). In addition, they are designed to carry out control operations in the event of a short circuit.

They can also assure additional functions such as insulation, thereby totally fulfilling the function of “motor starter unit”. They comply with standard IEC 60947-6-2, which notably defines the assigned values and utilisation categories of a CPS, as do standards IEC 60947-1 and 60947-4-1.

The functions performed by a CPS are combined and coordinated in such a way as to allow for uptime at all currents up to the Ics working short circuit breaking capacity of the CPS. The CPS may or may not consist of one device, but its characteristics are assigned as for a single device. Furthermore, the guarantee of “total” coordination of all the functions ensures the user has a simple choice with optimal protection which is easy to implement.

Although presented as a single unit, a CPS can offer identical or greater modularity than the “three product” motor starter unit solution. This is the case with the “Tesys U” starter-controller made by Telemecanique *(⇨ Fig. 7)*. This starter-controller can at any time bring in or change a control unit with protection and control functions for motors from 0.15A to 32A in a generic “base power” or “base unit” of a 32 A calibre.

Additional functionality’s can also be installed with regard to:

- **power, reversing block, limiter**
- **control**
  - functions modules, alarms, motor load, automatic resetting, etc,
  - communication modules: AS-I, Modbus, Profibus, CAN-Open, etc,
  - auxiliary contact modules, added contacts.

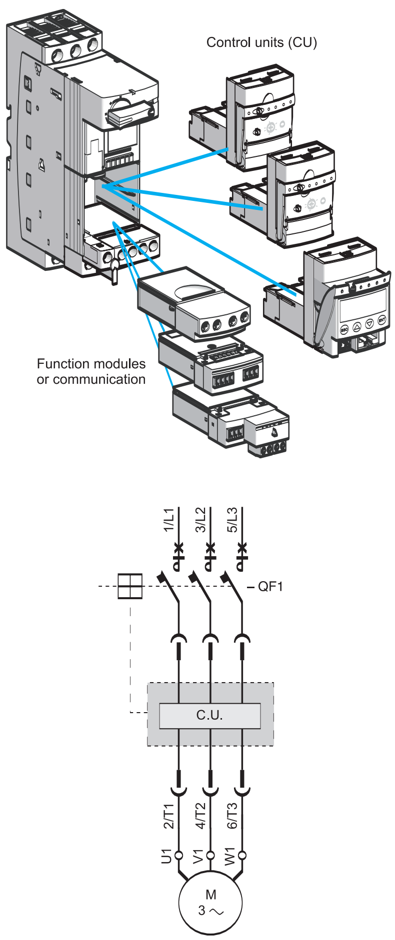


Fig. 7 *Example of a CPS modularity (Tesys U starter controller by Telemecanique)*

Communications functions are possible with this system *(⇨ Fig. 8)*.

Available functions :	Control units : Standard	Upgradeable	Multifunction
Starter status (ready, running, with default)	■	■	■
Alarms (overcurrents…)			■
Thermal alarm		■	■
Remote resetting by bus		■	■
Indication of motor load		■	■
Defaults differentiation		■	■
Parameter setting and protection function reference			■
“Log file” function			■
“Monitoring” function			■
Start and Stop controls	■	■	■

■ *Information conveyed by bus (Modbus) and functions performed*

Fig. 8 *Tesys U Communication functions*

What sort of coordination does one choose?

The choice of the coordination type depends on the operation parameters.

It should be made to achieve the best balance of user needs and installation costs.

- **Type 1**

Acceptable when uptime is not required and the system can be reactivated after replacing the faulty parts.

In this case the maintenance service must be efficient (available and competent).

The advantage is reduced equipment costs.

- **Type 2**

To be considered when the uptime is required.

It requires a reduced maintenance service.

When immediate motor starting is necessary, **“Total coordination”** must be retained. No maintenance service is necessary.
The coordinations offered in the manufacturers’ catalogues simplify the users’ choice and guarantees that the motor starter unit complies with the standard.

Selectivity

In an electric installation, the receivers are connected to mains by a series of breaking, protection and control devices.

Without a well-designed selectivity study, an electrical defect can trig several protection devices. Therefore just one faulty load can cut off power to a greater or lesser part of the plant. This results in a further loss of power in fault-free feeders.

To prevent this loss, in a power distribution system *(⇨ Fig. 9)*, the aim of selectivity is to disconnect the feeder or the defective load only from the mains, while keeping as much of the installation activated as possible. Selectivity therefore combines security and uptime and makes it easier to locate the fault.

To guarantee a maximum uptime, it is necessary to use protection devices which are coordinated amongst themselves. For this, different techniques are used which provide total selectivity if it is guaranteed for all the fault current values up to the maximum value available in the installation or partial selectivity otherwise.

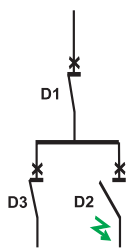


Fig. 9 *Selectivity between two circuit-breakers D1 and D2 fitted in a series and crossed by the same fault current ensures that only the D2 circuit-breaker placed downstream from D1 will open*

Selectivity techniques

There are several types of selectivity:

- **amperemetric**, using a differential between the tripping thresholds of the circuit-breakers fitted in series;
- **chronometric**, with a delay of a few dozen or hundred milliseconds before the upstream circuit breaker trips, or using the normal operation characteristics linked to the device ratings. Selectivity will may therefore be ensured between two overload relays by respecting the condition $I_{r1} > 1{,}6.\ I_{r2}$ (with r1 upstream of r2);
- « **Sellim** » ou « **energy** », in the power distribution area, where a limiting upstream circuit-breaker opens for the time it takes for the downstream circuit-breaker to work and then closes;
- **logic**, by passing on from one circuit breaker to another the information of the threshold reached to allow the circuit-breaker the furthest downstream to open.

For more information of selectivity, see the *Schneider-Electric Cahier Technique n° 167.*

Process selectivity

For process control equipment (manufacturing chain, chemical production units, etc.), the commonest selectivity techniques between the motor starter units and power distribution to the process are usually amperemetric or chronometric. In most cases, selectivity is ensured by a power limiter or ultra-limiter in the motor starter units.

5.5 Speed controllers

This section describes the details of all the aspects of speed controllers. Some very specific technologies such as cycloconverters, hyposynchronous cascade, current wave inverters for synchronous or asynchronous motors, to name but a few, will not be discussed. The use of these speed controllers is very specific and reserved to special markets. There are specialised works dedicated to them.

Speed control for direct-current motors, though widely replaced by frequency changer speed control, is nonetheless described because the understanding of its operating principle smoothes the approach to certain special features and characteristics of speed control in general.

History and reminders

History

To start electric motors and control their speed, the first solutions were resistance type starters, mechanical controllers and rotating groups (Ward Leonard especially). Then electronic starters and speed controllers came into industry as a modern, economical, reliable maintenance free solution.

An electronic starter or speed controller is an energy converter designed to modulate the electric power supply to the motor.

Electronic starters are designed exclusively for asynchronous motors. They belong to the family of voltage dimmers.

Speed controllers ensure gradual acceleration and deceleration. They enable speed to be adjusted precisely to the operating conditions. DC electronic speed controllers are types of controlled rectifiers to supply direct-current motors. Those for alternating current motors are inverters specifically designed to supply AC motors and named AC drives.

Historically, the first solution brought to the market was the electronic speed controller for direct-current motors. Progress in power semiconductors and microelectronics has led to the development of reliable and economical AC drives. Modern AC drives enable of the shelves asynchronous motors to operate at performances similar to the best DC speed controllers. Some manufacturers even offer asynchronous motors with electronic speed controllers incorporated in an adapted terminal box. This solution is available for low power assemblies (a few kW).

Recent developments in electronic speed controllers are discussed at the end of this section, along with the trends seen by the manufacturers.

These elegant developments considerably widen the offers and possibilities of controllers.

□ Reminders: main functions of starters and electronic speed controllers

- **Controlled acceleration**

Motor acceleration is controlled by a linear or S-shaped acceleration ramp. This can usually be adjusted to choose the right speed suitable for the purpose.

- **Speed controller**

A speed controller is not necessarily a regulator. It can be a crude system where a variable voltage is supplied to the motor. It is called an “open loop”. Speed will vary in large proportion according to the load, the temperature of the motor.

A better arrangement can be made using voltage across the motor and motor current. These information are used in a close loop arrangement.

The speed of the motor is defined by an input variable (voltage or current) called setting or reference. For a given setting value, interference (variations in the control supply voltage, load and temperature) can make the speed vary.

The speed range is expressed according to the rated speed.

- **Speed regulation by sensor**

A speed regulator *(⇨ Fig. 10)* has a control system with power amplification and a loop feadback. It is called a “closed loop”.

Motor speed is defined by a setting.

The setting value is always compared to the feedback signal which is the image of the motor speed. This signal is delivered by a tacho-generator or a pulse generator set up on the tail shaft of the motor or else by an estimator that determines the motor speed by the electrical values available in the speed controller.

High performance AC drives are often equipped with such electronic estimators.

If a differential is detected after a speed variation, the values applied to the motor (voltage and/or frequency) are automatically corrected so as to bring the speed back to its initial value.

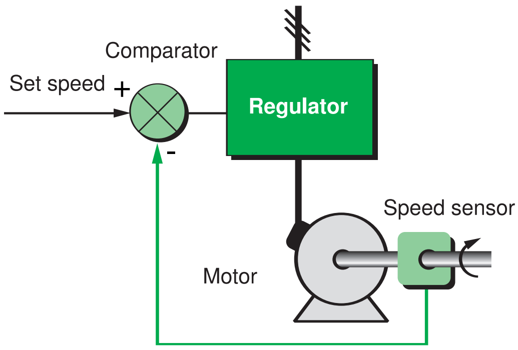
Regulation makes speed practically independent of perturbation (load variation, temperature etc.).

The precision of the regulator is generally expressed as a % of the rated value of the values to regulate.

- **Controlled deceleration**

When a motor is slowing down, its deceleration is solely due to the machine load torque (natural deceleration).

Starters and electronic speed controllers are used to control deceleration with a straight or S-shaped ramp, usually independent of the acceleration ramp.



↑ *Fig. 10* *Speed regulation principle*

This ramp can also be regulated for a delay time to change from steady state to intermediary or zero speed:

- if the desired deceleration is faster than natural deceleration, the motor must develop a braking torque which is added to the machine load torque. This is often referred to as electronic braking and can be done either by sending the energy back to the mains network, or dissipation in a dynamic brake resistor,
- if the desired deceleration is slower than natural deceleration, the motor must develop a load torque higher than the machine torque and continue to drive the load until it comes to a standstill.

- **Reversing**

Reversing the supply voltage (direct-current motor controllers) or reversing the order of the motor powering phases is done automatically either by reversing the input settings, or by a logical order on a terminal, or by using information sent by a field bus. This function is standard on most of the current controllers for AC motors.

- **Braking to a standstill**

This braking involves stopping a motor without actually controlling the deceleration ramp. For asynchronous motor starters and AC drives, this is done in an economical way by injecting direct current in the motor with a special operation of the power stage. All the mechanical energy is dispersed in the machine's rotor, so braking can only be intermittent. On a direct current motor controller, this function can be fulfilled by connecting a resistor to the armature terminals.

- **Built-in protections**

Modern controllers generally ensure thermal protection of the motors and their own protection. Using the current measure and information on the speed (if motor ventilation depends on the rotation speed), a microprocessor calculates the increase of the motor temperature and gives an alarm or trip signal in the event of excessive overheating.

Controllers, especially AC drives, are also usually equipped with protection against:

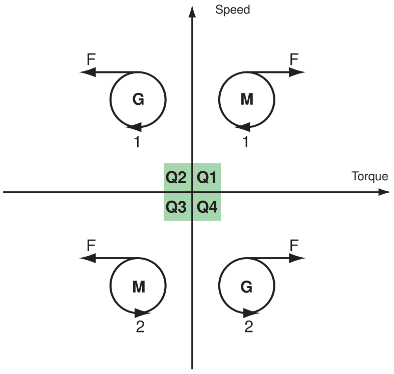
- short circuits between phase-to-phase and phase-to-ground;
- voltage surges and drops;
- phase unbalances;
- single-phase operation.

■ Main operating modes and main types of electronic speed controllers

□ Main operating modes

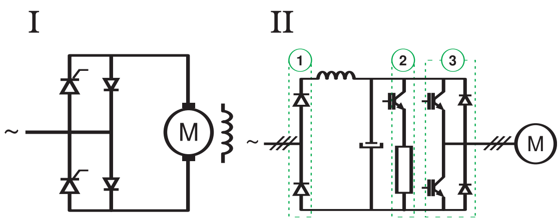
Depending on the electronic converter, speed controllers can either make a motor work in one rotation direction, "one-direction", or control both rotation directions, "two-direction".

Controllers can be "reversible" when they can work as a generator (braking mode).



Rotation direction	Mode	Torque T	Speed S	Product TS	Quadrant
1 (clockwise)	Driver	yes	yes	yes	1
	Generator		yes		2
2 (anticlockwise)	Driver			yes	3
	Generator	yes			4

↑ *Fig. 11* *The four situations possible for a machine in a torque-speed diagram*



↑ *Fig. 12* *Working diagrams (I) DC converter with mixed bridge; (II) indirect converter with (1) input diode bridge, (2) braking device (resistor and chopper), (3) frequency converter*

Reversibility is achieved either by sending the power a running motor back to the mains (reversible input bridge) or by dissipating this power in a resistor with a braking chopper or, for low power, in machine losses. The *figure 12* illustrates the four possible situations in the torque-speed diagram of a machine as summed up in the table below.

• **One-direction controller**

This type of controller, is made for:

- direct-current motors, with a DC converter or controlled rectifier (AC => DC) with a diode and thyristor mixed bridge *(⇨ Fig.12 I)*,
- an AC motor with an indirect converter (with intermediate transformation in direct current) with a diode bridge at the input followed by a inverter which makes the machine work with the 1 quadrant *(⇨ Fig. 12 II)*. In certain cases this assembly can be used as two-direction controller (quadrants 1 and 3).

An indirect converter with a braking chopper and a correctly sized resistor is perfectly suitable for momentary braking (in slowing down or on a hoisting appliance when the motor must develop a braking torque when going down to hold back the load).

For prolonged use with a driving load, a reversible converter is essential as the charge is then negative, e.g., on a motor used as a brake on a test bench.

• **Two-direction controller**

This type of controller can be a reversible or non-reversible converter. If it is reversible, the machine runs in all four quadrants *(⇨ Fig. 11)* and can be used for permanent braking.

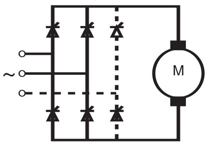
If it is not reversible, the machine only runs in quadrants 1 and 3.

The design and the size of the controller or the starter are directly affected by the nature of the driving load, especially with regard to its capacity to supply an adequate torque enabling the driven motor to gather speed.

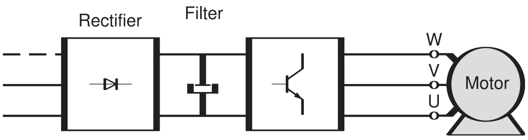
The families of machines and their typical curves are dealt with in section 4: Technology of loads and actuators.

◻ Main types of controllers

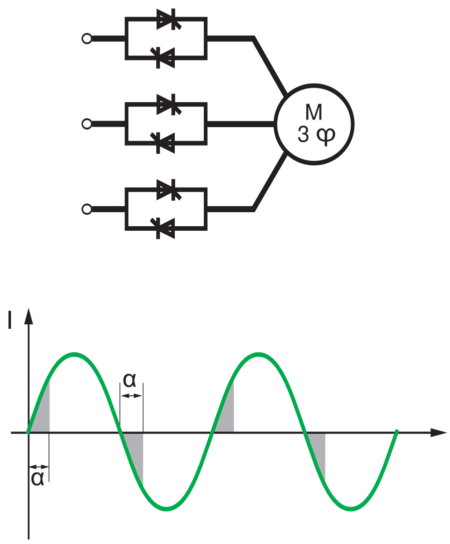
As previously mentioned, in this section, only the most common controllers and the most common technologies are described.



↑ *Fig. 13* *DC bridge for a DC motor*



↑ *Fig. 14* *Working diagram of a AC drive*



↑ *Fig. 15* *Asynchronous motor starter and supply current waveform*

• Controlled rectifiers for direct-current motors

This supplies direct current from an AC single-phase or 3-phase power supply.

The semiconductors are arranged in a single-phase or 3-phase Graëtz bridge *(⇨ Fig. 13)*. The bridge can be a combination of diodes/thyristors or thyristors only.

The latter solution is the most frequent as it allows for a better form factor in the current drawn from the mains.

A DC motor is most often of the wounded field type, except in low power where permanent magnet motors are quite common.

This type of speed controller is well adapted to any purpose. The only limits are imposed by the DC motor, particularly the difficulty of reaching high speeds and the maintenance requirement (brush replacement).

DC motors and their controllers were the first industrial solutions. In the last ten years, their use has steadily diminished as people are turning more to AC drives. Furthermore, the asynchronous motor is more robust and more cost-effective than a DC motor. Unlike DC motors, standardised in the IP55 envelope, it is hardly affected by the environment (rain, dust, dangerous atmospheres, etc.).

• AC drive for asynchronous motors

This supplies AC 3-phase voltage with an RMS value and variable frequency *(⇨ Fig. 14)*. The mains power supply can be single-phase for low power (a few kW) and 3-phase for higher power.

Some low power controllers take single- or 3-phase voltage indifferently. The output is always 3-phase as asynchronous single-phase motors are poorly adapted to frequency changer supply. AC drives power standard cage motors, with all the advantages linked to them: standardization, low cost, ruggedness, sealing and maintenance free. As these motors are self-ventilated, their only limit is being used for a long period of time at a low speed because of a decrease in ventilation. If such an operation is required, a special motor equipped with an independent blower should be provided.

• Voltage controller to start asynchronous motors

This type of controller (commonly known as a soft starter) is basically exclusively used to start motors. In the past, combined with special motors (resistant squirrel cage motors), it was used to control the speed of these motors.

This device provides an alternating current from an AC power supply at a frequency equal to the mains frequency, and controls the RMS voltage by modifying the triggering of the power semiconductors. The most common arrangement has two thyristors mounted head to tail in each motor phase *(⇨ Fig. 15)*.

5.6 Structure and components of starters and electronic speed controllers

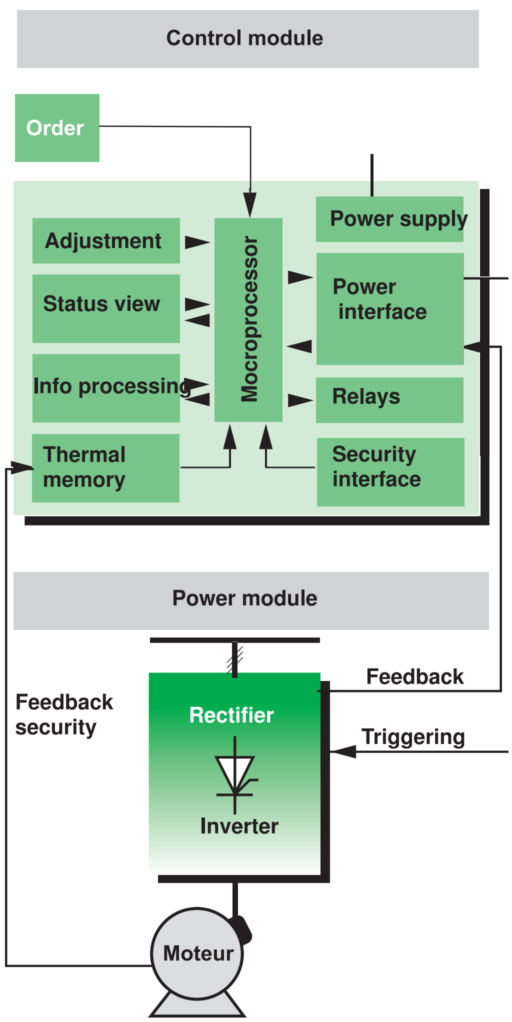


Fig. 16 Overall structure of an electronic speed controller

■ Structure

Starters and electronic speed controllers consist of two modules, generally grouped together in the same envelope (⇨ Fig. 16):
- a control module to manage the machine's operations,
- a power module to supply the motor with electrical energy.

□ Control module

On modern starters and controllers, all the operations are controlled by a microprocessor which takes into account the settings, the commands transmitted by an operator or a processing unit and the feedback's for the speed, current, etc.

The calculation capacity of the microprocessors and dedicated circuits (ASIC) have led to the development of powerful command algorithms and, in particular, recognition of the parameters of the driven machine. With this information, the microprocessor manages the acceleration and deceleration ramps, controls the speed and limits the current and generates the command of the power components. Protection and security are dealt with by a special circuit (ASIC) or built into the power modules (IPM).

The settings (speed limits, ramps, current limitation, etc.) are done either by a built-in keyboard or with PLCs via a field bus or with a PC to load the standard settings. Furthermore, commands (start, stop, brake, etc.) can be given through MMI dialogue, by the programmable PLCs or via a PC. The operational parameters and the alarm and defect information can be visualised by lights, by light emitting diodes, by a segment or liquid crystal display or sent to supervisors via field buses.

Relays, which are often programmable, give information about:
- defects (mains power, thermal, product, sequence, overload, etc.),
- supervision (speed threshold, pre-alarm, end of starting).

The voltage required for all the measurement and control circuits is supplied by a power supply built into the controller and separated electrically from the mains network.

□ The power module

The power module mainly consists of:
- power components (diodes, thyristors, IGBT, etc.),
- voltage and/or current measurement interfaces,
- often a ventilation system.

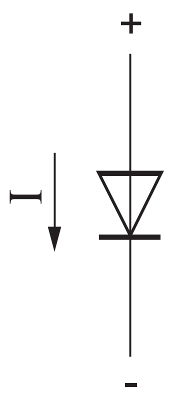
- Power Components

The power components are semiconductors and so comparable to static switches which can either be in a closed or off-state.

These components, arranged in a power module, form a converter which powers an electric motor with a variable voltage and/or frequency from a fixed voltage and frequency network.

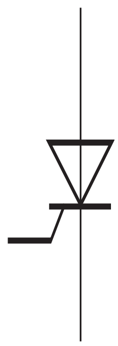
The power components are the keystones of speed controllers and the progress made in recent years has led to the development of electronic speed controllers.

Semiconductor materials, such as silicon, have a resistance capacity which may change between that of a conductor and that of an insulant.



Diode

↑ *Fig. 17* *Power components*



Thyristor

↑ *Fig. 17b*

Their atoms have 4 peripheral electrons. Each atom combines with 4 neighbouring atoms to form a stable structure of 8 electrons.

A P type semiconductor is obtained by incorporating into the silicon a small proportion of a body whose atoms have 3 peripheral electrons. Therefore, one electron is missing to form a structure with 8 electrons, which develops into an excess of positive loads.

An N type semiconductor is obtained by incorporating a body whose atoms have 5 peripheral electrons. There is therefore an excess of electrons, i.e. an excess of negative loads.

Diode *(⇨ Fig.17a)*
A diode is a non-controlled semiconductor with two regions – P (anode) and N (cathode) – and which only lets the current pass in one direction, from anode to cathode.

Current flows when the anode has a more positive voltage than that of the cathode, and therefore acts like a closed switch.

It blocks the current and acts like an open switch if the anode voltage becomes less positive than that of the cathode.

The diode had the main following characteristics:

- **in a closed state:**
  - a voltage drop composed of a threshold voltage and an internal resistance,
  - a maximum admissible permanent current (up to about 5000A RMS for the most powerful components).
- **in an off-state:**
  - a maximum admissible reverse voltage which may exceed 5000 V.

Thyristor *(⇨ Fig.17b)*
This is a controlled semiconductor made up of four alternating layers: P-N-P-N. It acts like a diode by transmission of an electric pulse on an electrode control called “gate”. This closing (or ignition) is only possible if the anode has a more positive voltage than the cathode. The thyristor locks itself when the current crossing it cancels itself out.

The ignition energy to supply on the “gate” is not linked to the current to switch over. And it is not necessary to maintain a current in the gate during thyristor conduction.

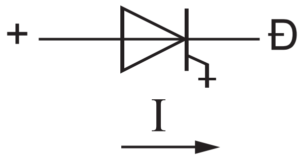
The thyristor has the main following characteristics:

- **in a closed state:**
  - a votage drop composed of a threshold voltage and an internal resistance,
  - a maximum admissible permanent current (up to about 5000A RMS for the most powerful components).
- **in an off-state:**
  - an invert and direct maximum admissible voltage, (able to exceed 5000 V),
  - in general the direct and invert voltages are identical,
  - an recovery time which is the minimum time a positive anode cathode voltage cannot be applied to the component, otherwise it will spontaneously restart itself in the close state,
  - a gate current to ignite the component.

There are some thyristors which are destined to operate at mains frequency, others called “fast”, able to operate with a few kilohertz, and with an auxiliary extinction circuit.

Fast thyristors sometimes have dissymmetrical direct and invert locking voltage.

In the usual arrangements, they are often linked to a connected antiparallel diode and the manufacturers of semiconductors use this feature to increase the direct voltage that the component can support in an off-state. Fast thyristor are now completely superseded by the GTO, power transistors and especially by the IBGT (Insulated Gate Bipolar Transistor).



GTO

↑ Fig. 17c

The GTO thyristor (Gate Turn Off thyristor) *(⇨ Fig.17c)*
This is a variation of the rapid thyristor which is specific in that it can be locked by the gate. A positive current sent into the "gate" causes conduction of the semiconductor as long as the anode is at a more positive voltage than the cathode. To maintain the GTO conductor and the limit the drop of potential, the trigger current must be maintained.
This current is generally very much less than is required to initialise conduction. Locking is done by inverting the polarity of the gate current.

The GTO is used on very powerful converters as it is able to handle high voltages and currents (up to 5000V and 5000A). However, progress in the IGBT has caused their market share to drop.

The GTO thyristor has the main following characteristics:

- **in a closed state:**
  - a voltage drop composed of a threshold voltage and an internal resistance,
  - a holding current designed to reduce the direct drop of potential,
  - a maximum admissible permanent current,
  - a blocking current to interrupt the main current in the device.
- **in an off-state:**
  - invert and direct maximum admissible voltages, often dissymmetrical, like with fast thyristors and for the same reasons,
  - an recovery time which is the minimum time during which the extinction current must be maintained, otherwise it will spontaneously restart itself,
  - a gate current to switch on the component.

GTOs can operate with low kilohertz frequencies.

Transistor *(⇨ Fig.17d)*
This is a controlled bipolar semiconductor made up of three alternating regions P-N-P or N-P-N. The current can only flow in one direction: from the emmiter to the collector in P-N-P technology and from the collector to the emmiter in N-P-N technology.

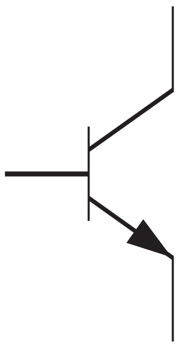
Power transistors able to operate with industrial voltages are the N-P-N type, often "Darlington" assembled. The transistor can operate like an amplifier.

The value of the current which crosses it therefore depends on the control current circulating in the base. But it can also operate like a static switch, i.e. open in the absence of a base current and closed when saturated. It is the latter operating mode which is used in controller power circuits.

Bipolar transistors cover voltages up to 1200V and support currents up to 800A.

This component is now supplanted by IGBT converters.

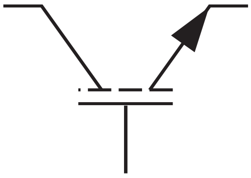
In the operations which interest us, the bipolar transistor has the main following characteristics:


Transistor
NPN

↑ Fig. 17d

- **in a closed state:**
  - a voltage drop composed of a threshold voltage and an internal resistance,
  - a maximum admissible permanent current,
  - a current gain (to maintain the transistor saturated, the current injected in the base must be higher than the current in the component, divided by the gain).
- **in an off-state:**
  - a maximum admissible direct voltage.

The power transistors used in speed controllers can operate on low kilohertz frequencies.



↑ Fig. 17e

IGBT *(⇨ Fig.17e)*
This is a power transistor controlled by a voltage applied to an electrode called grid or “gate” and isolated from the power circuit, whence the name “Insulated Gate Bipolar Transistor”.

This component needs very little energy to make strong currents circulate. Today it is the component used in discrete switch in most AC drives up to high powers (about a MW). Its voltage current characteristics are similar to those of bipolar transistors, but its performances in energy control and switching frequency are decidedly greater than any other semiconductor.

IGBT characteristics progress very rapidly and high voltage (> 3 kV) and large current (several hundred amperes) components are currently available.

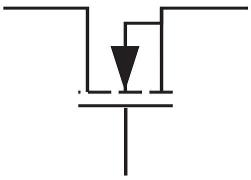
The IGBT transistor has the main following characteristics:

- **voltage control:**
  - allowing for conduction and locking of the component.
- **in a closed state:**
  - a voltage drop composed of a threshold voltage and an internal resistance,
  - a maximum admissible permanent current.
- **in an off-state:**
  - a maximum admissible direct voltage.

IGBT transistors used in speed controllers can operate on frequencies of several dozen kilohertz.

MOS transistor *(⇨ Fig.17f)*
This component operates in a completely different way from the previous one, altering the electric field in the semiconductor by polarising an isolated grid, hence the name “Metal Oxide Semiconductor”.

Its use in speed controllers is limited to low voltage (speed controllers powered by battery) or low power, as the silicon surface required for a high locking voltage with a small voltage drop in a closed state is economically unfeasible.



↑ Fig. 17f

The MOS transistor has the main following characteristics:

- **a voltage control :**
  - allowing for the conduction and the locking of the component.
- **in a closed state:**
  - internal resistance,
  - a maximum admissible permanent current.
- **in an off-state:**
  - a maximum admissible direct voltage (able to go over 1000 V).

The MOS transistors used in speed controllers can operate at frequencies of several hundred kilohertz. They are practically universal in switching power supply stages in the form of discrete components or as built-in circuits with the power (MOS) and the control and adjustment circuits.

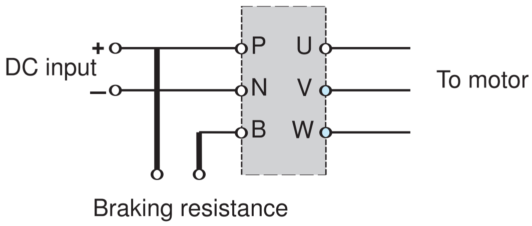


Fig. 18 *Intelligent Power Module (IPM)*

L'IPM (Intelligent Power Module)

It is not strictly speaking a semiconductor but an assembly of IGBT transistors. This module *(⇨ Fig.18)* groups an inverter bridge with IGBT and low-level electronics to control the semiconductors.

In the same compact package are:

- 7 IGBT components, six for the converter bridge and one for braking resistor,
- the IGBT control circuits,
- 7 power diodes combined with IGBT to allow for circulating current,
- protections against short circuits, overload and temperature overshooting,
- electrical insulation of the module.

The input diode rectifier bridge is mostly built into this module.

The assembly allows for a better control of the IGBT wiring and control constraints.

5.7 Controller - regulator for DC motors

General principle

The forerunner of speed controllers for DC motors is the Ward Leonard generator set *(⇨ see section on motors)*.

This set, consisting of a driving motor, generally asynchronous, and a variable excitation DC generator, powers one or more DC motors. Excitation was adjusted by an electromechanical device (Amplidyne, Rototrol, Regulex) or by a static system (magnetic amplifier or electronic regulator).

Today this device has been completely abandoned and speed controllers with semiconductors have taken over, carrying out the same operations but with higher performance and no maintenance.

Electronic speed controllers are supplied from a constant voltage from an AC network and feed the motor with DC variable voltage.

A diode or thyristor bridge, usually single-phase, powers the excitation circuit.

The power circuit is a rectifier. Since the voltage has to be variable, the rectifier must be controllable, i.e. have power components whose conduction can be controlled (thyristors). The variation of the output voltage is obtained by limiting more or less the conduction time of the components.

The more the ignition of the thyristor is delayed compared to zero of the half cycle, the more the average value of the voltage is reduced, reducing the motor speed (remember that extinction of the thyristor steps in automatically when the current passes by zero).

For low power controllers, or controllers supplied by a storage battery, the power circuit, sometimes made up of power transistors (chopper), varies the continuous output voltage by adjusting the conduction time. This operation mode is called PWM (Pulse Width Modulation).

Regulation

Regulation consists of exactly maintaining the speed at the imposed speed despite interference (variation of load torque, power voltage, temperature). However, during acceleration or in case of overload, the magnitude of the current must not reach a dangerous value for the motor or the power devices.

A control loop built in the controller limits the current at an acceptable value. This limit can be accessed for adjustment according to the characteristics of the motor. The speed reference is set by an analogue or digital signal sent by a field bus or any other device which gives an information corresponding to the requisite speed.

The reference can be set or vary during the operating cycle of the driven machine.

Adjustable acceleration and deceleration ramps gradually apply the voltage reference corresponding to the requisite speed.

The setting of the ramps defines the time for acceleration and deceleration.

In a closed loop, the actual speed is permanently measured by a tachymetric dynamo or a pulse generator and compared to the reference. If a differential is noticed, the electronic control corrects the speed. The speed ranges from several revolutions per minute to the maximum speed. In this variation range, it is easy to achieve precision better than 1% in analogue regulation and better than 1/1000 in digital regulation, by combining all the possible variations (empty/load, voltage variation, temperature, etc). This regulation can also be done by measuring the motor voltage taking into account the current crossing it.

In this case performance is clearly lower with regard to speed range and precision (a few % between run-free and load operation).

Inversion of direction of rotation and regenerative braking

To invert the direction of rotation, the armature voltage must be inverted. This can be done with contactors (a solution now dropped) or statically by inverting the output polarity of the speed controllers or the polarity of the excitation current.

The last solution is not very common due to the time-constant of the inductor.

When controlled braking is required or the nature of the load imposes it (driving torque), the energy must be sent back to the mains. During braking, the controller acts like an inverter, so in other words the power which crosses it is negative.

Controllers able to carry out these two operations (inversion and regenerative braking) are equipped with two bridges connected in an antiparallel arrangement (⇨ *Fig.19*).

Each one of these bridges can invert the voltage and the current as well as the sign of energy circulating between the mains and the load.

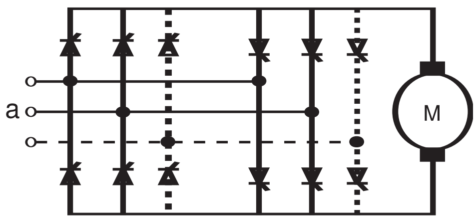


Fig. 19 *Diagram of a controller with inversion and regenerative braking for a DC motor*

Possible operation modes

Operation called "constant torque"

At constant excitation, the motor's speed depends on the voltage applied to its armature. Speed can be varied from standstill to the rated voltage of the motor chosen according to the AC voltage supply.

The motor torque is proportional to the armature current, and the rated torque of the machine can be obtained continuously at all speeds.

Operation called "constant power"

When a machine is powered with rated voltage, it is still possible to increase its speed by reducing the excitation current. In this case the speed controller must have a controlled rectifier bridge powering the excitation circuit.
The armature voltage therefore remains fixed and equal to the rated voltage and the excitation current is adjusted to obtain the requisite speed.

Power is expressed as:
P = E . I
with
E as its armature voltage,
and

I the armature current.

The power, for a given armature current, is therefore constant in all speed ranges, but the maximum speed is limited by two parameters:
- the mechanical limit linked to the armature and in particular the maximum centrifugal force a collector can support,
- the switching possibilities of the machine are generally more restrictive.

The motor manufacturer must therefore be consulted to make a good choice of motor, particularly with regard to speed range at a constant horsepower.

5.8 AC drives for asynchronous motors

General principle

An AC drive, supplied at a fixed voltage and frequency by the mains, converts this voltage to a variable frequency alternative voltage, depending on the speed requirements. To power an asynchronous constant torque motor suitably, whatever the speed, the flux inside the motor must be constant. For this the voltage and frequency must evolve simultaneously in the same ratio.

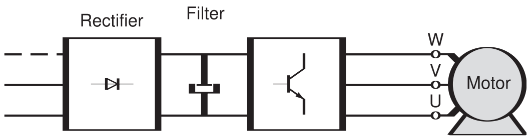


Fig. 20 Working diagram of a AC drive

Structure

Usually the power circuit consists of a rectifier converting the power supply to a DC voltage feeding an inverter which produces an alternative voltage at a variable frequency (⇨ Fig. 20). To comply with the EU (European Union, CE label directive) and relevant standards, a "network" filter is placed upstream of the rectifier bridge.

The rectifier

In general the rectifier is equipped with a diode rectifier bridge and a filter circuit composed of one or several capacitors depending on the power. A limitation circuit controls the value of the inrush current when the unit is connected to mains. Some converters use a thyristor bridge to limit the inrush current of these filter capacitors which are charged at a value virtually equal to the peak value of the sine wave network (about 560V in 400V 3-phase).

Note: despite the presence of discharge circuits, these capacitors are likely to continue having a dangerous voltage even if there is no mains voltage. Any intervention within such products should only therefore be made by trained people who know exactly what essential precautions to take (additional discharge circuit or knowledge of waiting time).

The inverter

The inverter bridge, connected to the capacitors, uses six power semiconductors (usually IGBTs) and associated diodes.

This type of controller is designed for powering asynchronous squirrel cage motors. Therefore Altivar, a Telemecanique brand, creates tiny electronic networks which have variable voltage and frequency capable of powering a single motor or several motors in parallel.

It has:
- a rectifier with a filter capacitor,
- an inverter with 6 IGBTs and 6 diodes,
- a chopper connected to a braking resistance (in general on the outside of the product),
- IGBT transistor control circuits,
- a control unit around a microprocessor, to ensures control of the inverter,
- internal sensors to measure the motor current at the capacitor terminals and in certain cases the voltages at the rectifier bridge and the motor terminals as well as the values required to control and protect the entire motor controller,
- a power supply for the low-level electronic circuits.

This power supply is made by a switching circuit connected to the filter capacitor terminals to profit from the power reserve. This arrangement allows Altivar to be unaffected by mains fluctuations and short-term voltage disappearance, which gives it remarkable performance in power supply conditions with high interference.

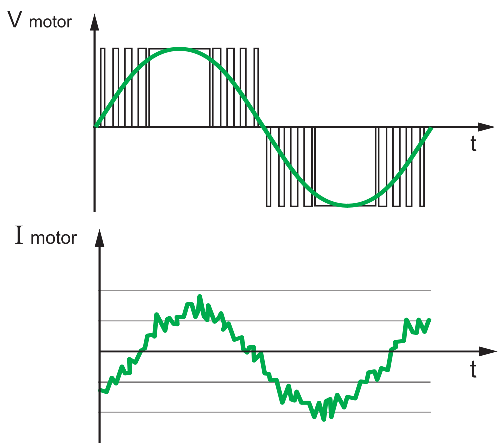


Fig. 21 Pulse width modulation

Speed variation

Generation of the output voltage is obtained by switching the rectified voltage with pulses where the time length, and therefore width, is modulated so that the resulting alternating current is as sine waved as possible (⇨ Fig.21).

This engineering, known under the name of PWM (Pulse Width Modulation) conditions regular rotation at low speed and limits overheating.
The modulation frequency retained is a compromise as it must be high enough to reduce the current ripple and the acoustic noise in the motor without at all increasing losses in the inverter bridge and in the semiconductors.

Two ramps set the acceleration and deceleration.

Built-in protections

The controller protects itself and the motor against excessive overheating by locking itself until the right temperature is restored.

The same thing happens for any sort of interference or fault which could alter the overall functioning, such as over- or under-voltage, or the disappearance of an input or output phase. In certain ratings, the rectifier, inverter, chopper, control and protections against the short circuits are built into a single IPM model – Intelligent Power Module –.

AC drive operation

Former AC drives made use a voltage frequency law, named constant U/F ratio or scalar operation. At that time it was the only economical choice. Introduction of microcontrollers opens the door to flux vector control and outstanding performances. Today, leading manufacturers offer in the same pacakge enhanced scalar operation allong with sensor and sensorless vector control operation.

U/f operation

In this type of operation, the speed reference imposes a frequency on the inverter output and consequently, on the motor, which determines the rotation speed. The power voltage is in direct relationship to the frequency *(⇨Fig.13)*. This operation is often called a U/f operation or scalar operation.

If no compensation is made, the real speed varies with the load, which limits the operating range. A crude compensation can be made taking the internal impedance of the motor into consideration to limit the speed variation.

Controller with sensorless flux vector control

Performances are greatly enhanced by an electric control using a flux vector control – CVF - *(⇨ Fig.22)*.

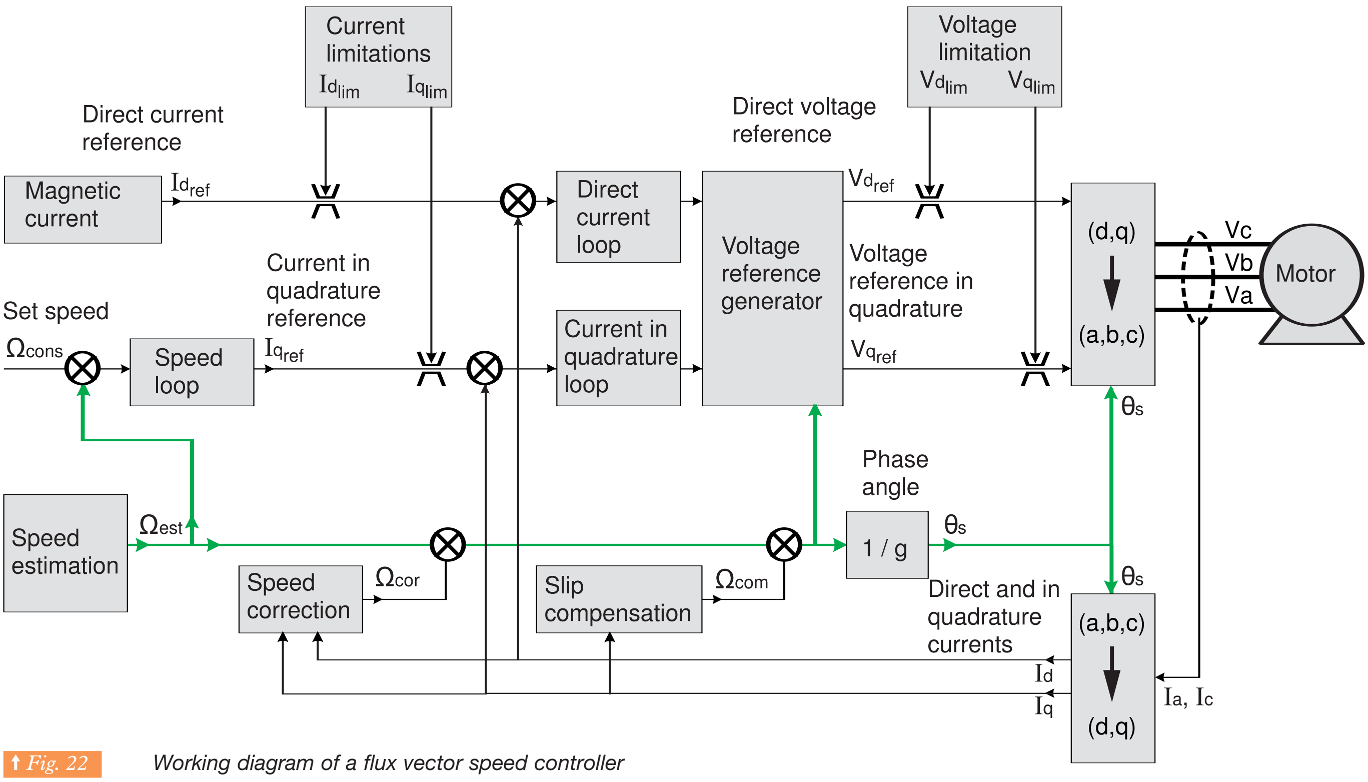


Fig. 22 *Working diagram of a flux vector speed controller*

In most modern controllers, this device is factory built. Knowledge or estimation of the machine parameters permits one to dispense with a speed sensor for most uses. In this case a standard motor can be used with the usual limitation of prolonged operations at low speed.
The controller processes the information from the values measured at the machine terminals (voltage and current).
This control mode ensures correct performance without increasing the cost.
To achieve such a result, certain machine parameters must be known.
Upon commissioning, the machine's debugger must in particular introduce the characteristics stamped on the motor in the settings for the controller such as:

- rated motor voltage,
- rated stator frequency,
- rated stator current,
- rated speed,
- motor power factor.

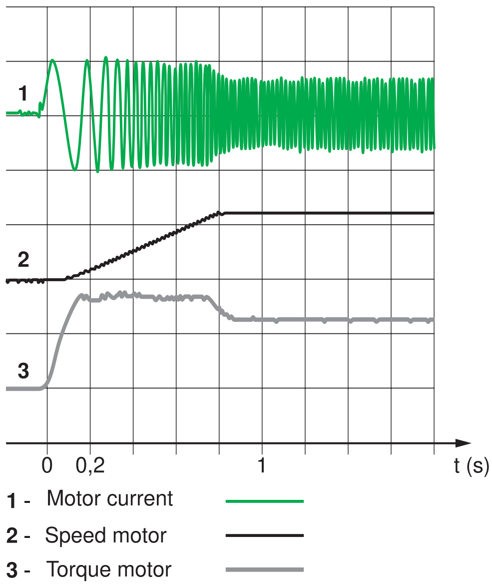
With these values, the controller calculates the rotor characteristics: Lm, Tr. (Lm: magnetising inductance, Tr: torque moment).

On powering up, a controller with a flux vector control and no sensor (type ATV58F – Telemecanique) self-tunes to enable it to determine the stator parameters Rs, Lf. The length of time varies according to the power of the motor (1 to 10 s).

These values are memorised and enable the product to process the control profiles.

The oscillogram *(⇨ Fig.23)* shows a motor gathering speed, loaded with a rated torque and powered by a controller without a sensor.

We can note the speed at which the rated load is reached (less than 0.2 s) and the linearity of acceleration. The rated speed is obtained in 0.8 seconds.

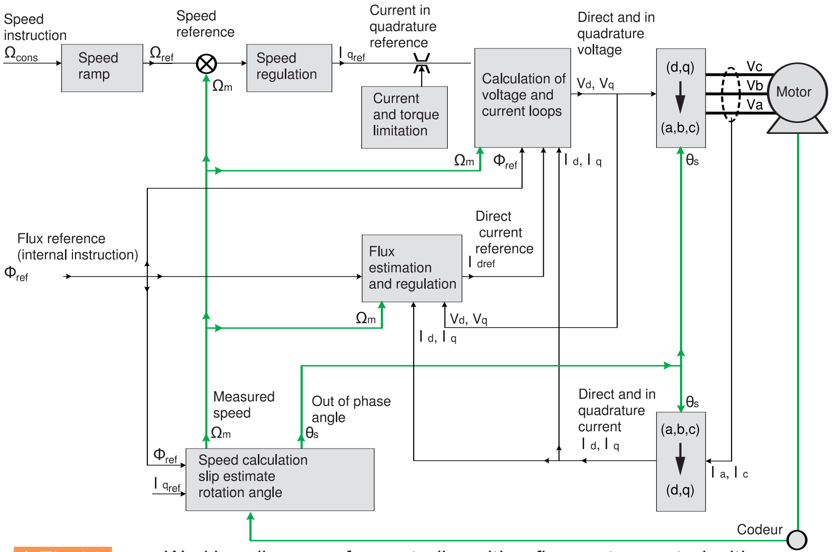


↑ Fig. 23 *Characteristics of a motor fed by a sensorless flux vector controller (e.g. ATV58F – Telemecanique)*

Controller with closed loop flux vector control and sensor

Another option is the closed loop flux vector control with a sensor. This solution uses Park transformation and independently controls the current (Id) ensuring the flux in the machine and the current (Iq) ensuring the torque (equal to the product Id. Iq). The control of the motor is similar to that of a DC motor.

This solution (⇨ *Fig.24*) is an answer to demanding uses: high available torque during transients, speed precision, and rated torque at standstill.



↑ Fig. 24 *Working diagram of a controller with a flux vector control with a sensor*

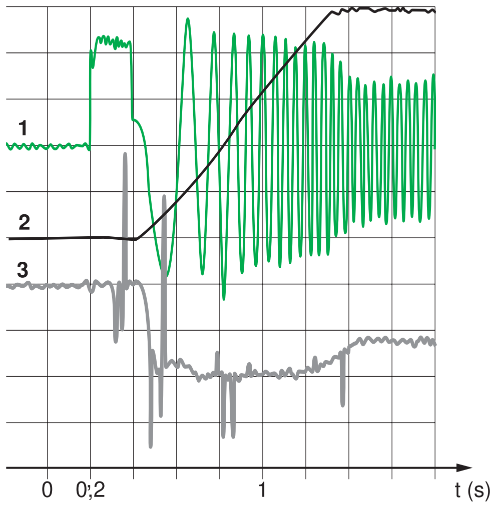
The maximum transient torque is equal to 2 or 3 times the rated torque depending on the motor type.

Moreover, the maximum speed often reaches twice the rated speed, or more if the motor has enough power.

This type of control also allows for very high frequency bandwidths and performances comparable to or higher than the best DC controllers. This is why the motor is not of standard manufacturing owing to the presence of a sensor, or sometimes an external ventilation blower.

The oscillogram (⇨ *Fig.25*) shows the acceleration of a motor loaded with a rated torque and powered by a controller with a flux vector control with a sensor. The time scale is 0.1 seconds per division. Compared to the same product without a sensor, the performance increase is obvious. The rated torque is achieved in 80ms and the time for speed increase in the same load conditions is 0.5 seconds.

To conclude, the table (⇨ *Fig.26*) compares the respective performances of a controller in the three possible configurations.



1 - Motor current
2 - Speed motor
3 - Torque motor

↑ Fig. 25 *Oscillogram of the acceleration of a motor loaded with a rated torque and powered by a controller with a sensor flux vector control (e.g. ATV58F – Telemecanique)*

	Scalar control	With flux vector control without sensor	with sensor
Speed range	1 à 10	1 à 100	1 à 1000
Bandwidth	5 à 10 Hz	10 à 15 Hz	30 à 50 Hz
Speed precision	1\%	1\%	0.01\%

↑ Fig. 26 *Respective performances of a speed controller in three possible configurations (e.g. ATV58F – Telemecanique)*

Inversion of direction of rotation and braking

To invert the direction of rotation, an external order (either on an input made for this purpose, or on a signal circulating on a communication bus) causes the inversion of the operational order of the inverter components, and hence the rotation direction of the motor.

Several operations are possible.

- **Case 1: immediate inversion of the order the semiconductors operate in**

If the motor is still in rotation at the moment of the reversing, a large slip occurs and the current in the controller is therefore equal to the utmost maximum (internal limitation). The braking torque is weak due to the strong slip and the internal regulation brings the speed reference to a small value. When the motor reaches zero speed, the speed reverses itself, following the ramp. The energy not absorbed by the load torque and friction is dissipated in the rotor.

- **Case 2: inversion of the order the semiconductors operate in preceded by deceleration with or without a ramp**

If the load torque of the machine is such that natural deceleration is faster than the ramp set by the controller, it will continue to power the motor. The speed gradually decreases and reverses itself. But, if the load torque of the machine is such that natural deceleration is weaker than the ramp set by the controller, the motor acts like a hypersynchronous generator and restores the energy to the controller. But the presence of diode bridges prevents the energy being sent to the network, so the filter capacitors charge themselves, the voltage increases and the safety devices built in the controller locks itself. To avoid this, it is necessary to have a resistance connected to the capacitor terminals through a chopper so as to limit the voltage to a suitable value. The braking torque is only limited by the capacity of the speed controllers as the speed gradually decreases and reverses itself.

For this use, the controller manufacturer supplies braking resistors sized to match the power of the motor and the energy to be dissipated. Since, in most cases, the chopper is included in the controller, only the presence of a dynamic braking resistor distinguishes a controller that can ensure controlled braking. This braking method is therefore particularly economical.

It goes without saying that this operation mode can slow down a motor to a standstill without necessarily reversing the rotational direction.

- **Case 3: continuous operation in braking mode**

A typical instance of use is seen on the motor test bench. The energy produced cannot be dissipated in resistors, as the energy outcome would be unacceptable and heat dissipation would be a problem.

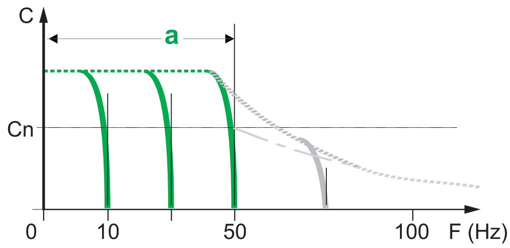
Most manufacturers offer combinations allowing the energy to be sent back to the network.

In general, the diode bridge is replaced by a controlled semiconductor bridge made up of IGBTs. Operation, by an appropriate MLI control, is most often done in a sine wave current.

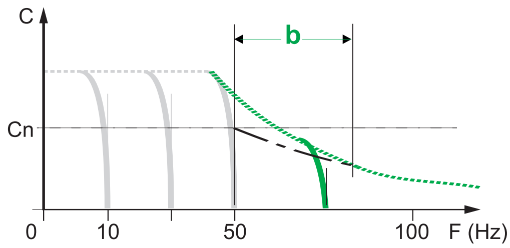
- **Deceleration braking by injection of direct current**

Cost-effective braking can easily be done by making the controller's output stage work as a chopper to inject direct current into the windings. The braking torque is not controlled. It is not very efficient, especially at high speeds and due to this, the deceleration ramp is not controlled.

Nevertheless, it is a practical solution to shorten the machine's natural stopping time. Since the energy is dissipated in the rotor, this operation mode can only be occasional.



↑ Fig. 27a Torque of an asynchronous motor powered by a frequency converter (a) – constant torque operation zone



↑ Fig. 27b Torque of an asynchronous motor powered by a frequency converter (b) – constant power operation zone

■ The possible operation modes

□ "Constant torque" operation

As long as the voltage delivered by the controller can evolve and if the flux in the machine is constant (the constant U/f ratio or better still with flux vector control), the driving torque will be roughly proportional to the current and the rated torque of the machine can be reached over the whole speed range *(⇨ Fig.27 part a)*.

However prolonged operation at the rated torque at low speed is only possible if the motor is externally fan cooled, and this requires a special motor. Modern controllers have protection circuits which build a thermal image of the motor based on the current, operational cycles and rotation speed to ensure its protection.

□ "Constant power" operation

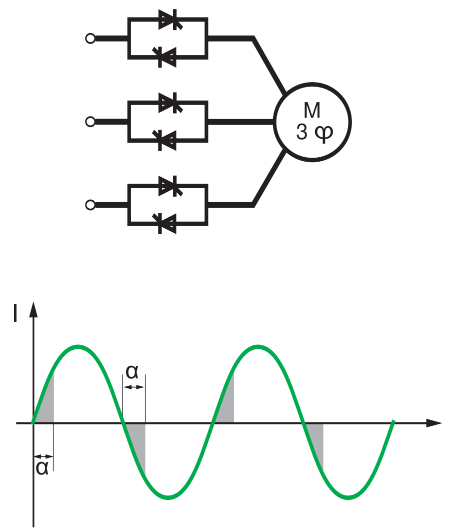
When a machine is powered at the rated voltage and frequency, the speed can still be increased by powering it at a higher frequency.
But as the output voltage of the converter cannot exceed that of the mains, the available torque decreases inversely in proportion to the speed *(⇨ Fig.27 part b)*.

Above its rated speed, the motor does not run at constant torque but at constant power (P = Cω), insofar as its natural characteristic allows.

The maximum speed is limited by two parameters:
- the mechanical limits of the rotor,
- the reserve of available torque.

For an asynchronous machine powered by constant voltage, as the maximum torque varies with the speed squared *(⇨ see the section on motors)*, "constant power" operation is only possible in a limited range determined by the torque characteristic of the machine itself.

5.9 Voltage controller for asynchronous motors

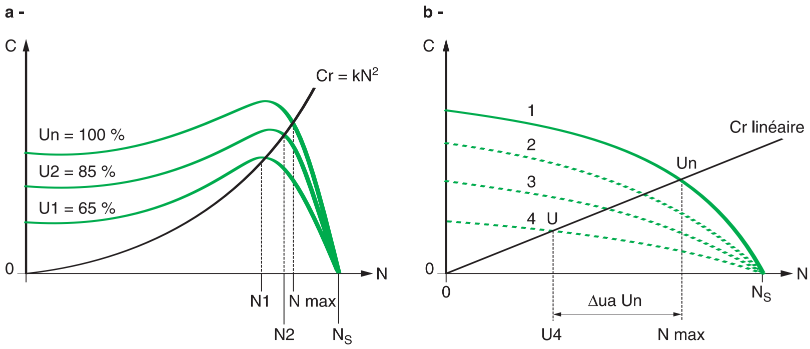


↑ *Fig. 28* *Asynchronous soft starter and current shape*

General presentation

This voltage variation device only works with resistant or slip-ring asynchronous squirrel cage motors *(⇨ Fig.28)*. And is named soft starter voltage controller.

The operation mode is illustrated *(⇨ Fig.29)*.



↑ *Fig. 29* *Available torque in an asynchronous motor powered by variable voltage and with a receiver with a parabolic resistant torque (fan)*
(a) – squirrel cage motor
(b) – resistant cage motor

These asynchronous motors are mostly 3-phase, and sometimes single-phase for low powers (up to about 3kW).

Most of the time used as for soft starting and decelerating, insofar as a high starting torque is not necessary, a voltage controller limits the inrush current, the subsequent drop of potential and mechanical shocks due to the sudden emergence of the torque.

Its most common uses include starting of centrifugal pumps, belt conveyors, escalators, rollover carwash systems, machines equipped with belts, etc. and in speed controllers on very low power motors or on universal motors as in portable electric tools. But for certain uses, such as speed controllers in small fans, voltage controllers have pretty well given way to AC drives, which are cheaper to operate.

In pumps, the deceleration function does away with water hammer.
But certain precautions must be taken when choosing this device for speed controllers. When a motor slips, the losses are proportional to the resistant torque and inversely proportional to the speed. Therefore, the operating principle of a controller involves reducing the motor torque by reducing the voltage in order to balance the resistant torque at the requisite speed.
The high resistance cage motor must therefore be able, at a low speed, to dissipate losses (small motors up to 3kW usually are). Beyond this, a fan cooled motor must be used. In slip ring motors, the resistors must be sized to match the operation cycles. The decision should be taken by a specialist who can select the right motor for the operation cycles.

There are three types of starter on the market: controlled single-phase with low power, controlled 2-phase (the third being a direct connection) and with all phases controlled. The first two systems should only be used for operation cycles that are low-strain due to a higher rate of harmonics.

General principle

The power circuit has 2 thyristors mounted head-to-tail per phase (⇨ *Fig. 28*).

Voltage variation is obtained by varying the conduction time of these thyristors. The longer turn on is delayed, the lower the value of the resulting voltage.

Thyristor control is managed by a microprocessor which also ensures the following functions:

- ramp control to increase and decrease adjustable voltage. The deceleration ramp can only be followed if the natural deceleration time of the driven system is longer,
- current limitation,
- starting torque adjustment,
- braking control by injection of direct current,
- protection of the controller against overloads,
- protection of the motor against overheating due to overloads or too frequent startings,
- detection of phase unbalance or absence of a phase and thyristor faults.

An instrument panel displaying operation parameters helps implementation, use and maintenance.

Some controllers, such as Altistart (Telemecanique) can control the starting and deceleration of:

- a single motor,
- several motors together, within the limits of its rating,
- several motors successively by commutation. This type of operation is common in pumping stations, as only one starter is used to bring to speed an additional pump according to the needs of the application network. In the steady state, each motor is powered directly by the mains supply through a contactor.

Only Altistart has a patent allowing for estimation of a driving torque for linear acceleration and deceleration and, if necessary, to limit the driving torque.

Reversal and braking

Reversal is achieved by inverting the starter input phase.

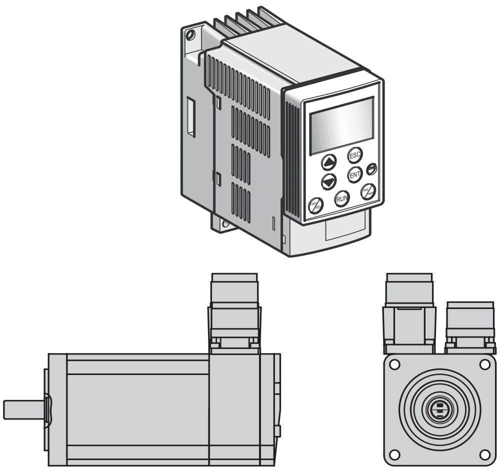
Counter-current braking results and all the energy is dissipated in the machine rotor. The operation is therefore naturally intermittent.

Deceleration braking by injection of direct current

Cost-effective braking can be easily achieved by making the output stage of the starter to run as a rectifier injecting direct current into the windings.

The braking torque is not controlled and braking is not very efficient, especially at high speeds and due to this, the deceleration ramp is not controlled. Nevertheless, it is a practical solution to shorten the machine's natural stopping time. Since the energy is dissipated in the rotor, this operation mode can only be occasional.

5.10 Synchronous motor-speed controller



↑ Fig. 30 *Photo of a synchronous motor-speed controller (Lexium controller + motor, Schneider Electric)*

General principle

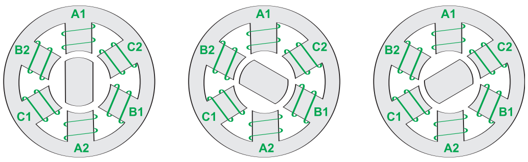
Synchronous motor-speed controllers (⇨ *Fig. 30*) are a combination of a frequency inverter and a permanent magnet synchronous motor equipped with a sensor. These motors are often called “brushless motors”.

Motor-speed controller units are designed for specific markets such as robots or machine tools where smaller motors, acceleration and bandwidth are prerequisites.

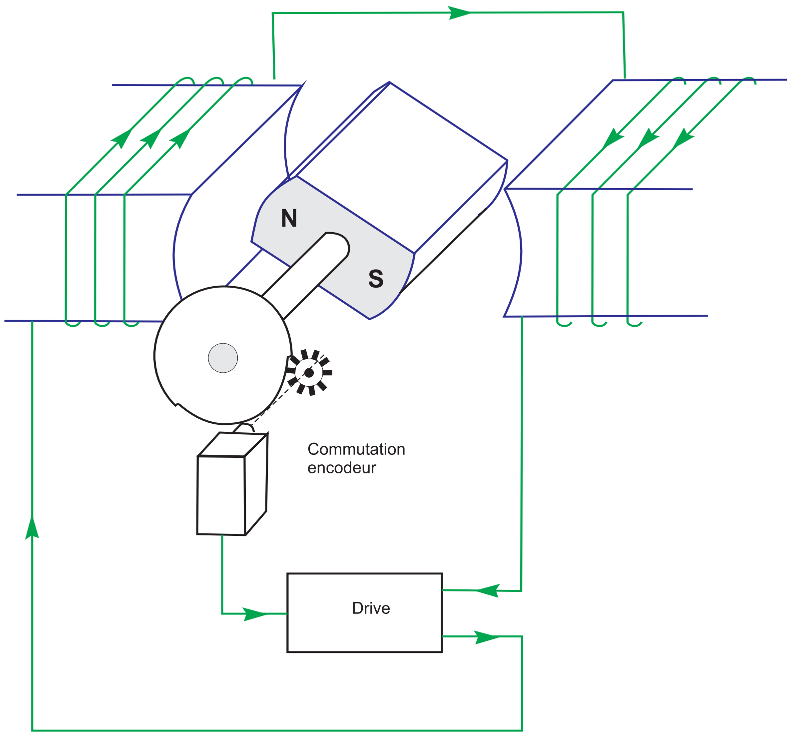
Motor

The motor’s rotor is fitted with permanent magnets in rare earth to produce a high field in a small space (see the section on motors for detailed explanations). The stator has 3-phase windings (⇨ *Fig.31*).

These motors support high overload currents for fast acceleration. They have a sensor to indicate the angular position of the motor poles to the controller to manage winding commutation (⇨ *Fig.32*).



↑ Fig. 31 *A simplified representation of a permanent magnet synchronous stator motor - “brushless motor”*



↑ Fig. 32 *Simplified representation of a permanent magnet synchronous stator motor - "brushless motor" – with a sensor showing the angular position of the rotor*

Controller

Basically, the controller is like an AC drive and works in a similar way.

It also has a rectifier and a pulse width modulation (PWM) GTO bridge to produce an output current in a sine waveform. Several controllers of this type are often powered by a single source of direct current. Thus on a machine tool, each controller operates one of the motors linked to the machine axes. This type of installation enables the entire set to use the energy resulting from the braking of one of the axes.

As in frequency changers, a braking resistor combined with a chopper is used to dissipate surplus braking energy.

Electronic interlocking functions and low mechanical and electrical constants enable acceleration and, more generally, high bandwidths together with high speed dynamics.

5.11 Stepper motor controllers

General principle

Stepper motor controllers combine electronic power switching, similar in design to a AC drive, with a stepper motor *(⇨ Fig. 33)*.

They work in an open loop (without a sensor) and are used for positioning.

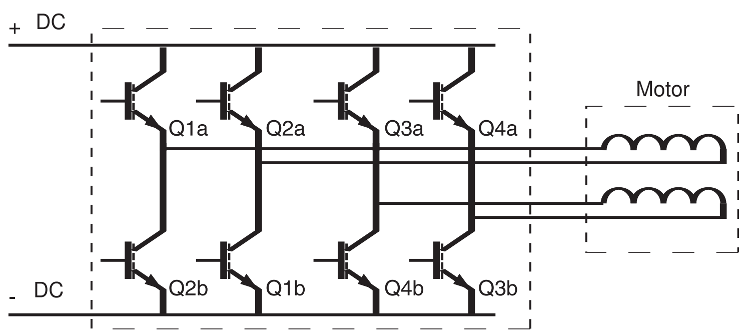
Motor

Stepper motors can be variable reluctance, magnetic or both *(⇨ see the section on motors for more detailed explanations)*.

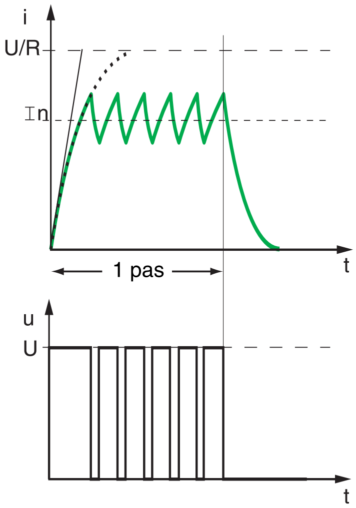
Controller

In structure, the controller is like a AC drive (rectifier, filter and bridge made up of power semiconductors).

However, its performance is fundamentally different in that its purpose is to inject constant current into the windings.



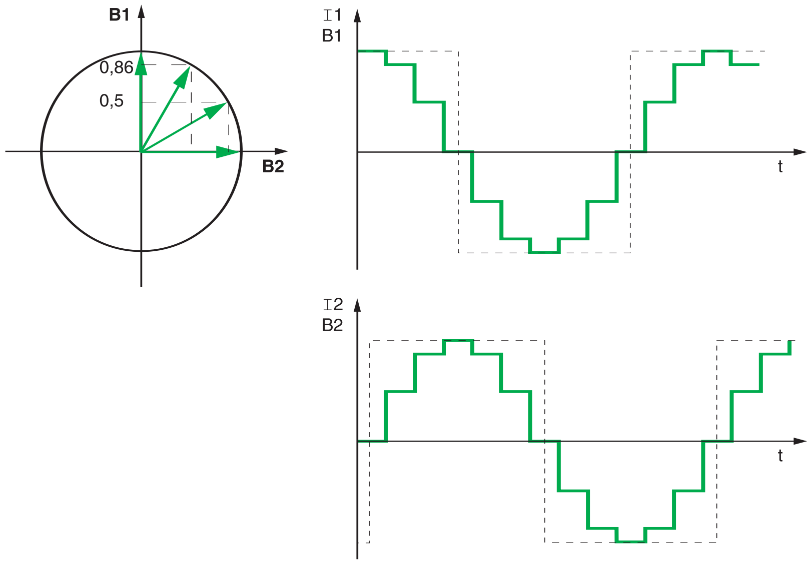
↑ *Fig. 33* *Working diagram of a bipolar stepper motor controller*



↑ *Fig. 34* *Appearance of current with a PWM command*

Sometimes it uses pulse width modulation (PWM) to enhance performance, especially in current access time (⇨ *Fig. 34)*, and widen the scope of its operating range.

Operation (⇨ *Fig.35)* in micro-steps (see the section on motors for more details) artificially multiplies the number of possible rotor positions by generating a succession of graduations in the coils in each sequence. The currents in the two coils behave like two alternating currents offset by 90°.



↑ *Fig. 35* *Diagram, current curves and graduation principle for micro-step control of a stepper motor-speed controller*

The resulting field is the vectorial composition of the fields created by the 2 coils. The rotor therefore takes on all possible intermediary positions.

The schema represents the supply current of coils B1 and B2. The rotor positions are represented by the vector.

5.12 Additional functions of speed controllers

Dialogue capacity

To ensure proper motor performance, controllers have a number of sensors to monitor voltage, currents and thermal status. This information, mandatory for the controllers, can also be useful for operation.

Recent controllers and starters include dialogue functions by taking advantage of the field bus. It is thus possible to generate information which is used by PLC and a supervisor to operate the machine. The control information comes to the PLC by the same channel in the same way.

The incoming information includes:
- speed references,
- start and stop signals,
- initial controller settings or changes to settings in operation,
- controller status (running, stopped, overload, faults),
- alarms,
- motor status (speed, torque, current, temperature).

Dialogue capacity is also used in a PC link to simplify the start up settings (downloading) or backup the initial settings.

Built-in functions

To cover a good number of uses efficiently, the controllers have many adjustments and settings such as:

- acceleration and deceleration ramp times,
- ramp shapes (linear, S- or U-shaped),
- ramp switching for two acceleration or deceleration ramps for, e.g. coasting speed,
- decrease of maximum torque controlled by a discrete input or instruction,
- jog operation,
- management of brake control for hoisting,
- choice of preselected speeds,
- summing inputs to total speed references,
- switching of references at the controller input,
- PI regulator (e.g. speed or flow rate),
- automatic stop following a loss of power supply allowing the motor to brake,
- automatic catch on-the-fly restart function with search for motor speed,
- thermal protection of the motor based on an image generated in the controller,
- connection of PTC sensors built into the motor,
- machine resonance frequency skipping (the critical speed is inhibited to prevent permanent operation at this frequency),
- timed locking at low speed in pumping systems where the fluid helps to lubricate the pump and prevent it seizing up.

On advanced controllers, these functions are already standard features as in Altivar (ATV71) Telemecanique.

Optional cards

For more complex applications, manufacturers offer optional cards either for specific functions, such as a flux vector control with sensor, or for a specific industry.

These cards include:

- “pump switching” cards for a cost-effective pumping station with just one controller successively powering several motors,
- “multi-motor” cards,
- “multi-parameter” cards, to toggle the preset parameters in the controller automatically,
- custom cards developed at the request of an individual.

Some manufacturers also offer PLC cards built into in the controller for simple applications. The operator can use programming, input and output instructions for small automated systems where a full PLC would be too expensive.

5.13 Speed controllers and energy assessment

Outphasing factor

Reminder

The outphasing factor, or φ cosine is the cosine of the current phase angle compared to the voltage. The outphasing factor is only significant for voltages and sinusoidal currents of the same frequency. If there are harmonic currents at the source, which is the case for most speed controllers, the power factor will, by definition, be the outphasing of the fundament current (or first harmonic) compared to the fundament supply voltage.

Case 1: the circuit entry consists of semiconductors controlled by thyristors: e.g. a direct-current motor controller.

The outphasing factor is obviously equal to the cosine of the triggering delay angle. In other words, if the output voltage is low (low speed), the φ cosine is low. If the output voltage is high (high speed) the φ cosine is close to one.

In a reversible speed controller, the φ cosine becomes negative if the controller restores energy to the mains.

Case 2: diode bridge consisting of diodes: e.g. a frequency changer for asynchronous motors.

The fundament current is almost in phase with the supply voltage and the φ cosine is close to 1.

Case 3: the circuit entry consists of semiconductors controlled by IGBTs

This arrangement is used to sample the sinusoidal current. With the right PWM control, the φ cosine is equal or close to 1.

A frequency changer on an asynchronous motor has a better outphasing factor than the motor itself. The diode bridge usually fitted to this type of converter has an outphasing factor close to 1. It is the filter capacitors incorporated into the controller that act as a "reservoir" for reactive power.

Power factor

Reminder

The power factor is the ratio of the apparent power **S** and the active power **P**.

$$F_p = P/S$$

The active power **P** is the product of the fundament voltage multiplied by the fundament current and the φ cosine.

$$P = U \times I \times \varphi \text{ cosine}$$

The apparent power **S** is equal to the product of the RMS value of the voltage multiplied by the RMS value of the current. If the voltage and the current are distorted, the quadratic sum of the RMS value of each item must be calculated.

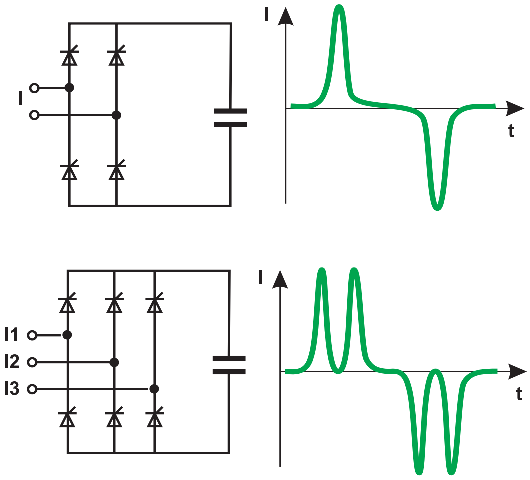
If mains impedance is low (which is generally the case), the voltage supply will be close to the sine wave, but the current absorbed by the semiconductors is rich in harmonics, and all the richer the lower mains impedance is.

The RMS value of the current is shown in the following way:

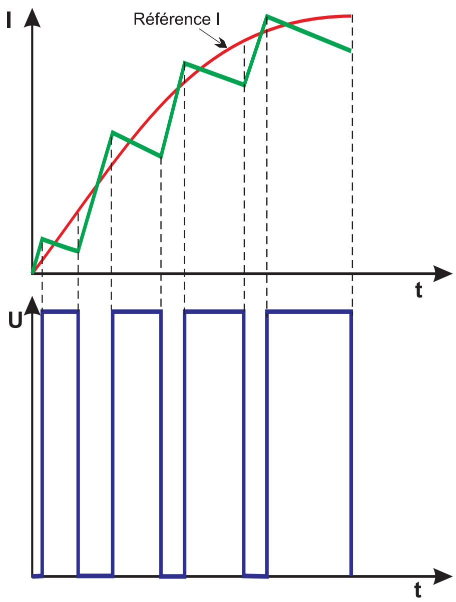
$$I_{eff} = (I_1\_ + I_2\_ + I_3\_ + \ldots\ldots In\_)^{0.5}$$

And the apparent **S** power by: $S = V_{eff} \times I_{eff}$

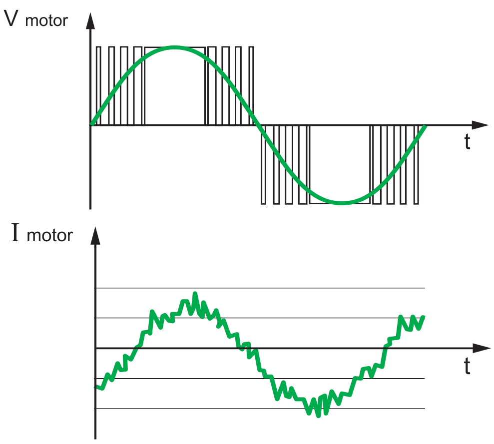
or more or less: $S = V \times I_{eff}$



↑ Fig. 36 *Current in a DC bridge feeding a capacitor*



↑ Fig. 37 *PWM operation*



↑ Fig. 38 *Shape of the motor current*

A low P/S ratio signifies a mains supply overload due to the harmonics likely to overheat the conductor which must be designed accordingly.

- **Case 1: the circuit entry consists of semiconductors controlled by thyristors:** e.g. direct-current motor controller.

Current sampling is approximately square. The power factor is low at low output voltage and improves when the output voltage increases to reach a value of about 0.7.

- **Case 2: diode bridge consisting of diodes:** e.g. a frequency inverter for asynchronous motors.

The current sample is rich in harmonic *(⇨ Fig.36)* and the power factor is low whatever the motor speed. This phenomenon is sustainable for low powers but eventually becomes unacceptable as powers increase.
To reduce it, line chokes and chokes in the DC source circuit in series with the filter capacitors are required. They can decrease the amplitude of the harmonics and greatly improve the power factor. AC drives with a diode bridge, without a line choke or in the DC circuit have a power factor around 0.5.

- **Case 3: The circuit entry consists of semiconductors controlled by IGBTs** *(⇨ Fig.37)*.

Using PWM control, this arrangement is used to sample a sinusoidal current.

The sampling method gives current close to the sine wave and an optimal power factor approximately equal to the outphasing factor and close to 1.

Given the price of such a solution, this type of sampling not widespread in manufacturers' offers.

Converter losses

When considering the efficiency of a drive, one should take into account the losses in the drive (the converter) and losses into the driven motor.

Semiconductors are the main source of energy losses in two ways:
- conduction losses due to residual voltage of about one volt and the internal resistance,
- losses by commutation linked to the switching frequency.

Semiconductors with rapid switching times have the smallest commutation losses; this is the case with IGBTs, which enable high switching frequencies.

Due to this, the converters have excellent efficiency exceeding 90%.

Motor losses

Motors with converters suffer additional losses due to switching of the working voltage. However, as the switching frequency is high, the current absorbed is nearly sinusoidal and additional losses may be considered insignificant *(⇨ Fig.38)*.

5.14 Speed controllers and savings in power and maintenance

■ Choice of motor

AC drives can feed standard motors without any special precautions, apart from low speed derating in self-cooled motors.

However, it is always preferable to choose a motor with the greatest efficiency and highest φ cosine (power factor).

For low power, a wise choice is a synchronous motor controller because of its high efficiency. The additional cost is soon recouped.

■ Load types

Ac drices are best for pump and fan output control. A detailed explanation is given in section 4.

Compared to discrete systems or control systems requiring valves, flaps or shutters, speed controllers ensure substantial power savings.

These savings can only be assessed with perfect knowledge of the application; manufacturers' experts have this knowledge to guide users in their choice.

■ Reduced maintenance

AC drives and electronic soft starters *(see the section on starting motors)* eliminate the mechanical stress on the machine so it can be directly optimised at the design stage.

For multi-motor control (e.g. a pumping station), adequate monitoring of the motors regulates the operating hours of each and increases the uptime and sustainability of the plant.

■ Conclusion

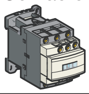
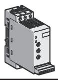
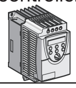
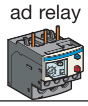
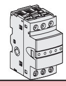
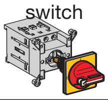
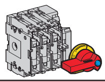
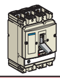
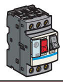
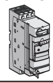
The choice of a starter or speed controller being contingent on the type of load driven, the performance demanded and the protections required, the definition and choice must be based on an analysis of functional requirements for the equipment then the performance required for the motor itself.

Other widely-mentioned features in the documentation of speed controller suppliers are constant torque, variable torque, constant horsepower, flux vector control, reversible speed controller, etc.

These terms describe all the data required to choose the most suitable type of controller. It is advisable to ask for detailed advice from manufacturers' experts who can help choose the speed controller with the best performance/price ratio.

The wrong choice of controller can lead to disappointing operating results.

5.15 Choice table for motor starters

Product / Fonction	Contactor 	Soft starter 	Speed controller 	Overlo ad relay 	Extra protection 	Fuse holder 	Fuse switch 	Switch 	Lin circuit breaker 	Motor circuit breaker 	Starter controler 
Disconnect											
Breaking capacity											
Short circuit protection											
Overload											
Additional functions											
Commutation (DOL, star delta)											
Soft start											
Variable speed drive											

5

6

chapter

Data acquisition: detection

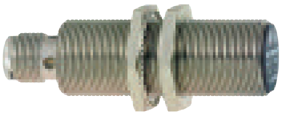
Presentation:

- *Detection features and technologies*
- *Selection table*

6 - Data acquisition: detection

Summary

6 - Data acquisition: detection



↑ *Fig. 1* *Sensors functions*

The field of data capture is divided into two families. The first, called detection, comprises products that can detect a threshold or limit or estimate a physical measurement. The second – measurement or instrumentation – measures a physical measurement to a given level of accuracy.

In this section, we shall only describe sensors and detection devices for machines and their related automation systems.

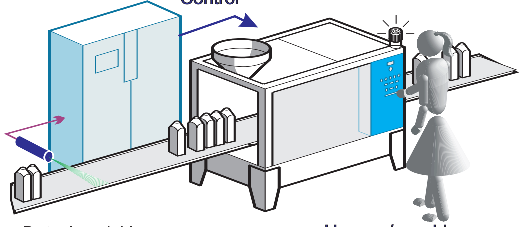
Sensors designed for machine safety are dealt with in appropriate section.

For those who are interested, there are many works on machine safety describing all the devices available on the market.

These products have three essential functions as shown in the figure 1.

The diversity of these functions requires manufacturers to produce a great number of product variants to cover all the requirements. Recent innovations in product modulation enable Schneider Electric to offer smaller ranges with more versatile applications.

6.1 Introduction



↑ *Fig. 2* *Data chain in an industrial process*

Detection: an essential function

The “detection” function is essential because it is the first link in the data chain *(⇨ Fig. 2)* of an industrial process.

In an automatic system, detectors ensure that data is captured:
- on all the events needed for operation that are used by the control systems according to a preset program;
- on the progress of all the process phases when the program is running.

Detection functions

There is a wide range of detection needs.

The basic ones are:
- controlling the presence, absence or position of an object,
- checking the movement, flow or obstruction of objects,
- counting.

These are usually dealt with by “discrete” devices, as in typical parts detection applications in manufacturing chains or handling operations and in the detection of persons or vehicles.

There are other more specific needs such as detection of:
- presence (or level) of a gas or fluid,
- shape,
- position (angular, linear, etc.),
- a label, with reading and writing of encoded data.

There are many additional requirements, especially with regard to the environment, where, depending on their situation, detectors must be able to resist:
- humidity or submersion (e.g.: higher water-tightness),
- corrosion (chemical industries or agricultural installations, etc.),
- wide temperature variations (e.g. tropical regions),
- soiling of any kind (in the open air or in the machines),
- and even vandalism, etc.

To meet all these requirements, manufacturers have developed all kinds of detectors using different technologies.

Detector technologies

Detector manufacturers use a range of physical measurements, the main ones being:
- mechanical (pressure, force) for electromechanical limit switches,
- electromagnetic (field, force) for magnetic sensors, inductive proximity detectors,

- light (light power or deflection) for photoelectric cells,
- capacitance for capacitive proximity detectors,
- acoustic (wave travel time) for ultrasound detectors,
- fluid (pressure) for pressure switches,
- optic (image analysis) for viewing.

These systems have advantages and limits for each type of sensor: some are robust but need to be in contact with the part to detect, others can work in hostile environments but only with metal parts.

The description of the technologies used, outlined in the following sections, is designed to help understand what must be done to install and use the sensors available on the market of industrial automation systems and equipment.

Auxiliary detector functions

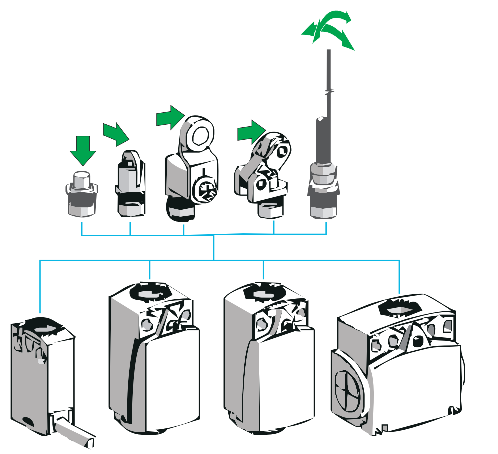
A number of functions have been developed to facilitate the use of detectors, one of which is learning.

The learning function can involve a button to press to define what the device actually detects, e.g. for learning maximum and minimum ranges (very precise foreground and background suppression of ± 6mm for ultrasound detectors) and environmental factors for photoelectric detectors.

6.2 Electromechanical limit switches

Detection is done by making physical contact (probe or control device) with a mobile or immobile object. The data is sent to the processing system by a discrete electrical contact.

These devices (control device and electrical contact) are called limit switches. They are found in all automated installations and different applications because of the many inherent advantages of their technology.



↑ *Fig. 3* *Illustration of movements in commonly-used sensors*

Detector movements

A probe or control device can have different kinds of movement *(⇨ Fig. 3)* so it can detect in many different positions and easily adapt to the objects to detect:
- rectilinear,
- angular,
- multi-directional.

Contact operating mode

Manufacturers' offers are differentiated by the contact operating technology used.

Snap action contact, or quick-break switch

Contact operation is characterised by a hysteresis phenomenon, i.e. distinct action and release points *(⇨ Fig. 4)*.

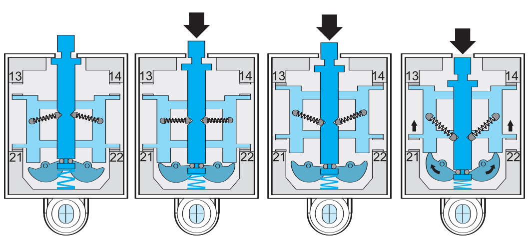
The speed at which the mobile contacts move is independent of the speed of the control device. This feature gives satisfactory electrical performance even when the control device runs at low speed.

More and more limit switches with action snap action contacts have positive opening operation; this involves the opening contact and is defined as follows:

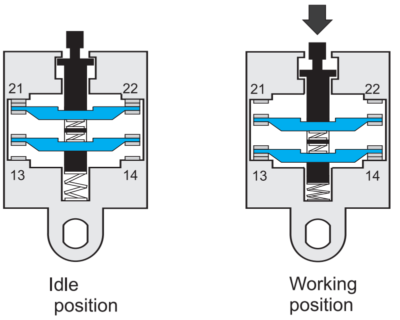
“A device meets this requirement when one can be sure that all its opening contact elements can be brought to their opening position, i.e. without any elastic link between mobile parts and the control device subjected to the operating effort.”

This involves the electrical contact of the limit switch and also the control device which has to transmit the movement without distortion.

Use for safety purposes requires devices with positive opening operation.



↑ *Fig. 4* *Positions of a snap action contact*



↑ *Fig. 5* *Positions of a slow break contact*

□ **Slow break contact** *(⇨ Fig. 5)*

This operating mode features:
- non-distinct action and release points,
- mobile contact speed equal or proportional to the control device speed (which should be no less than 0.1m/s = 6m/min). Below this, the contacts open too slowly, which is not good for the electrical performance of the contact (risk of an arc maintained for too long),
- an opening distance also dependent on the control device stroke.

The design of these contacts sets them naturally in positive opening operation mode: the push-button acts directly on the mobile contacts.

6.3 Inductive proximity detectors

The physical principles of these detectors imply that they only work on metal substances.

Principle

The sensitive component is an inductive circuit (L inductance coil). This circuit is linked to a C capacitor to form a circuit resonating at frequency Fo usually ranging from 100kHz to 1MHz.

An electronic circuit maintains the oscillations of the system based on the formula below:

$$Fo = \frac{1}{2\pi\sqrt{LC}}$$

These oscillations create an alternating magnetic field in front of the coil.

A metal shield set in the field is the seat of eddy currents which induce an extra load and alter the oscillation conditions *(⇨ Fig. 6)*.

The presence of a metal object in front of the detector lowers the quality factor of the resonant circuit.

Case 1, no metal shield: $Q_1 = \frac{R_1}{Lw}$

Reminder:

$$Q = \frac{R}{Lw} = \frac{Lw}{r} \text{ fi } R = Q^2 r$$

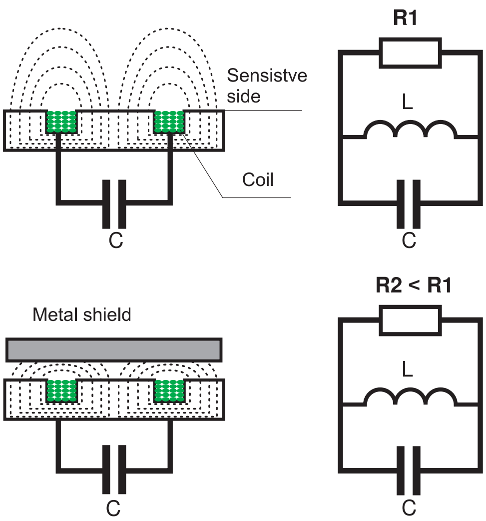
Case 2, with metal shield: $Q_2 = \frac{R_2}{Lw}$

$$R_2 < R_1 => Q_2 < Q_1$$

Detection is done by measuring variation in the quality factor (approx. 3% to 20% of the detection threshold).

The approach of the metal shield causes the quality factor to drop and thereby a drop in the oscillation range.

The detection distance depends on the nature of the metal to detect.



↑ *Fig. 6* *Operating principle of an inductive detector*

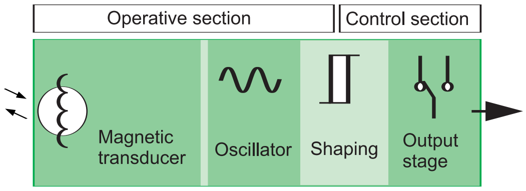


Fig. 7 Diagram of an inductive detector

Description of an inductive detector (⇨ Fig. 7)

Transducer: this consists of a stranded copper coil (Litz wire) inside a half ferrite pot which directs the line of force to the front of the detector.

Oscillator: there are many kinds of oscillators, including the fixed negative resistance oscillator –R, equal in absolute value to the parallel resistance pR of the circuit oscillating at the rated range:

- if the object to detect is beyond the rated range, |Rp| > |-R|, oscillation is maintained,
- otherwise, if the object to detect is within the rated range, |Rp| < |-R|, oscillation is no longer maintained and the oscillator is locked.

Shaping stage: this consists of a peak detector monitored by a two-threshold comparator (Trigger) to prevent untimely switching when the object to detect nears the rated range. It creates what is known as detector hysteresis (⇨ Fig. 7bis).

Power input and output stages: this powers the detector over wide voltage ranges (10VDC to 264VAC). The output stage controls loads of 0.2A in DC to 0.5A in AC, with or without short-circuit protection.

Inductive detection influence quantities

Inductive detection devices are particularly affected by certain factors, including:

- detection distance,
- this depends on the extent of the detection surface,
- rated range (on mild steel) varies from 0.8mm (detector of ø 4) to 60mm (detector of 80 x 80),
- hysteresis: differential travel (2 to 10% of Sn) to prevent switching bounce,
- frequency with which objects pass in front of the detector, called switching (maximum current 5kHz).

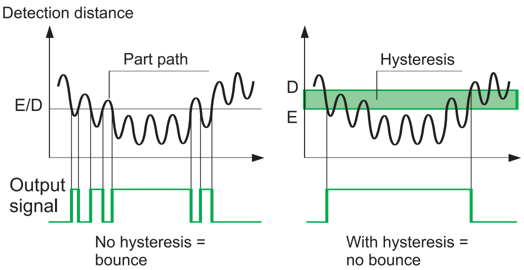


Fig. 7bis Detector hysteresis

Specific functions

- Detectors protected against magnetic fields generated by welding machines.
- Detectors with analogue output.
- Detectors with a correction factor of 1* where the detection distance is independent of the ferrous or non-ferrous metal detected.
- Detectors to select ferrous and non-ferrous metals.
- Detectors to control rotation: these under-speed detectors react to the frequency of metal objects.
- Detectors for explosive atmospheres (NAMUR standards).

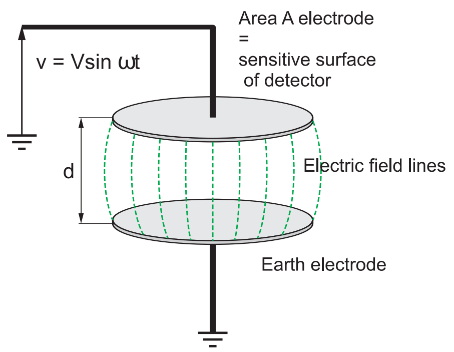
**When the object to detect is not made of steel, the detection distance of the detector should be proportional to the correction factor of the substance the object is made of.*

$D_{Mat\ X} = D_{Steel} \times K_{Mat\ X}$

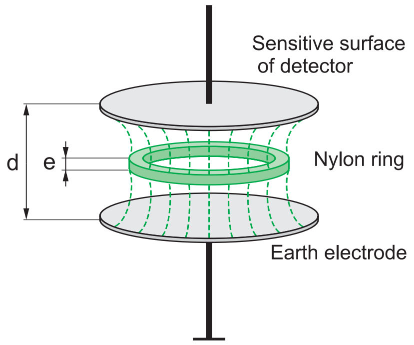
Typical correction factor values (KMat X) are:
- Steel = 1 -
- Stainless steel = 0.7
- Brass = 0.4
- Aluminium = 0.3
- Copper = 0.2

Example: $D_{Stainless} = D_{Steel} \times 0.7$

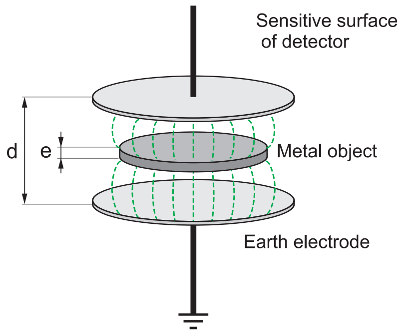
6.4 Capacitive proximity detectors



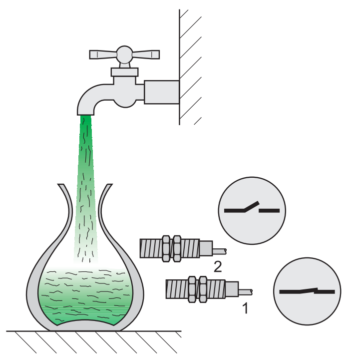
↑ *Fig. 8* *No object between electrodes*



↑ *Fig. 9* *Presence of an isolating object between electrodes*



↑ *Fig. 10* *Presence of a conductive object between electrodes*



↑ *Fig. 11* *Detection of water in a glass or plastic recipient*

This technology is used to detect all types of conductive and isolating substances such as glass, oil, wood, plastic, etc.

Principle

The sensitive surface of the detector constitutes the armature of a capacitor.

A sinusoidal voltage is applied to this surface to create an alternating electric field in front of the detector.

Given that this voltage is factored in relation to a reference potential (such as an earth), a second armature is constituted by an electrode linked to the reference potential (such as a machine housing).

The electrodes facing each other constitute a capacitor with a capacity of:

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d}$$

where ε_0 = 8,854187.10^{-12} F/m permittivity of vacuum and ε_r relative permittivity of substance between the 2 electrodes.

Case 1: No object between electrodes *(⇨ Fig. 8)*

$$\varepsilon_r \approx 1 \text{ (air)} \Rightarrow C \approx \varepsilon_0 \cdot \frac{A}{d}$$

Case 2: Isolating substance between electrodes *(⇨ Fig. 9)*

=> (ε_r = 4)

In this case, the earth electrode could be, e.g. the metal belt of a conveyor.

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d}$$

When mean ε_r exceeds 1 in the presence of an object, C increases.

Measurement of the increase in the value of C is used to detect the presence of the isolating object.

Case 3: Presence of a conductive object between electrodes *(⇨ Fig. 10)*

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d - e}$$

where ε_r 1 (air) => $C \approx \varepsilon_0 \cdot \frac{A}{d - e}$

The presence of a metal object also causes the value of C to increase.

Types of capacitive detectors

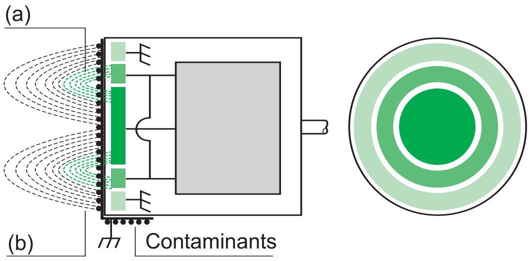
Capacitive detectors with no earth electrode

These work directly on the principle described above.

A path to an earth (reference potential) is required for detection.

They are used to detect conductive substances (metal, water) at great distances.

Typical application: Detection of conductive substances through an isolating substance *(⇨ Fig. 11)*.



(a) compensation field (eliminate of earlier contamination)
(b) main electric field

Main electrode
Compensation electrode
Earth electrode

Fig. 12 *Principle of a capacitive detector with earth electrode*

Substance	ε_r
Acetone	19.5
Air	1.000264
Ammonia	15-25
Ethanol	24
Flour	2.5-3
Glass	3.7-10
Glycerine	47
Mica	5.7-6.7
Paper	1.6-2.6
Nylon	4-5
Petroleum	2.0-2.2
Silicone varnish	2.8-3.3
Polypropylene	2.0-2.2
Porcelain	5-7
Dried milk	3.5-4
Salt	6
Sugar	3.0
Water	80
Dry wood	2-6
Green wood	10-30

Fig. 13 *Dielectric constants of a number of substances*

Capacitive detectors with earth electrode

It is not always possible to find a path to an earth. This is so when the empty isolating container described above has to be detected.

The solution is to incorporate an earth electrode into the detection surface.

This creates an electric field independent of an earth path *(⇨ Fig. 12)*.

Application: detection of all substances.

Ability to detect isolating or conducting substances behind an isolating barrier, e.g.: cereals in a cardboard box.

Influence quantities of a capacitive detector

The sensitivity of capacitive detectors, according to the above-mentioned basic equation, depends on the object–sensor distance and the object's substance.

Detection distance

This is related to the dielectric constant or relative permittivity of the object's substance.

To detect a wide variety of substances, capacitive sensors usually have a potentiometer to adjust their sensitivity.

Substances

The table *(⇨ Fig. 13)* gives the dielectric constants of a number of substances.

6.5 Photoelectric detectors

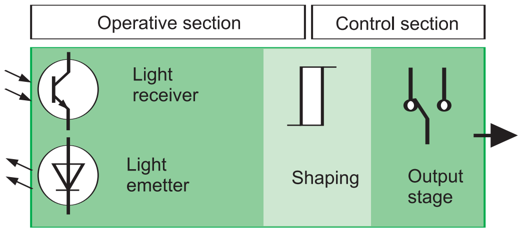


Fig. 14 *Principle of a photoelectric detector*

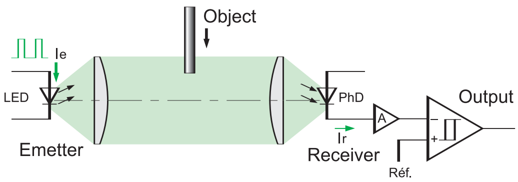


Fig. 14bis *Through-beam detection*

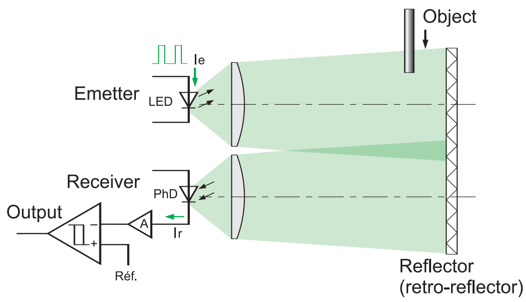


Fig. 15 *Principle of photoelectric reflex detection*

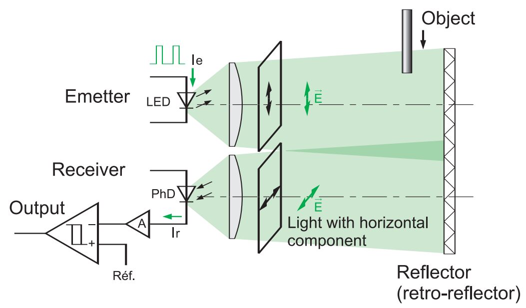


Fig. 16 *Principle of polarised photoelectric reflex detection*

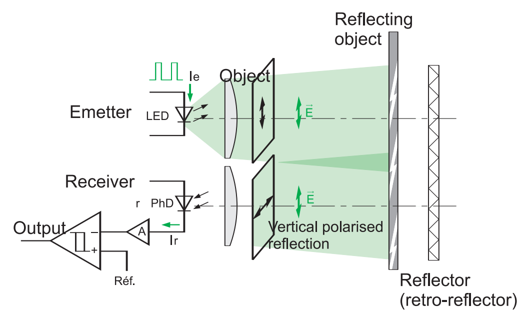


Fig. 17 *Polarised reflex system: principle of non-detection of reflecting objects*

These work on a principle suiting them to the detection of all types of object, be they opaque, reflective or virtually transparent. They are also used for human detection (door or safety barrier opening).

Principle *(⇨ Fig. 14)*

A light-emitting diode (LED) emits luminous pulses, usually in the close infrared spectrum (850 to 950nm).

The light is received or otherwise by a photodiode or phototransistor according to whether the object to detect is present or not.

The photoelectric current created is amplified and compared to a reference threshold to give discrete information.

Detection system

Through-beam *(⇨ Fig. 14bis)*

The emitter and receiver are in separate housings.

The emitter, a LED in the cell of a converging lens, creates a parallel light beam.

The receiver, a photodiode (or phototransistor) in the cell of a converging lens, supplies a current proportional to the energy received.

The system issues discrete information depending on the presence or absence of an object in the beam.

Advantage: The detection distance (range) can be long (up to 50m or more); it depends on the lens and hence detector size.

Disadvantages: 2 separate housings and therefore 2 separate power supplies.

Alignment for detection distances exceeding 10m can be problematic.

Reflex systems

There are two so-called Reflex systems: standard and polarised.

• **Standard reflex** *(⇨ Fig. 15)*

The light beam is usually in the close infrared spectrum (850 to 950nm).

Advantages: the emitter and receiver are in the same housing (a single power supply). The detection distance (range) is still long, though less than the through-beam (up to 20m).

Disadvantage: a reflective object (window, car body, etc.) may be interpreted as a reflector and not detected.

• **Polarised reflex** *(⇨ Fig. 16)*

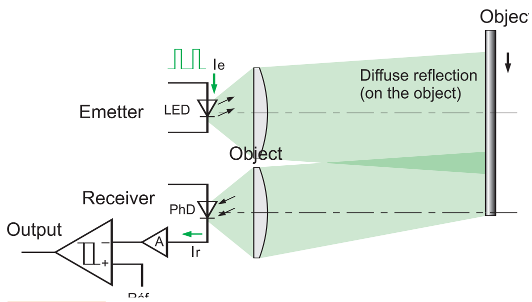
The light beam used is usually in the red range (660 nm).

The emitted radiation is vertically polarised by a linear polarising filter. The reflector changes the state of light polarisation, so part of the radiation returned has a horizontal component. The receiving linear polarising filter lets this component through and the light reaches the receiver.

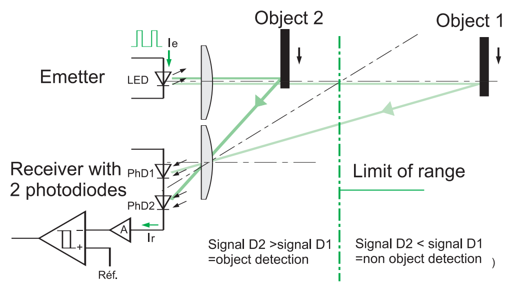
Unlike the reflector, a reflective object (mirror, sheet metal, glazing) does not alter the state of polarisation so the light it reflects cannot reach the receiving polariser *(⇨ Fig. 17)*.

Advantage: this type of detector overcomes the drawback of the standard reflex.

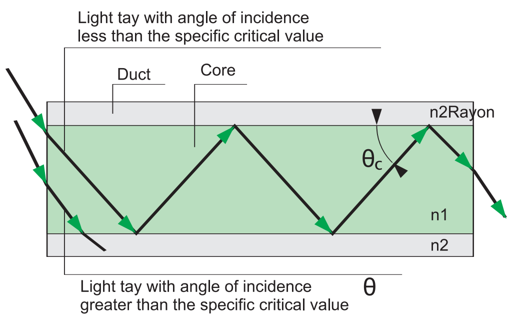
Disadvantages: this detector is more expensive and its detection distances are shorter:
IR reflex -->15m
Polarised reflex ---> 8m



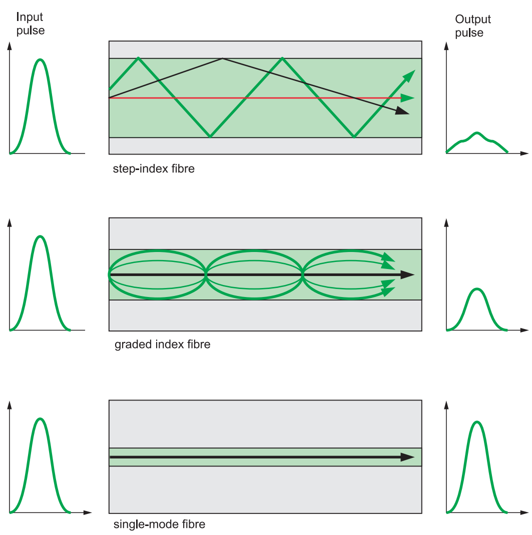
↑ *Fig. 18* *Principle of standard direct photoelectric detection*



↑ *Fig. 19* *Principle of direct photoelectric detection with background suppression*



↑ *Fig. 20* *Principle of light wave propagation in fibre optics*



↑ *Fig. 21* *Types of optic fibres*

Direct reflection (on the object)

• **Standard direct reflection** *(⇨ Fig.18)*

This system is based on the reflection of the object to detect.

Advantage: no need for a reflector.

Disadvantages: the detection distance is very short (up to 2m). It also varies with the colour of the object to "see" and the background behind it (at a given setting, the distance is greater for a white object than a grey or black one); a background which is lighter than the object to detect can make detection impossible.

• **Direct reflection with background suppression** *(⇨ Fig.19)*

This detection system uses triangulation.

The detection distance (up to 2m) does not depend on the reflectivity of the object but on its position, so a light object is detected at the same distance as a dark one and a background beyond the detection range will be ignored.

Optic fibres

• **Principle**

The principle of light wave propagation in fibre optics is based on total internal reflection.

Internal reflection is total when a light ray passes from one medium to another with a lower refractive index. The light is reflected in totality *(⇨ Fig. 20)* with no loss when the angle of incidence of the light ray is greater than the critical angle [θ_c].

Total internal reflection is governed by two factors: the refraction index of each medium and the critical angle.

These factors are related by the following equation:

$$\sin\theta_c = \frac{n_2}{n_1}$$

If we know the refractive indexes of the two interface substances, the critical angle is easy to calculate.

Physics defines the refractive index of a substance as the ratio of the speed of light in a vacuum (c) to its speed in the substance (v).

$$n = \frac{c}{v}$$

The index of air is considered as equal to that of a vacuum 1, since the speed of light in air is almost equal to that in a vacuum.

There are two types of optic fibres: multimode and single-mode.

• **There are two types of optic fibres: multimode and single-mode** *(⇨ Fig.21)*

- Multimode

These are fibres where the diameter of the core, which conducts light, is large compared to the wavelength used ($\phi \approx 9$ to 125 µm, L_o = 0.5 to 1 mm). Two types of propagation are used in these fibres: step index and graded index.

- Single-mode

By contrast, these fibres have a very small diameter in comparison to the wavelength used ($\phi <= 1$ µm, L_o = usualy 1.5 µm). They use step-index propagation. They are mostly used for telecommunication.

This explanation illustrates the care that has to be taken with these fibres when, for example, they are pulled (reduced tensile strength and moderate radii of curvature, according to manufacturers' specifications).

Multimode optical fibres are the most widely used in industry, as they have the advantage of being electromagnetically robust (ECM – ElectroMagnetic Compatibility) and easy to implement.

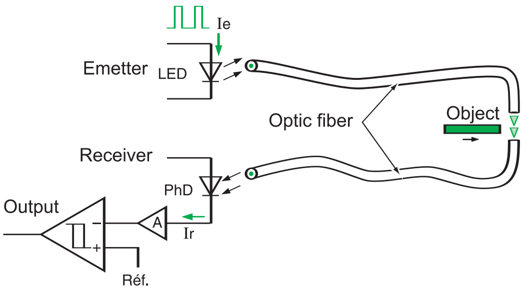


Fig. 22 *Principle of an optic fibre detector*

• **Detector technology**

The optic fibres are positioned in front of the emitting LED and in front of the receiving photodiode or phototransistor (⇨ *Fig.22*).

This arrangement is used to:
- position electronic components away from the monitoring point,
- operate in confined areas or at high temperature,
- detect very small objects (of around 1mm),
- depending on the configuration of the fibre ends, operate in through-beam or proximity mode,

Note that extreme care must be taken with the connections between the emitting LED or receiving phototransistor and the optic fibre to minimise light signal losses.

Influence quantities in detection by photoelectric systems

A number of factors can influence the performance of these detection systems.

Some have been mentioned already:
- distance (detector-object),
- type of object to detect (diffusing, reflective or transparent substance, colour and size),
- environment (light conditions, background, etc.).

6.6 Ultrasonic detectors

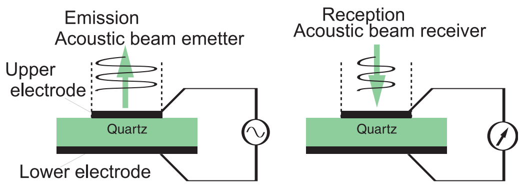


Fig. 23 *Principle of an electroacoustic transducer*

Principle

Ultrasonic waves are produced electrically with an electroacoustic transducer (piezoelectric effect) supplied with electrical energy which it converted into mechanical vibrations by piezoelectricity or magnetostriction phenomena (⇨ *Fig. 23*).

The principle involves measuring the time it takes for the acoustic wave to propagate between the sensor and the target.

The speed of propagation is 340m/s in air at 20°C, e.g. for 1m the measuring time is about 3ms.

This time is measured by the counter built in a microcontroller.

The advantage of ultrasonic sensors is that they can work over long distances (up to 10m) and, above all, detect any object which reflects sound, regardless of its shape or colour.

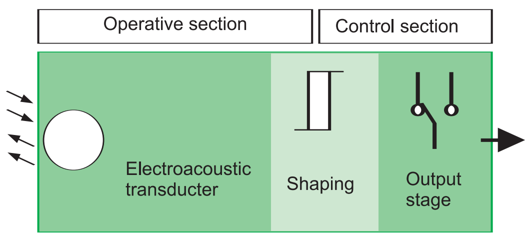
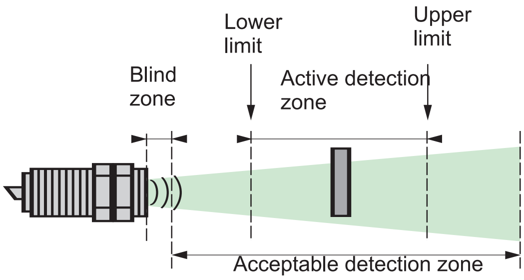


Fig. 24 *Principle of an ultrasonic detector*

Application (⇨ *Fig.24*)

Excited by the high-voltage generator, the transducer (emitter-receiver), generates a pulsed ultrasonic wave (100 to 500kHz, depending on the product) which travels through the ambient air at the speed of sound.
As soon as the wave meets an object, a reflected wave (echo) returns to the transducer. A microprocessor analyses the incoming signal and measures the time interval between the emitted signal and the echo.
By comparing it with preset or ascertained times, it determines and monitors the status of the outputs. If we know the speed at which sound is propagated, we can calculate a distance using the following formula:
D = T.Vs/2 where
D: distance between detector and object,
T: time elapsed between mission and reception of the wave,
Ss: speed of sound (300m /s).

The output stage monitors a static switch (PNP or NPN transistor) corresponding to an opening or closing contact, or provides an analogue signal (current or voltage) directly or inversely proportional to the measured distance of the object.



↑ *Fig. 25* *Working limits of an ultrasonic detector*

Specific features of ultrasonic sensors

Definitions (⇨ *Fig.25*)

Blind zone: zone between the sensing face of the detector and the minimum range where no object can be reliably detected. It is impossible to detect objects correctly in this zone.

Objects should never be allowed through the blind zone when the detector is operating as this could make the outputs unstable.

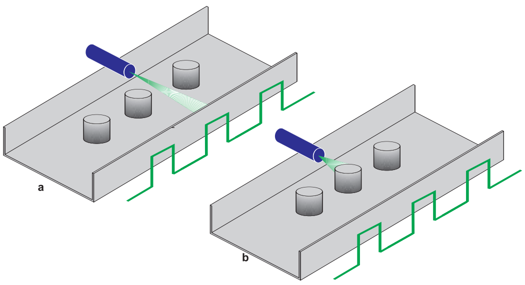
Detection zone: the area within which the detector is sensitive. Depending on the model, this zone can be adjustable or fixed with an ordinary push button.

Influence quantities: ultrasonic detectors are especially suitable for detecting hard objects with a flat surface perpendicular to the detection axis.

However, there are a number of factors that can disrupt ultrasonic detector operation:

- Sudden strong draughts can accelerate or divert the acoustic wave emitted by the object (part ejected by air jet).
- Steep temperature gradients in the detection field. When an object gives off a lot of heat, this creates differing temperature zones which alter the wave propagation time and prevent reliable detection.
- Sound-absorbing materials. Materials such as cotton, cloth and rubber absorb sound; the ''reflex" detection mode is advised for products made of these.
- The angle between the front of the target object and the detector's reference axis. When this angle is other than 90°, the wave is not reflected in the detector axis and the working range is reduced. The greater the distance between the object and the detector, the more apparent this effect is. Beyond ± 10°, detection becomes impossible.
- The shape of the object to detect. Owing to the above-mentioned factor, very angular objects are more difficult to detect.

Operating mode (⇨ *Fig.26*)



↑ *Fig. 26* *Uses of ultrasonic detection. a/ In proximity or diffuse mode, b/ In reflex mode*

- **Diffuse mode:** a single detector emits the sound wave and senses it after it has been reflected by an object.

  In this case, it is the object that reflects the wave.
- **Reflex mode:** a single detector emits the sound wave and receives it after reflection by a reflector, so the detector is permanently active. In this case, the reflector is a flat, rigid part, such as a part of the machine. The object is detected when the wave is broken. This mode is especially suited to detecting absorbent substances or angular objects.
- **Through-beam mode:** the through-beam system consists of two separate products, an ultrasonic emitter and a receiver, set opposite each other.

Advantages of ultrasonic detection

- No physical contact with the object, so no wear and ability to detect fragile or freshly-painted objects.
- Any substance, regardless of its colour, can be detected at the same range with no adjustment or correction factor.
- Static devices: no moving parts inside the detector, so its lifetime is unaffected by the number of operating cycles.
- Good resistance to industrial environments: vibration- and impact-resistant devices, devices resistant to damp and dusty environments.
- Learning function by pressing a button to define the working detection field. The minimum and maximum ranges are learnt (very accurate suppression of background and foreground to ± 6mm).

6.7 RFID -Radio Frequency IDentification- detection

This section describes devices that use a radio frequency signal to store and use data in electronic tags.

Overview

Radio Frequency IDentification (RFID) is a fairly recent automatic identification technology designed for applications requiring the tracking of objects or persons (traceability, access control, sorting, storage).

It works on the principle of linking each object to a remotely accessible read/write storage capacity.

The data are stored in a memory accessed via a simple radio frequency link requiring no contact or field of vision, at a distance ranging from a few cm to several metres. This memory takes the form of an electronic tag, otherwise known as a transponder (TRANSmitter + resPONDER), containing an electronic circuit and an antenna.

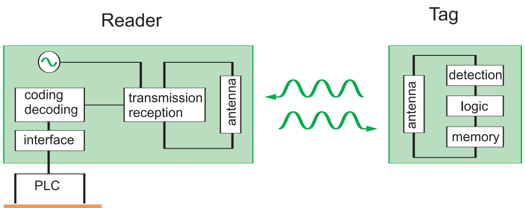


Fig. 27 *Layout of a RFID system*

Operating principles

A RFID system consists of the following components *(⇨ Fig.27 and 28)*:

- An electronic tag,
- A read/write station (or RFID reader).

The reader

Modulates the amplitude of the field radiated by its antenna to transmit read or write commands to the tag processing logic. Simultaneously, the electromagnetic field generated by its antenna powers the electronic circuit in the tag.

Tag

This feeds back its information to the reader antenna by modulating its own consumption. The reader reception circuit detects the modulation and converts it into digital signals *(⇨ Fig.29)*.

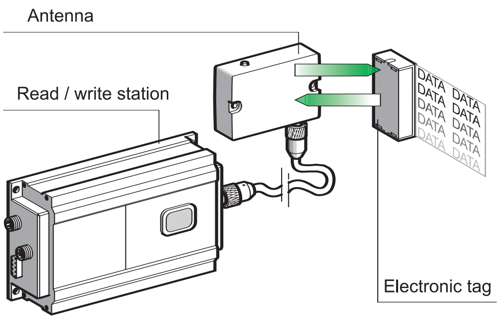


Fig. 28 *View of components in a RFID system (Telemecanique Inductel system)*

Description of components

Electronic tags

Electronic tags consist of three main components inside a casing.

- **Antenna** *(⇨ Fig.30)*:

This must be adjusted to the frequency of the carrier and so can take several forms:

- coil of copper wire, with or without a ferrite core (channelling of field lines), or etched on a flexible or rigid printed circuit, or printed (with conductive ink) for frequencies of less than 20MHz;
- dipole etched onto a printed circuit, or printed (with conductive ink) for very high frequencies (>800MHz).

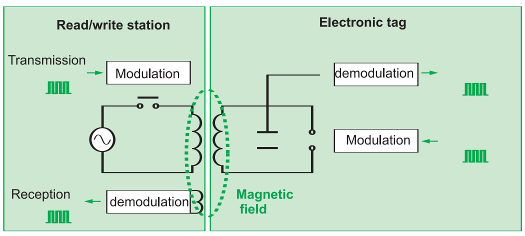


Fig. 29 *Operation of a RFID system*

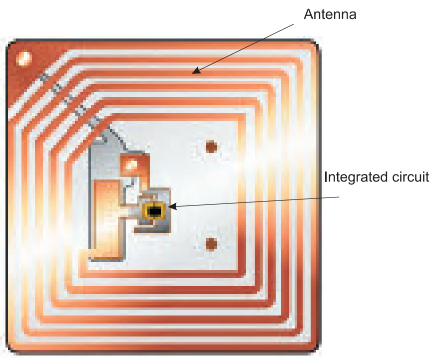


Fig. 30 *Inside of an RFID tag*

- **Logical processing circuit**

This acts as an interface between the commands received by the antenna and the memory.

Its complexity depends on the application and can range from simple shaping to the use of a microcontroller (e.g. payment cards secured by encryption algorithms).

- **Memory**

Several types of memory are used to store data in electronic tags *(⇨ Fig.31)*.

Type	Advantages	Disadvantages
ROM	• Good resistance to high temperatures • Inexpensive	• Read only
EEPROM	• No battery or backup battery	• Fairly long read/write access time • Number of write operations limited to 100,000 cycles per byte
RAM	• Fast data access • High capacity	• Need for backup battery built into tag
FeRAM (ferroelectric)	• Fast data access • No battery or backup battery • High capacity	• Number of write operations limited to 10^{12}

Fig. 31 *Storage capacities range from a few bytes to several dozen kilobytes*

6

Fig. 32 a et b *a - RFID formats designed for different uses*
b - RFID industrial (Telemecanique Inductel)

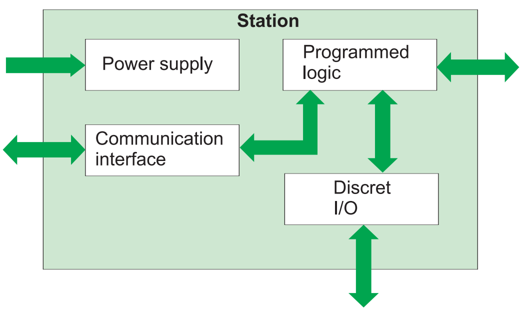


Fig. 33a *Diagram of a RFID reader*

Fig. 33b *Photo of a RFID reader (Telemecanique Inductel Station)*

"Active" tags contain a battery to power their electronic components. This configuration increases the dialogue distance between the tag and the antenna but requires regular replacement of the battery.

Casing

Casings have been designed for each type of application to group and protect the three active components of a tag: *(⇨ Fig.32a)*

- credit card in badge format to control human access,
- adhesive support for identification of library books,
- glass tube, for identification of pets (injected under the skin with a syringe),
- plastic "buttons", for identification of clothing and laundry,
- label for mail tracking.

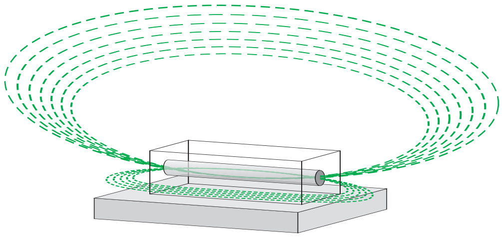
There are many other formats, including: key ring, plastic "nails" to identify wooden pallets, shockproof and chemical-resistant casings for industrial applications (surface treatment, furnaces, etc.) *(⇨ Fig.32b)*.

Stations

A station *(⇨ Fig.33a)* acts as an interface between the control system (PLC, computer, etc.) and the electronic tag via an appropriate communication port (RS232, RS485, Ethernet, etc.).

It can also include a number of auxiliary functions suited to the particular application:

- discrete inputs/outputs,
- local processing for standalone operation,
- control of several antennas,
- detection with built-in antenna for a compact system *(⇨ Fig.33b)*.



↑ Fig. 34 Influence of a ferrite antenna on electromagnetic field lines

☐ Antennas

Antennas are characterised by their size (which determines the shape of the zone where they can exchange information with the tags) and the frequency of the radiated field. Ferrite cores are used to concentrate the electromagnetic field lines to increase the reading distance (⇨ Fig.34) and reduce the influence of any metal bodies in the vicinity of the antenna.

The frequencies used by the antennas cover several distinct bands, all of which have advantages and disadvantages (⇨ Fig.35).

Frequency	Advantages	Disadvantages	Typical applications
125-134 khz (LF)	• Immune to the environment (metal, water, etc.)	• Small storage capacity • Long access time	• Identification of pets
13.56 Mhz (HF)	• Standard antenna/tag dialogue protocols (ISO 15693 - ISO 14443 A/B)	• Sensitive to metallic environments	• Library book tracking • Access control • Payment systems
850 - 950 Mhz (UHF)	• Very low-cost tags • Long dialogue range (several metres)	• Frequency ranges differ with the country • Interference in dialogue zones caused by obstacles (metal, water, etc.)	• Product control in retailing
2.45 Ghz) (microwaves)	• Very high speed of transfer between tag and antenna • Long dialogue range (several metres)	• “Dips” that are hard to control in the dialogue zone • Cost of reading systems	• Vehicle tracking (motorway tollgates)

↑ Fig. 35 Description of frequency bands used in RFID

Power ratings and frequencies used vary with the applications and countries. There are three major zones: North America, Europe and Rest of World. Each zone and each frequency has an authorised emission spectrum range (CISPR standard 300330) within which every RFID station/antenna must operate.

☐ Codes and protocols

The exchange protocols between stations and tags are defined by international standards (ISO 15693 – ISO 14443 A/B).

More specialised standards are in the definition process, such as those intended for mass retailing (EPC - Electronic Product Code) or identification of animals (ISO 11784).

■ Advantages of RFID

Compared to barcode systems (labels or marks and readers), RFID has the following advantages:

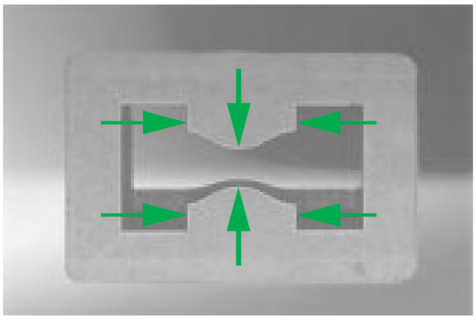
- data in the tag can be modified,
- read/write access through most non-metallic materials,
- insensitive to dust, soiling, etc.,
- several thousand characters can be recorded in a tag,
- data confidentiality (tag data access lock).

These advantages all contribute to its development in the service sector (e.g. ski run access control) and retailing.

Furthermore, the ongoing fall in the cost of RFID tags will probably result in their replacing conventional barcodes on containers (boxes, parcels, baggage) in logistics and transport and also on products in the industrial manufacturing process.

It should be noted however that the appealing idea of using these systems for automatic identification of trolley contents without having to unload them at supermarket checkouts is not yet feasible for physical and technical reasons.

6.8 Vision



↑ Fig. 36 *Inspection of a mechanical component. The arrows indicate the zones checked by the system*

Principle

The eye of a machine which gives sight to an automation system. A camera takes a photo of an object and digitises its physical characteristics to provide information on (⇨ Fig.36):
- its dimensions,
- its position,
- its appearance (surface finish, colour, brightness, any defect),
- its markings (logos, characters, etc.).

The user can also automate complex functions such as:
- measurement,
- guidance,
- identification.

Key points in vision

Industrial vision consists of an optical system (lighting, camera and lens) linked to a processing unit and an actuator control system.

• Lighting
It is vital to have the right sort of lighting, specially designed to create an adequate, stable contrast to highlight the elements to inspect.

• Camera and Lens
The quality of the image (contrast, sharpness) depends on the choice of lens together with a defined distance between camera and object and a specifically determined object to inspect (size, surface finish and details to record).

• Processing unit
The camera image is transmitted to the processing unit which contains the image formatting and analysis algorithms required for checking.

The results are then sent to the automation system or trigger a direct actuator response.

Lighting systems

• Lighting technologies
- LED (Light-Emitting Diode)
Now the most widely-used system: it provides uniform lighting and has a very long lifetime (30,000 hours).

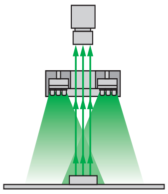
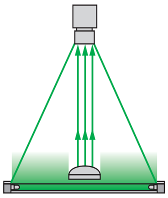
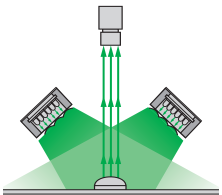
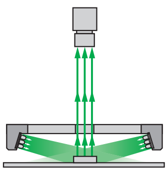
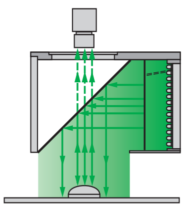
It is available in colour, but then only covers a field of about 50cm.

- High-frequency fluorescent tube
This gives off a white light and has a long lifetime (5000 hours). The area illuminated (field) is large, though this obviously depends on the power used.

- Halogen
This also gives off a white light. It has a short lifetime (500 hours) but a very high lighting power so can cover a large field.

These lighting technologies can be used in different ways. Five main systems *(⇨ Fig.37)* are used to highlight the features to check:

- ring light,
- back lighting,
- direct front light,
- dark field,
- coaxial.

Systems	Characteristics	Applications type
Ring light 	• LEDs arranged in a ring • Very powerful lighting system: • Lights an object in its axis from above	• Precision, inspection such as markings
Back lighting 	• Lighting behind an object and facing the camera • Highlights the contours of an object (shadowgraph)	• Measuring the dimensions of an object or analysing opaque items
Direct front lighting 	• Highlights a detail of an object to check and creates a heavy shadow	• Finding specific defects, checking screw threads, etc.
Dark field 	• Detects the edges of an object • Checks markings • Detects flaws on glass or metal surfaces	• Checking printed characters, surface finish, detecting scratches, etc.
Coaxial 	• Highlight smooth surfaces perpendicular to the optical axis by reflecting the light to a semi-reflective mirror surface	• Inspecting, analysing and measuring smooth metal surfaces and other reflective surfaces

↑ Fig. 37 *Table of lighting technologies for industrial vision systems*

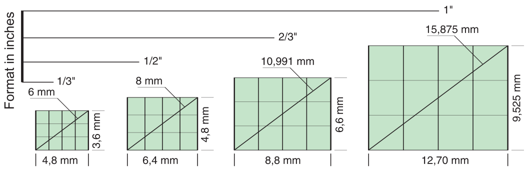


Fig. 38 Sensor formats used in industry

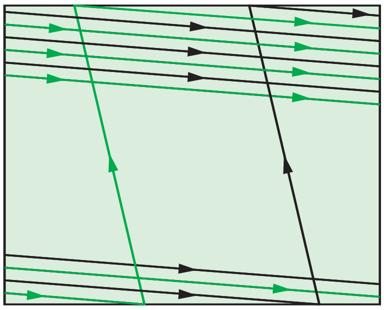


Fig. 39 Interlaced scan

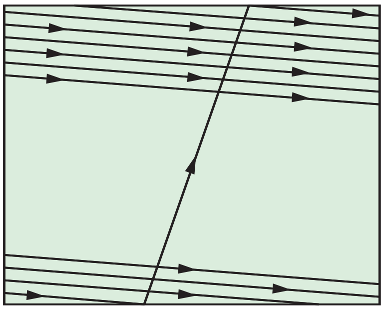


Fig. 40 Progressive scan

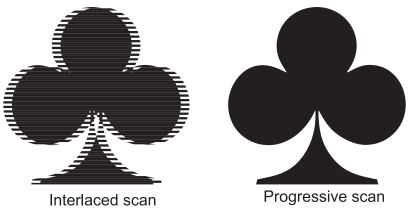


Fig. 41 Comparison of scanning systems

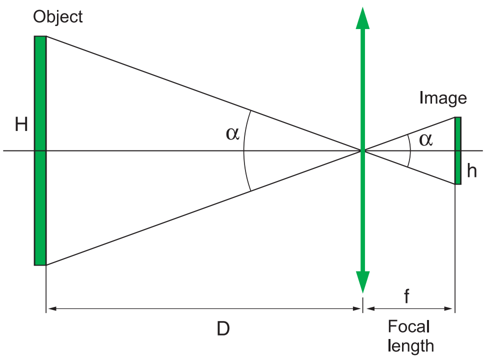


Fig. 42 Focal length

Cameras and lenses

- **Camera technologies**

  - Caméra CCD (Charged Coupled Device)
  These cameras are now preferred for their good definition.

  For continuous processes, linear cameras (linear CCD) are used.

  For all other purposes, matrix cameras (matrix CCD) are used.

  Industrial cameras use a number of sensor formats (⇨ Fig.38) defined in inches: 1/3, 1/2 and 2/3 (1/3 and 1/2: camcorder, 2/3 and over: industrial high resolution, television, etc.).

  There are specific lenses for each format to ensure full use of the pixels.

  - CMOS
  Gradually being superseded by CCD

  Inexpensive -> basic applications

  - Vidicon (tube)
  Now obsolete.

- **Scanning**

The cameras are either interlaced image or progressive scan/full frame types.

Where vibration or image capture on the fly is common, it is recommended to use progressive scan (for reading on the fly) or full frame sensors.

CCD ensures exposure of all the pixels at the same time.

- **Interlaced scan**

This system derives from video. It analyses an image by scanning odd and even lines alternately (⇨ Fig.39).

It is designed to save half the bandwidth, at the cost of a few defects hardly visible on screen, notably flicker. One frame, represented by black lines, analyses the odd lines and the other, green, analyses the even lines.

- **Progressive scan**

This is the type of image analysis used in information technology. It works by describing all the lines of an image at the same time (⇨ Fig.40).
It has the advantage of eliminating flicker and providing a stable image (⇨ Fig.41).

- **Lens**
  - "C" and "CS" screw mounts with a diameter of 25.4mm are the most commonly used in industry.
  - The focal length (f in mm) is calculated from the height of the object to frame (H in mm), the distance between the object and the lens (D in m) and the height of the image (h in mm): f= D x h/H (⇨ Fig.42). There is also a field angle = 2 x arctg (h/(2xf)). Therefore, the shorter the focal length, the larger the field.
  - The type of lens is therefore chosen according to the distance D and the size of the field viewed H.

Processing unit

Its electronic system has two functions: format the image and then analyse the enhanced image.

- **Image formatting algorithms**

Preprocessing changes the grey scale value of the pixels. Its purpose is to enhance the image so it can be analysed more effectively and reliably. The most common preprocessing operations are:
  - binarisation,
  - projection,
  - erosion/dilation,
  - opening/closing.

- **Image analysis algorithms**

The table (⇨ *Fig. 43*) shows a number of image analysis algorithms.

Note the image processing operations prior to analysis in the "Prerequisites" column.

Image analysis algorithm	Operating principle and primary use	Prerequisite	Advantage(s)	Limits
Line	Pixel and object counting Présence/Absence, counting	Binarisation and exposure adjustment if necessary	Very fast (<ms)	Binarisation can affect image stability
Binary window	Pixel counting Présence/Absence, surface analysis, intensity check	Binarisation and exposure adjustment if necessary	Fast (ms)	Binarisation can affect image stability
Grey scale window	Average grey scale calculation Présence/Absence, surface analysis, intensity check	None		
Binary edge	Edge location on binary image Measurement, presence/absence, positioning	Binarisation and exposure adjustment if necessary		Pixel-accurate at best.Binarisation can affect image stability
Grey scale edge	Edge location on grey scale image. Measurement, presence/absence, positioning	None and position adjustment if necessary	Sub-pixel accuracy possible. Grey scale projection possible by preprocessing	Requires accurate repositioning
Shape extraction	Counting, object detection, measurement and geometrical parameter reading Positioning, repositioning, measurement, sorting, identification.	Binarisation and explosure adjustment if necessary	Many results extracted, versatile. Repositioning by 360° possible	Pixel-accurate at best. Binarisation can affect image stability. Slow (>10..100 ms)
Advanced comparison	Shape recognition, positioning, re-positioning, measurement, sorting, counting, identification	None	Easy to implement	Recognition limited to 30°. Slow (> 10.. 100 ms) if large template and/or search zone
OCR/OCV	Character recognition (OCR) or verification of characters or logos (OCV)	Special attention to image contrast. Maximise image size.	All types of character or logo read by learning a library	Stability of mark to inspect can deteriorate over time. (ex stamped parts)

↑ *Fig. 43* *Image analysis algorithms used in industrial vision systems*

6.9 Optical encoders

↑ Fig. 44 *Example of an optical sensor (Telemecanique)*

Overview of an optical encoder

Construction

A rotary optical encoder is an angular position sensor comprising a light-emitting diode (LED), a photosensitive receiver and a disc, with a series of opaque and transparent zones, physically connected by its shaft to the part of the machine to inspect.

The light emitted by the LEDs hits photodiodes whenever it crosses the transparent zones of the disc, whereupon the photodiodes generate an electrical signal, which is amplified and then converted into a square wave signal before being sent to a processing system. When the disc rotates, the encoder output signal takes the form of successive of square wave signals. (⇨ Fig. 44) illustrates a typical example.

Principles

Rotation of a graduated disc generates identical pulses at the optical sensor output dependent on the movement of the object to inspect.
The resolution, i.e. number of pulses per revolution, corresponds to the number of graduations on the disc or to a multiple of this number.
The higher the number is, the more the number of measurements per revolution more accurately divides the movement or speed of the moving part connected to the encoder.
Typical application: cutting to length.
The resolution is expressed by

$$\frac{\text{distance covered in 1 revolution}}{\text{number of points}}$$

For example, if the product to cut drives a measuring wheel of 200mm in circumference, for a precision of 1mm the encoder resolution must be 200 points. For a precision of 0.5mm the encoder resolution must be 400 points.

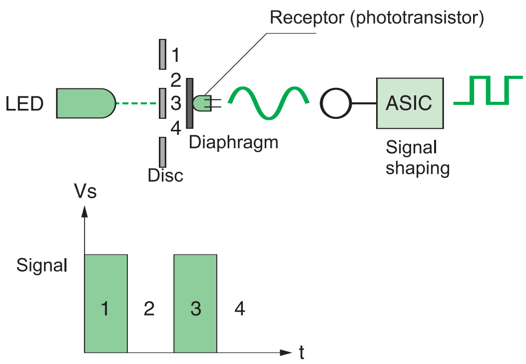
Technical implementation (⇨ Fig. 45)

The emitting section comprises a triple light source with three photodiodes or LEDs (for redundancy), with a lifetime of 10 to 12 years.

An ASIC connected to the optical sensor system of the sine wave signal produces square wave signals after amplification.

The disc is in unbreakable POLYFASS (Mylarmica) for resolutions up to:
- 2048 points for a diameter of 40mm,
- 5000 points for a diameter of 58mm,
- 10000 points for a diameter of 90mm,

or GLASS for higher resolutions and high reading frequencies up to 300KHz.



↑ Fig. 45 *Principle of an incremental encoder*

Optical encoder families

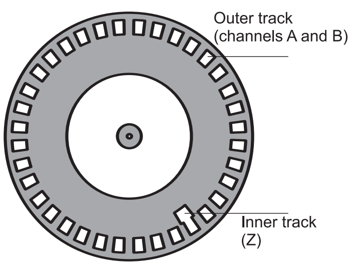
Manufacturers offer a range of products to cover all industrial applications. This comprises two main families:
- incremental encoders which detect the position of a moving part and monitor its movement by incrementing or decrementing the pulses they generate,
- absolute position encoders which give the exact position over one or more revolutions.

These families can include variants such as:
- absolute multi-revolution encoders,
- tachy-encoders which supply information on speed,
- tachometers which process data to supply information on speed.

All these devices use similar techniques. They differ from each other in their disc windowing and the way they encode or process the optical signal.

Incremental encoders (⇨ Fig. 46)

Incremental encoders are designed for applications to position moving parts and monitor their motion by incrementing and decrementing the pulses they generate.



↑ Fig. 46 *View of graduated disc in an incremental encoder*

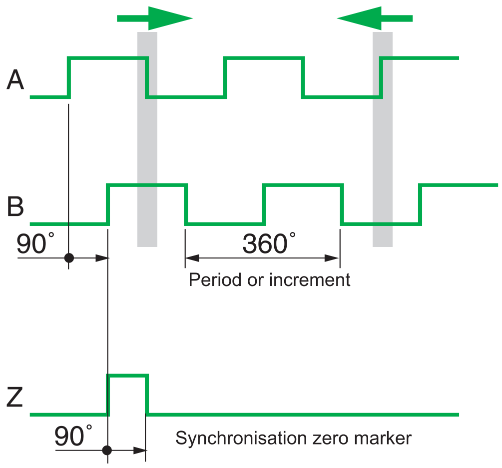


Fig. 47 *Principle for detection of rotation direction and the zero marker*

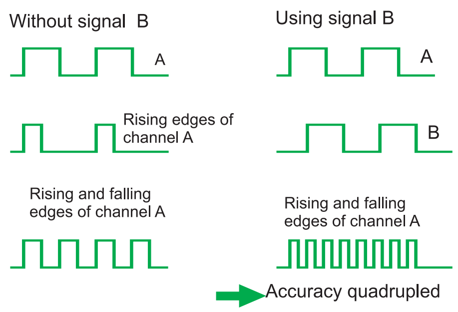


Fig. 48 *Increase in number of points*

- **The disc of an incremental encoder has two types of track:**
  - an outer track (channels A and B) divided into "n" alternately opaque and transparent intervals with equal angles, "n" being the resolution of number of periods. Two out-of-phase photodiodes behind this track generate square wave signals A and B every time the light beam crosses a transparent zone. The 90 electrical degree (1/4 of a period) phase shift of signals A and B defines the direction of rotation *(⇨ Fig.47)*. When rotating in one direction B is equal to 1 when A changes from 0 to 1 when in the opposite direction of rotation B is equal to 0,
  - an inner track (Z) with a single transparent window. The Z signal, called the zero marker, with a period of 90 electrical degrees, is synchronised with signals A and B. It defines a reference position and is used to reinitialise with every revolution.

- **Operation of channels A and B**

Incremental encoders provide three levels of operating accuracy:
  - using the rising edge of channel A only: single operation corresponding to the encoder resolution,
  - using the rising and falling edges of channel A only: operating accuracy is doubled,
  - using the rising and falling edges of channels A and B: operating accuracy is quadrupled *(⇨ Fig.48)*.

- **Elimination of interference**

Any counting system can be disrupted by interference on the line, which is counted along with the pulses generated by the encoder.

To prevent this risk, most incremental encoders generate complementary signals A, B and Z in addition to the regular signals $\bar{A}$, $\bar{B}$ and $\bar{Z}$. If the processing system is designed to support them (numerical controls, for example), these complementary signals can be used to differentiate between encoder pulses and interference pulses *(⇨ Fig.49)*, to prevent them from being counted or to reconstruct the emitted signal *(⇨ Fig.50)*.

□ Absolute encoders

- **Design principle**

Incremental encoders are designed for applications to position moving parts and monitor their motion.

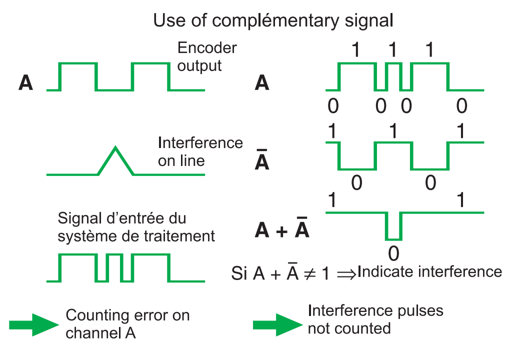


Fig. 49 *Elimination of interference pulses*

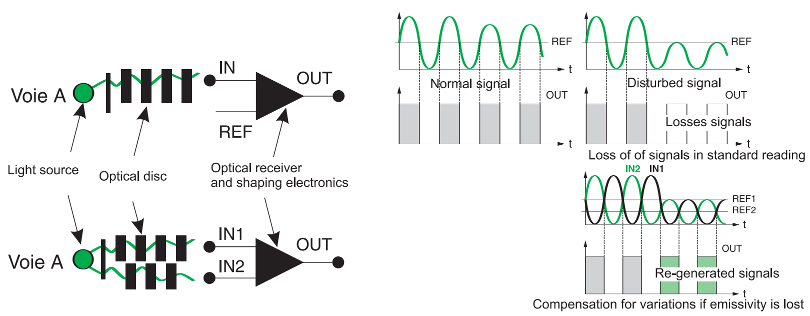


Fig. 50 *Reconstruction of a disrupted signal*

6.9 Optical encoders

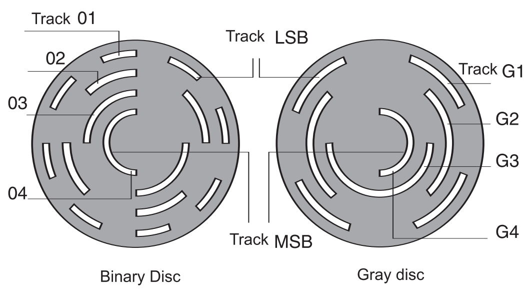


Fig. 51 *Etched discs in an absolute encoder*

Optical reading of disc

Value	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2^0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
2^2	0	0	1	1	1	1	0	0	0	0	1	1	1	1	0	0
2^4	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
2^8	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
2^{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

LSB

Signal generated by sensor

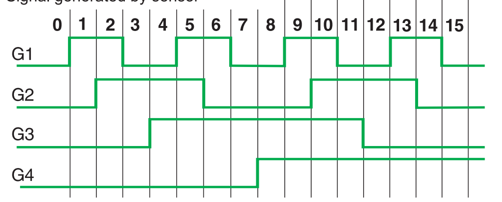


Fig. 52 *Signal produced in Gray code by a rotary absolute encoder*

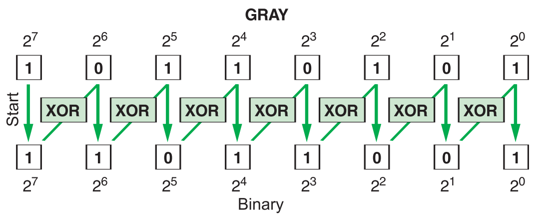


Fig. 53 *Principle of Gray conversion to binary*

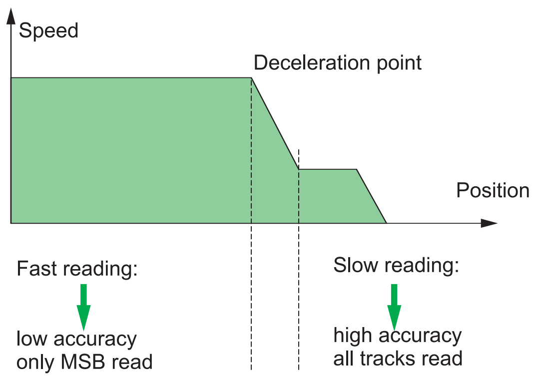


Fig. 54 *Position of a moving part on an axis*

These rotary encoders work in a similar way to incremental sensors, but differ by their disc, which has several concentric tracks divided into equal alternating opaque and transparent segments *(⇨ Fig.51)*. An absolute encoder continuously generates a code which is the image of the actual position of the moving part monitored.

The first inner track is half opaque and half transparent. It is read to ascertain the location of the object to the nearest half-revolution (MSB: Most Significant Bit).

The next tracks, from the centre to the edge of the disc, are divided into alternately opaque and transparent quarters. Reading the second track along with the preceding one (the first) ascertains in which quarter (1/4 or $1/2^2$) of a revolution the object is located. The following tracks successively ascertain in which eighth (1/8 or $1/2^3$), sixteenth (1/16) etc. of a revolution it is located.

The outer track corresponds to the lowest-order bit (LSB: Least Significant Bit).

The number of parallel outputs is the same as the number of bits or tracks on the disc. The image of the movement requires as many diode/phototransistor pairs as bits emitted or tracks on the disc. The combination of all the signals at a given moment gives the position of the moving part.

Absolute encoders emit a digital code, the image of the physical position of the disc, where a single code corresponds to a single position. The code produced by rotary absolute encoders is either natural binary (pure binary) or reflected binary, also called the Gray code *(⇨ Fig.52)*.

- **Advantages of absolute encoders**

Absolute encoders have two major advantages over incremental encoders:

- they are power failure-tolerant because, on start-up or after a power failure, the encoder supplies data on the actual angular position of the moving part that can be used by the processing system immediately. An incremental encoder has to be reset before the signals can actually be used,
- they are impervious to line interference. Interference can alter the code generated by an absolute encoder but it returns automatically to normal as soon as the interference stops. An incremental encoder takes interference data into account, unless complementary signals are used.

- **Using signals**

For each angular position of the shaft, the disc supplies a code, which can be binary or Gray:

- pure binary code. Used to perform 4 arithmetical operations on numbers expressed in this code, so processing systems (PLCs) can use it directly to run calculations.
  It does however have the drawback of having several bits which change their status between two positions and could give rise to ambiguous readings.
  To overcome this, absolute encoders generate an inhibit signal which blocks the outputs at each change of status.
- the Gray code, where only one bit changes status at a time, also avoids this ambiguity. But to be used by a PLC, this code must first be converted to binary *(⇨ Fig.53)*.

- **Using an absolute encoder**

In most applications, the pursuit of greater productivity demands rapid movements at high speed, followed by deceleration to obtain accurate positioning.

To achieve this objective with standard I/O cards, the MSBs must be monitored when the speed is high, so that deceleration is triggered at the nearest half revolution *(⇨ Fig.54)*.

Encoder variants

Many variants have been designed and several different types are available to answer different purposes, such as:
- multi-revolution absolute encoders,
- tacho-encoders and tachometers,
- solid-shaft encoders,
- hollow-shaft encoders,
- through-shaft encoders.

Encoders with processing units

Processing unit input circuits must be compatible with the flow of data from the encoders (⇨ Fig.55).

Processing unit		Encoder			
		Incremental			Absolute
		Signal frequency (kHz)			Parallel connection
		=< 0,2	=< 40	> 40	
PLC	Discrete inputs	X			X
	Fast count Axis cards	X	X		
Digital control		X	X	X	
Microcomputers	Parallel inputs				X
Special cards		X	X	X	X

Fig. 55 *Main types of processing units used in industry*

Speed sensors

The encoders above are able to provide speed data by a process suited to the output signal.

This description would not be complete without mentioning analogue speed sensors. These are mainly used for speed control and in particular in direct current motor speed controllers. To operate frequency converters in a closed loop, modern speed controllers use a virtual speed sensor, which uses the electrical quantities measured in the controller to recalculate the actual speed of the machine.

Tachometer alternator

This speed sensor (⇨ Fig.56) consists of a stator with several windings and a rotor with magnets.

This machine is similar to an alternator.

Rotation induces alternating voltages in both stator windings.

The amplitude and frequency of the signal generated is directly related to the speed of rotation.

The user can either use the voltage (rms or rectified) or the frequency to control or set speed.

Rotation direction can easily be detected by using winding phase displacement.

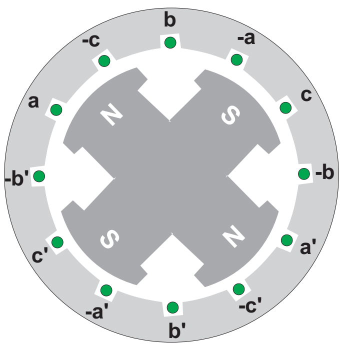


Fig. 56 *Diagram of a tachometer alternator*

Tachometer dynamo

This speed sensor consists of a stator with a fixed winding and a rotor with magnets. The rotor is equipped with a collector and brushes (⇨ Fig.57).

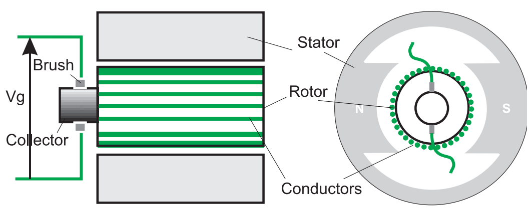


Fig. 57 *Diagram of a tachometer dynamo*

This machine is similar to a direct current generator.

The collector and the type of brush are chosen to limit threshold voltages and voltage discontinuity as the brushes pass. It can operate in a very wide range of speeds.

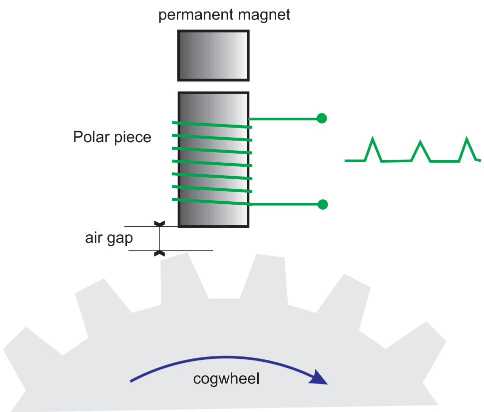
Rotation induces direct voltage where the polarity depends on the rotation direction and has an amplitude proportional to the speed.

The data on amplitude and polarity can be used to control or set speed.

The voltage produced by this type of sensor ranges from 10 to 60 volts/1000rpm and can, for some dynamos, be programmed by the user.

◻ Variable reluctance sensors

Diagram of this type of sensor is given *figure 58*.



↑ *Fig. 58* *Variable reluctance sensors diagram*

The magnetic core of the detecting coil is subjected to the induction flow of a permanent magnet; it faces a disc (polar wheel) or a ferromagnetic rotating part.

The procession of magnetic discontinuities (cogs, slots, holes) borne by the disc or rotating part causes periodic variation in the reluctance of the coil's magnetic circuit, inducing in it a frequency and amplitude voltage proportional to the speed of rotation.

The amplitude of the voltage depends on:
- the distance between the coil and the part,
- rotation speed: in principle, it is proportional to this speed; at low speed the amplitude may be too narrow for detection; below the speed limit, the sensor is unusable.

The measurement range depends on the number of magnetic discontinuities borne by the rotating part. The minimum measurable speed drops as the number of steps rises. Conversely, the maximum measurable speed rises as the number of steps drops, because of the difficulty of processing high frequency signals. Measurements can be taken in a range of 50rpm to 500rpm with a 60-cog pole wheel up to 500rpm to 10,000rpm with a 15-cog pole wheel.

The eddy current tachometer is built in a similar way and can be used facing a non-ferromagnetic metal rotating part.

Instead of the permanent coil system, there is an oscillating circuit. The coil, which is the measurement head, forms the inductance L of the tuning circuit of sine wave oscillator. The L and R characteristics of the coil are modified as a metallic conductor approaches.

When a cogwheel in front of the coil is in rotation, each cog that passes interrupts the oscillator detected, for example, by the alteration in its power supply current.

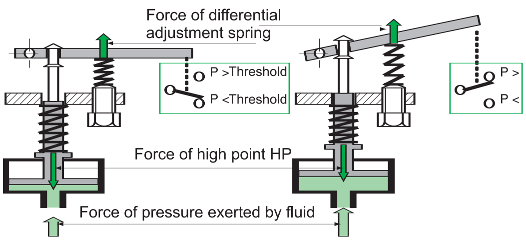
As the signal corresponding to a frequency proportional to the speed and amplitude of rotation is not determined here by the speed of rotation, it is independent of it. This means that this kind of sensor can be used at low speed.

This type of sensor can also be used for measuring over- and under-speed, as in "Inductive application detector for rotation control" by Telemecanique XSAV…. Or XS9….

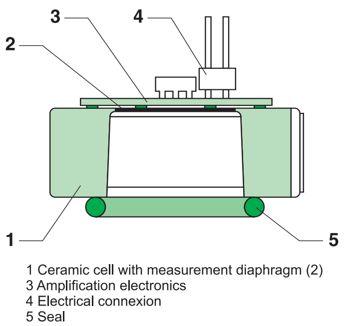
6.10 Pressure switches and vacuum switches

a b c

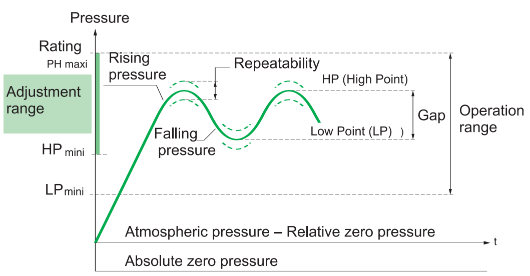
↑ Fig. 59 *Example of pressure detectors (Telemecanique),*
A: XML-B electromechanical pressure switch
B: XML-F electronic pressure switch
C: XML-G pressure transmitter



↑ Fig. 60 *Principle of an electromechanical detector (Telemecanique)*



↑ Fig. 61 *Section through an electromechanical pressure detector*



↑ Fig. 62 *Graphic illustration of commonly-used terms*

What is pressure?

Pressure is the result of a force applied to a surface area. If P is the pressure, F the force and S the surface area, we obtain the relation P=F/S.

The earth is surrounded by a layer of air which has a certain mass and therefore exerts a certain pressure called "Atmospheric pressure" equal to 1 bar at sea level.

Atmospheric pressure is expressed in hpa (hectopascal) or mbar.
1hP = 1mbar.

The international unit of pressure is the Pascal (Pa): 1 Pa = $1N/1m^2$

A more practical unit is the bar: 1bar = 105Pa = 105N/m2 = $10N/cm^2$

Pressure switches, vacuum switches and pressure transmitters are used to monitor, control or measure pressure or a vacuum in hydraulic or pneumatic circuits.

Pressure switches and vacuum switches convert a change in pressure into a discrete electrical signal when the displayed set-points are reached. Their technology can be electromechanical or electronic *(⇨ Fig.59)*.

Pressure transmitters (also called analogue sensors), which use electronic technology, convert pressure into a proportional electrical signal.

Pressure control detectors

Principle

Electromechanical devices use the movement of a diaphragm, piston or bellows to actuate electrical contacts mechanically *(⇨ Fig.60)*.

Telemecanique electronic pressure detectors are equipped with a piezo-resistive ceramic cell *(⇨ Fig.61)*. The distortion caused by the pressure is transmitted to the "thick-film" resistors on the Wheatston bridge screen-printed onto the ceramic diaphragm. The variation in resistance is then processed by the built-in electronics to give a discrete signal or a signal proportional to the pressure (e.g. 4-20mA, 0-10V, etc.).

Pressure control or measurement is the result of the difference between the prevailing pressures on both sides of the element under pressure. Depending on the pressure reference, the following terms are used:

Absolute pressure: measurement relative to a sealed value, usually vacuum.

Relative pressure: measurement in relation to atmospheric pressure.

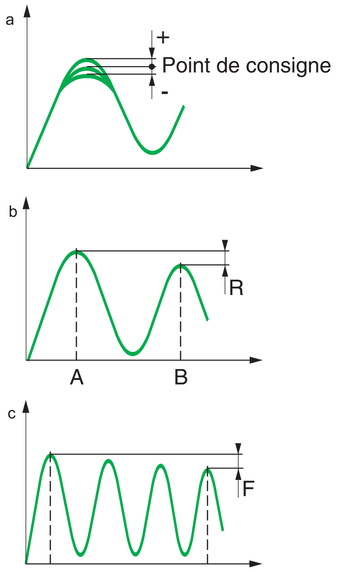
Differential pressure: measurement of the difference between two pressures.

Note that the electrical output contacts can be:
- power, 2-pole or 3-pole contacts, for direct control of single-phase and 3-phase motors (pumps, compressors, etc.),
- standard, to control contactor coils, relays, electrovalves, PLC inputs, etc.

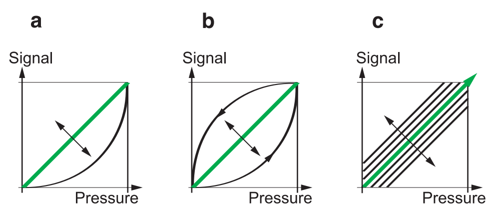
Terminology *(⇨ Fig.62)*

• **General terminology**

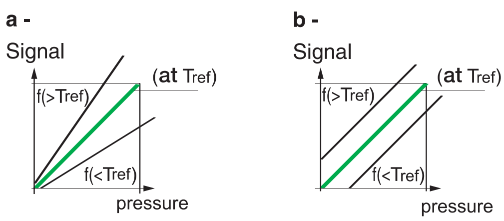
- Operating range
The interval defined by the minimum low point (LP) adjustment value and the maximum high point (HP) adjustment value for pressure switches and vacuum switches. It corresponds to the measurement range for pressure transmitters (also called analogue sensors). Note that the pressures displayed on the device are based on atmospheric pressure.



↑ Fig. 63 *Graphic illustration of electromechanical terms*



↑ Fig. 64 *Graphic illustration:*
a/ linearity
b/ hysteresis
c/ repeatability



↑ Fig. 65 *Graphic illustration of drifts:*
a/ in sensitivity
b/ from the zero point

- **Rating**
  Maximum value of the operating range for pressure switches.
  Minimum value of the operating range for vacuum switches.
- **High set-point (HP)**
  The maximum pressure value, selected and set on the pressure switch or vacuum switch, at which the output will change status when the pressure rises.
- **Low set-point (LP)**
  The minimum pressure value, selected and set on the pressure switch or vacuum switch, at which the output will change status when the pressure drops.
- **Differential**
  The difference between the high (HP) and low (LP) set-points.
- **Fixed differential devices**
  The low point (LP) is directly linked to the high point (HP) by the differential.
- **Adjustable differential devices**
  The differential can be adjusted to set the low point (LP).

• **Electromechanical terminology** *(⇨ Fig. 63)*

- **Accuracy of set-point display** *(⇨ Fig. 63a)*
  The tolerance between the displayed set-point value and the actual value at which the contact is activated. For an accurate set-point (first installation of a product), use the reference of a rating device (manometer, etc.).
- **Repeatability (R)** *(⇨ Fig. 63b)*
  The variation in the operating point between two successive operations.
- **Drift (F)** *(⇨ Fig. 63c)*
  The variation in the operating point over the entire lifetime of the device.

• **Electronic terminology**

- **Between pressure values measured** by the transmitter. It ranges from 0 bars to the pressure corresponding to the transmitter rating.
- **Accuracy** comprises linearity, hysteresis, repeatability and adjustment tolerances. It is expressed as a percentage of the measuring range of the pressure transmitter (% MR).
- **Linearity** is the greatest difference between the actual and rated curves of the transmitter *(⇨ Fig. 64a)*.
- **Hysteresis** is the greatest difference between the rising and falling pressure curves *(⇨ Fig. 64b)*.
- **Repeatability** is the maximum scatter band obtained by varying the pressure in specified conditions *(⇨ Fig. 64c)*.
- **Adjustment tolerances** are the tolerances for zero point and sensitivity adjustment specified by the manufacturer (curve gradient of the transmitter output signal).
- **Temperature drifts**
  The accuracy of pressure detector is always sensitive the operating temperature. It is proportional to it and is expressed as a percentage MR/°C.
- **Zero point and sensitivity drift** *(⇨ Fig. 65a et b)*

- **Permitted maximum pressure in each cycle** (Ps)
  The pressure a detector can withstand in each cycle with no adverse effect on its lifetime. It is equal to at least 1.25 times the device rating.
- **Permitted maximum accidental pressure**
  The maximum pressure, excluding pressure surges, which the detector can withstand occasionally without causing damage to the device.
- **Break pressure**
  The pressure beyond which the detector risks developing a leak or bursting.

All these definitions of pressure are essential for choosing the right sensors for an application, in particular for ensuring they can be used in hydraulic circuits where severe transitory phenomena can occur, such as water hammer.

Other features of presence detectors

This document has described the range of detection technologies.
Each has its own advantages and limitations.
There are other criteria to consider when choosing one. These are laid out in selection tables in the manufacturers' catalogues. Particularly relevant ones, depending on the detectors, include:
- Electrical characteristics,
- Environmental conditions,
- Options and ease of use.

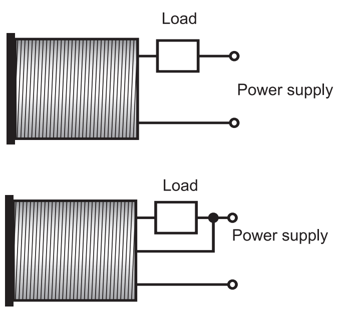


Fig. 66 *2-wire and 3-wire connections*

Choice criteria

The paragraphs below give some examples of criteria which, though not central to the basic function, are advantageous for implementation and operation.

Electrical characteristics

- **Supply voltage, AC or DC, the range of which varies.**
- **2-wire or 3-wire load switching techniques** *(⇨ Fig.66)*.

2-wire technique: the detector is powered in series with the load, so it is subject to a residual current in the open state and a voltage drop in the closed state. The output can be normally open or normally closed (NO/NC). The maximum intensity of the switched current at the AC or DC output can be higher or lower, with or without short-circuit protection.

3-wire technique: the detector has two wires for power supply and one for transmitting the output signal (or more for products with more than one output). The output can be transistorised PNP or NPN.

Both techniques are used by many manufacturers, but it is important to pay special attention to residual currents and voltage drops at the detector terminals: low values ensure greater compatibility with all types of load.

Environmental conditions

- **Electrical:**
- immunity to line interference,
- immunity to radio frequencies,
- immunity to electrical shocks,
- immunity to electrostatic discharge.

- **Thermal**

Usually from -25 to +70° but can be as much as -40 to +120°C.

- **Moisture/dust**

Degree of protection of the enclosure (seal): e.g. IP 68 for cutting oil in machine tooling.

□ **Options/ease of use**
- geometrical shape (cylinder or parallelepiped),
- metal/plastic casing,
- flush-mountable or not in metal frame,
- fastening devices,
- connection by cable or connector,
- self-teaching functions.

6.11 Conclusion

What does the future hold?

The performance of electronic sensors is bound to improve with developments in electronics, with regard to both the electrical characteristics of the components and their size.

With the boom in telecommunications (Internet, mobile phones), the operating frequencies of electronics have increased from a few hundred MHz to the GHz range. This will make it easier to measure wave propagation speed and do away with local physical phenomena. Moreover, technologies such as Bluetooth and Wi-Fi have opened the way to wireless sensor with radio links at frequencies of around 2.4GHz.

Digital processing of the signal is another advantage of modern electronics: the falling cost of microcontrollers means that simple sensors can be equipped with advanced functions (automatic adjustment to the environment with detection of moisture, smoke or nearby metallic objects, intelligent sensors with self-testing capacity).

This technical progress will make electronic sensors better suited to their initial requirements and more easily adaptable to process changes, without any significant alteration in price. But such innovation demands a heavy outlay that only the big sensor manufacturers are currently able to invest.

The importance of sensors

All designers and users of automatic systems, from the ordinary garage door to the production line, know that smooth running of an automated system depends on the choice of detectors which contribute to:
- the safety of property and people,
- the reliability of industrial processes,
- optimised control of industrial equipment,
- control of operating costs.

These detectors do however have requirements with regard to their implementation and use, which are inherent to their technologies as described in this guide.

This description should help give you a better understanding of the operating limits and requisite setting of all these sensors.

The right choice

It is essential to consult the manufacturers' catalogues to be sure of choosing the right detector.
It should be pointed out that some catalogues provide practical advice based on the experience of experts that only the big manufacturers, such as Schneider Electric, can rely on.

6.12 Technology selection guide

Object detected	Détection distance	Environment	Technology	Transfert and formating	Advantages
Non-deformable parts	By contact 0 to 400mm (by levier)	All types	Mechanical	Electromechanical contact	Intuitive, high-power dry contact Positive contact
Metal parts	--> 60mm		Inductive	Discrete or analogue static	Robust, sealed Not easily disrupted
Magnets	--> 100mm		Magnetic	Reed contact	Detects through all non-ferrous metals
All parts	--> 300m	No dust No fluids	Photoelectric	Discrete or analogue static	Wide range Detects all types of object
	--> 60 mm	Dry	Capacitive		Detects through all non-conductive substances
	--> 15m	No loud noises (shock waves) No steam	Ultrasonic		Robust Detects transparent substances and powders
Electronic tag, books, parts, parcels…	A few metres	Sensitive to metal	Radio-frequencies	Digital data	Read-write tag, traceability
	--> 1m	Requires specific lighting	Optical	Recognition algorithm Digital or analogue data	Detects presence, shape and colours

↑ *Fig. 67* *Sensors selection table*

6

7 chapter

Personnal and machines safety

Reminder of European legislation regarding safety for people and environment.
Reminder of IEC regulation for machines and products.
Examples of application, products and safety networks

7. Personnal and machines safety

Summary

After presenting and defining the rules which govern safety, we shall focus on the machinery and the product technologies to meet customer requirements and comply with constraints.

7.1 Introduction

Safety scope and definition

Legislation requires us to take preventive action to preserve and protect the quality of the environment and the human health. To achieve these objectives, there are European Directives which must be applied by plant operators and by manufacturers of equipment and machines.

It also assigns the responsibility for possible injury.

- **Notwithstanding the constraints, machine safety increases productivity by:**
  - preventing industrial accidents,
  - ensuring the health and safety of all personnel by suitable safety measures that take into account the machine's application and the local environment.
- **Cutting direct and indirect costs by:**
  - reducing physical harm,
  - reducing insurance premiums,
  - reducing production loss and delay penalties,
  - limiting harm and cost of maintenance.
- **Safe operation involves two principles: safety and reliability of operation** *(⇨ Fig. 1)*
  - Safety is the ability of a device to keep the risk incurred by persons within acceptable limits.
  - Reliability of operation is the ability of a system or device to perform its function at any moment in time and for a specified duration.
- **Safety must be taken into account from the design phase and kept in place throughout all stages of a machine's life cycle: transport, installation, adjustment, maintenance, dismantling.**
- **Machines and plants are sources of potential risk and the Machinery Directive requires a risk assessment for every machine to ensure that any risk is less than the tolerable one.**
- **Risk is defined in accordance with EN 1050 as follows** *(⇨ Fig. 2)***: seriousness multiplied by the probability of occurrence.**

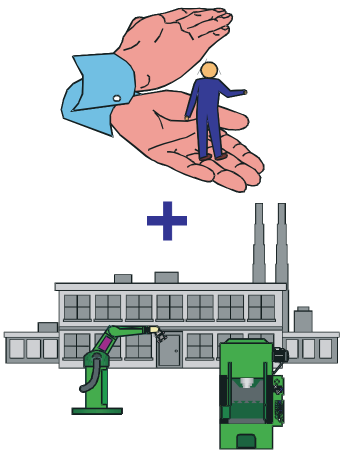
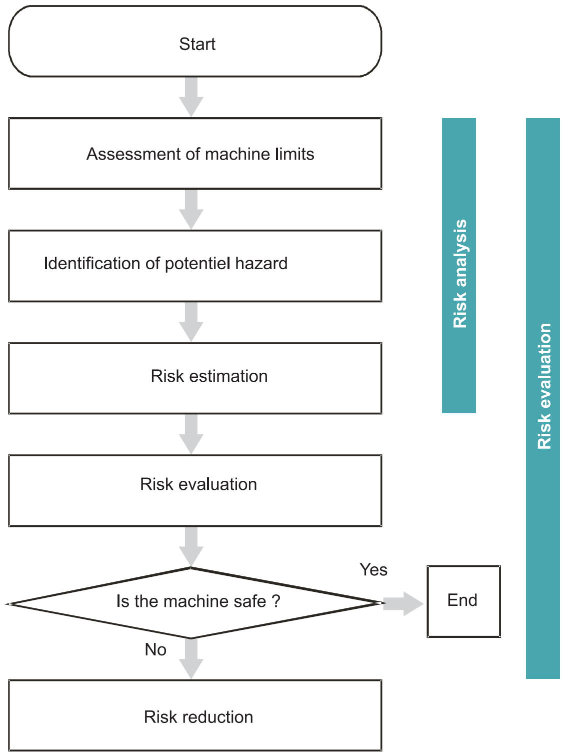


Fig. 1 Safety and reliability of a system

Risk related to potential hazard	=	**Severity** Of the possible harm for the considered hazard	x	**Probability of occurrence** Of the harm - frequency and duration of exposure - possibility of avoiding or limiting the harm - Probability of the occurrence of an event which may cause harm

Fig. 2 Definition of risk

• **The European Standard EN1050 (Principles of Risk assessment)** defines an iterative process to achieve safety in machinery. It states that the risk for each individual hazard can be determined in four stages. This method provides the basis for the requisite risk reduction using the categories described in EN954. The diagram *(⇨ Fig. 3)* shows this iterative process which will be detailed further on.



↑ Fig. 3 *Machine safety process*

7.2 Industrial accidents

An industrial accident occurs through work or in the workplace and causes minor to serious injury to a person operating or working on a machine (fitter, operator, maintenance worker, etc.).

Causes of accidents in the workplace

• **Human-related factors (designers, users)**
- Poor grasp of machine design.
- Over-familiarity with danger through habit and failure to take dangerous situations seriously.
- Underestimation of hazards, causing people to ignore safety guards.
- Relaxed attention to supervisory tasks (fatigue).
- Failure to comply with procedures.
- Increased stress (noise, work rates, etc.).
- Uncertainty of employment which can lead to inadequate training.
- Inadequate or bad maintenance, generating unsuspected hazards.

- **Machine-related factors**
  - Inadequate guards.
  - Sophisticated type of control and supervisory systems.
  - Inherent machine hazards (reciprocal motion of a machine, sudden starting or stopping).
  - Machines not suited to the application or environment (sound alarms deadened by the noise of surrounding machinery).
- **Plant-related factors**
  - Movement of personnel (automated production line).
  - Machinery from different sources and using different technologies.
  - Flow of materials or products between machines.

The consequences

- Varying degrees of physical danger to the user.
- Stoppage of the machine involved.
- Stoppage of similar machine installations for inspection, for example by the Health and Safety Inspectorate.
- Alterations to make machines comply with regulations where necessary.
- Change of personnel and training new personnel for the job.
- Damage to the company brand image.

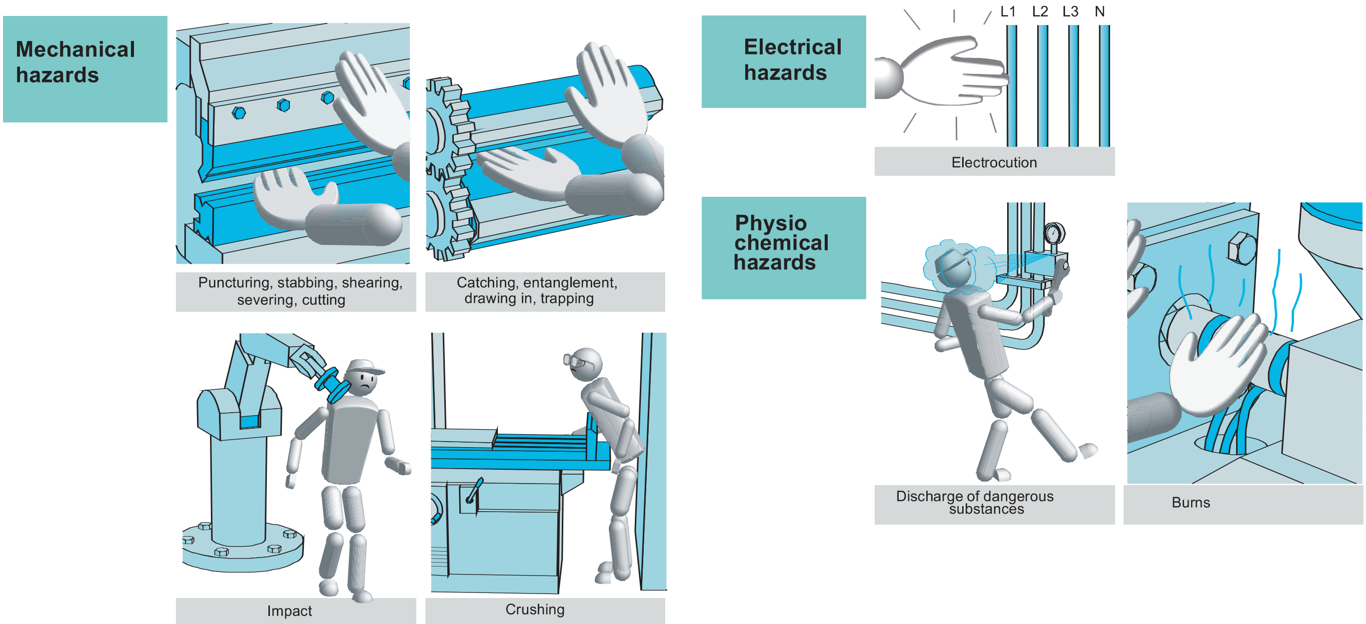
Conclusion

Damages for physical injuries are equivalent to about 20 billion euros paid out each year in the European Union.

Decisive action is required to reduce the number of accidents in the workplace. The first essentials are adequate company policies and efficient organisation. Reducing the number of industrial accidents and injuries depends on the safety of machines and equipment.

Types of hazards

The potential hazards of a machine can be classified in three main groups, as illustrated (⇨ *Fig. 4*).



↑ *Fig. 4* *The main hazards in a machine*

7.3 European legislation

The main purpose of Machinery Directive 98/37/EC is to compel manufacturers to guarantee a minimum safety level for machinery and equipment sold within the EU.

To allow free circulation of machinery within the European Union, the EC marking must be applied to the machine and an EC declaration of compliance issued to the purchaser.

This directive came into effect in January 1995 and has been enforced since January 1997 for all machines requiring compliance.

The user has obligations defined by the health and safety directives 89/655/EEC which are based on all standards.

■ Standards

□ Introduction

The harmonized European safety standards establish technical specifications which comply with the minimum safety requirements defined in the related directives.

Compliance with all applicable harmonized European standards ensures compliance with the related directive.

The main purpose is to guarantee a minimum safety level for machinery and equipment sold within the EU market and allow the free circulation of machinery within the European Union.

□ Three groups of European standards

• A standards
Basic safety standards which specify the basic concepts, design principles and general aspects valid for all types of machines.
EN ISO 12100 (former EN292).

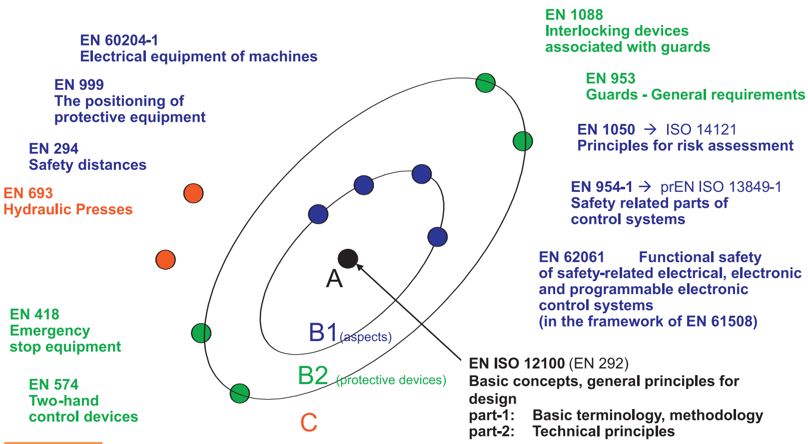
• B standards
Safety standards applying to specific aspects of safety or a particular device valid for a wide range of machines.

• B1 standards
Standards applying to specific safety aspects of electrical equipment of machines: EN 60204-1 (e.g.: Noise, safety distances, control systems, etc).

• B2 standards
Standards applying to emergency stop safety devices, including two-handed control stations (EN 574), safety guards (EN 418), etc.

• C standards
Safety standards stating detailed safety prescriptions applicable to a specific machine or group of machines (e.g.: EN 692 for hydraulic presses or robots).

The *figure 5* shows the non-exhaustive scope of the standards.



↑ *Fig. 5* Safety standards

7.3 European legislation

The *figure 6* lists the main European safety standards.

Standards	Type	Subject
EN ISO 12100-1, -2	A	Machinery safety - basic concepts, principles for design Part 1 Terminology Part 2 principles
EN 574	B	Two-handed control devices - design principles
EN 418	B	Emergency stop equipment - design principles
EN 954-1	B	Safety-related parts of control systems - design principles
EN 349	B	Minimum gaps to avoid crushing of human body parts
EN 294	B	Safety distances to prevent danger zones being reached by the upper limbs
EN 811	B	Safety distances to prevent danger zones being reached by the lower limbs
EN 1050	B	Machinery safety - Principles for risk assessment
EN 60204-1	B	Machinery safety - Electrical equipment of machines Part 1: general requirements
EN 999	B	Positioning of protective equipment in respect of approach speeds of body parts
EN 1088	B	Locking devices associated with guards - design and selection principles
EN 61496	B	Electro-sensitive protective equipment Part 1 general requirement Part 2 particular requirement for light barrier
EN 1037	B	Prevention of unexpected start-up
EN 60947-5-1	B	Switching for LV electromechanical control circuits
N 842	B	Visual danger signals - General requirements, design and testing
EN 201	C	Safety requirements for injection moulding machines for plastics and rubber
EN 692	C	Safety requirements for mechanical presses
EN 693	C	Safety requirements for hydraulic presses
EN 289	C	Safety requirements for moulding machines by compression and by transfer
EN 422	C	Safety requirements for design and construction of moulding machines by metal blowing
EN 775	C	Manipulating industrial robots - safety requirements
EN 415-4	C	Packaging machines Part 4: palletisers - safety requirements
EN 619	C	Safety and EMC requirements for equipment for mechanical handling of unit loads
EN 620	C	Safety and EMC requirements for fixed belt conveyors for bulk material
EN 746-3	C	Industrial thermo processing equipment Part 2: Safety requirements for the generation and use of atmosphere gases
EN 1454	C	Safety requirements for portable disc cutting machines with thermal motor

↑ *Fig. 6* *Some machinery safety requirements*

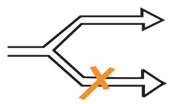
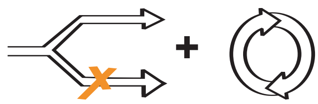
EN 954-1 Safety related parts of Control systems

Standard EN 954-1 “Safety related parts of control systems” came into force in March 1997. This type B standard stipulates the safety-related requirements for control systems. It specifies their categories and describes the characteristics of their safety functions.

In type C standards, these parts of the system are called categories.

In this standard, performance of safety-related parts with regard to occurrence of faults is classified in five categories. (B, 1, 2, 3, 4). An upgrade (prEN ISO 13849-1) is in the planning stage.

- **Fault categories** *(⇨ Fig. 7)*

	System behaviour	Principles to achieve safety
B	A fault can lead to loss of the safety function.	Component selection
1	As for category B but higher reliability required of the safety function.	Component selection
2	A fault can lead to loss of the safety function between inspection periods. Loss of the safety function is detected by the control (at each test).	Self-monitoring 
3	For a single fault, the safety function is always ensured. Only a few faults will be detected. Accumulation of undetected faults can lead to loss of the safety function.	Redundancy 
4	When faults arise, the safety function is always ensured. Faults will be detected in time to prevent loss of the safety function(s).	Redundancy + self-monitoring 

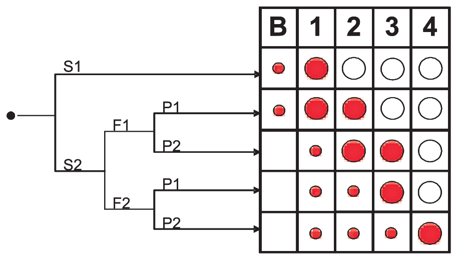
↑ Fig. 7 *The five fault categories*

- **Risk graph**

According to the definition of risk, standard EN 954-1 defines a practical method for selecting a category of control system and covers:
- **S** : Seriousness of injury.
- **F** : Frequency and/or exposure to a hazard.
- **P** : Possibility of preventing accident.

Resulting categories define resistance to faults and the behaviour of control systems in the event of a fault *(⇨ Fig. 8)*.

S	Accident result
S1	Slight injury
S2	Serious or permanent injury to or death of a person
F	Presence in the danger zone
F1	Rare to fairly frequent
F2	Frequent to permanent
P	Possibility of preventing accident
P1	Possible in certain circumstances
P2	Virtually impossible

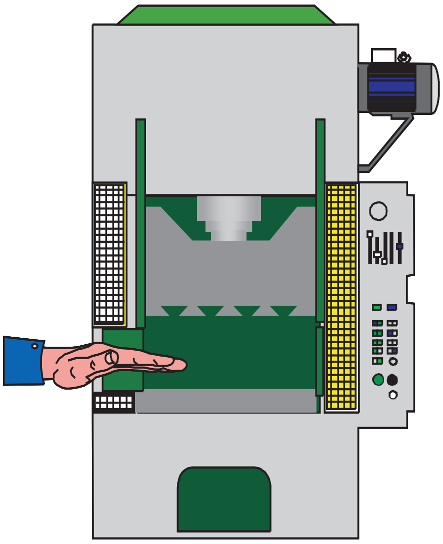


: Adapted categories

: Excessive measures

: Possible categories requiring extra measures (preventive maintenance)

↑ Fig. 8 *Choice table*



↑ *Fig. 9* *Assessment of risk in a hydraulic press*

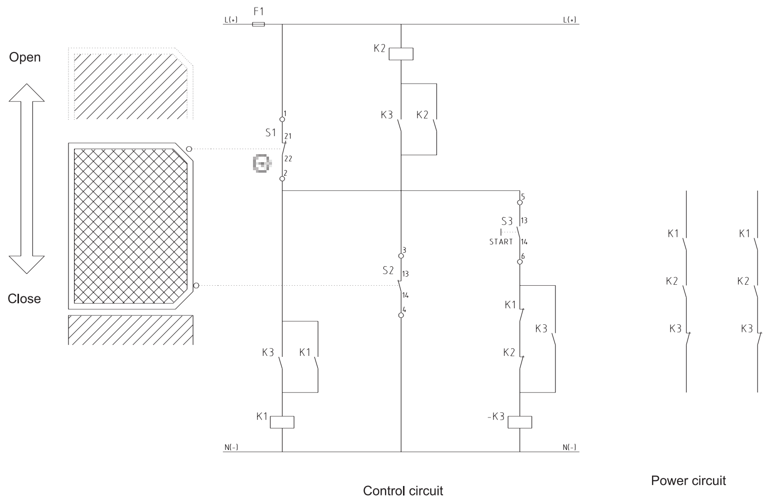
To illustrate those concepts we present an assessment of risk in a hydraulic press with manual materiel feeding (⇨ *Fig. 9)*.

- Seriousness of injury: **S2** since serious permanent injury could occur.
- Frequency and exposure time: **F2** since the operator is permanently present.
- Possibility of avoiding the hazard: **P2**since it is virtually impossible to avoid.

The result on the risk graph is category 4.

To supplement this example we will select the guard locking devices (EN 1088 standard).

In this example (⇨ *Fig. 10)* the diagram conforms to category 4. When faults occur, they are detected in time to prevent loss of the safety function.



↑ *Fig. 10* *Guard locking application*

◻ Functional safety and safety integrity level (SIL)

New technologies help to make savings which can be achieved by implementing an intelligent safety strategy. This standard takes into account the use of these new technologies in safety products and solutions and provides guidelines to calculate the probability of failures.

More and more devices and products dedicated to machinery safety now incorporate complex programmable electronic systems.

The complexity of these systems makes it difficult in practice to determine the behaviour of such safety devices in the event of a fault. This is why standard IEC/EN 61508 entitled “Functional safety of electrical, electronic and programmable electronic systems” provides a new approach by considering the reliability of safety functions.

It is a basic safety standard for industry and the process sectors.

IEC/EN 62061 stipulates the requirements and makes recommendations for the design, integration and validation of safety-related electrical, electronic and programmable electronic control systems (SRECS) for machinery within the framework of IEC/EN 61508.

EN 62061 is harmonised with the European Machinery Directive.

The Safety Integrity Level (SIL) is the new measure defined in IEC 61508 regarding the probability of failure in a safety function or system.

7.3 European legislation

• Definition of Functional Safety according to IEC/EN 61508
Functional safety is a part of the overall safety of equipment under control (EUC).

It depends on the correct functioning of safety-related systems which include electrical, electronic and programmable electronic parts and other external risk reduction devices.

• Safety Integrity Level (SIL)
There are two ways to define the SIL, depending on whether the safety system is run in low demand mode or in continuous or high demand mode *(⇨ Fig. 11)*. The scale of functional safety is on 4 levels, from SIL1 to SIL4, the latter having the highest level of safety integrity.

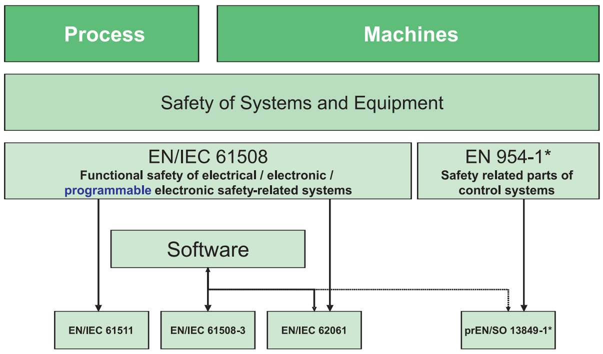


Fig. 11 *Risk reduction*

Safety is achieved by risk reduction (IEC/EN 61508) *(⇨ Fig. 12)*. The residual risk is the risk remaining after protective measures have been taken, Electrical, Electronic and Programmable Electronic safety-related systems (E/E/EP) contribute to risk reduction.

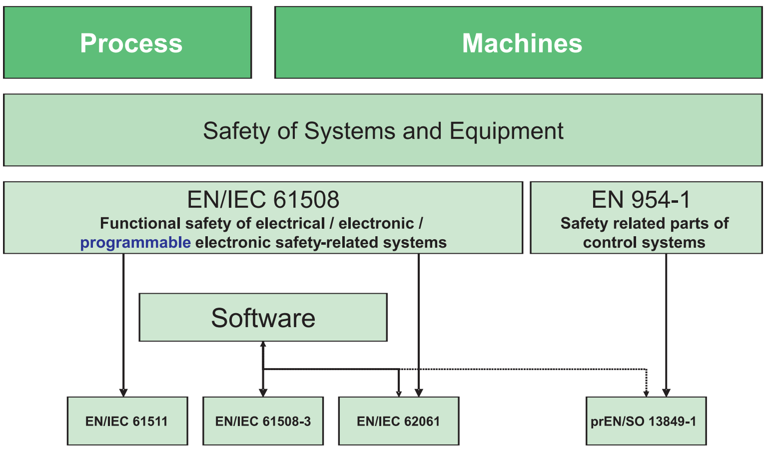


Fig. 12 *Position of standard EN 61508 and related standards*

Safety integrity levels estimate the probability of failure. For machinery, the probability of dangerous failure per hour in a control system is denoted in IEC/EN 62061 as the PFHd *(⇨ Fig. 13)*.

Safety integrity level **SIL**	High demand or continuous mode of operation (Probability of a dangerous failure per hour) **PFHd**	Low demand mode of operation (Average probability of failure to perform its design function on demand) **PFDaverage**
4	> = 10^{-9} to 10^{-8}	> = 10^{-5} to 10^{-4}
3	> = 10^{-8} to 10^{-7}	> = 10^{-4} to 10^{-3}
2	> = 10^{-7} to 10^{-6}	> = 10^{-3} to 10^{-2}
1	> = 10^{-6} to 10^{-5}	> = 10^{-2} to 10^{-1}

↑ *Fig. 13* *SIL integrity level*

IEC 61508 considers two modes of operation:

- high demand or continuous mode – where the frequency of demand made on a safety-related system is greater than one per year or greater than twice the proof test frequency,
- low demand mode – where the frequency of demand made on a safety-related system is no greater than one per year and no greater than twice the proof test frequency.

IEC/EN 62061 does not consider the low demand mode to be relevant for machinery safety.

SIL 4 is not considered in IEC/EN 62061, as it is not relevant to the risk reduction requirements normally associated with machinery.

Safety integrity levels are calculated by the probability of failure l which is expressed as follows: $\lambda = \lambda_s + \lambda_{dd} + \lambda_{du}$

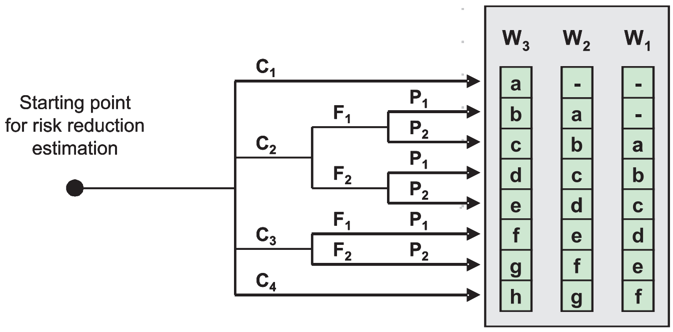
where:
λ_s rate of safe failures
λ_{dd} rate of detected dangerous failures
λ_{du} rate of undetected dangerous failures

In practice, dangerous failures are detected by specific functions.

The calculation of the PFH_d, for a system or subsystem depends on several parameters:

- the dangerous failure rate (λ_d) of the subsystem elements,
- the fault tolerance (i.e. redundancy) of the system,
- the diagnostic test interval (T2),
- the proof test interval (T1) or lifetime whichever is smaller,
- susceptibility to common failures (λ).

The graph *(⇨ Fig. 14)* illustrates IEC/EN 61508-5 and the graph *(⇨ Fig. 15)* the risk parameters.



a, b, c, d, e, f, g, h represent the necessary minimum risk reduction. The link between the necessary minimum risk reduction and the safety integrity level is shown in the table.

C = Consequence risk parameter

F = Frequency and exposure time risk parameter

P = Probability of avoiding hazard risk parameter

W = Probability of unwanted occurrence

a,b,c ... h = Estimates of the required risk reduction for the SRSs

Necessary minimum risk reduction	Safety integrity level
-	No safety requirements
a	No special safety requirements
b, c	1
d	2
e, f	3
g	4
h	An E/E/EP SRS is not sufficient

↑ *Fig. 14* *Risk graph*

Risk parameter		Classification	Comments
Consequences (C)	C1	Minor injury	1 The classification system has been developed to deal with injury and death to people. Other classification schemes would need to be developed for environmental or material damage
	C2	Serious permanent injury to one or more persons, death to one person	
	C3	Death to several people	2 For the interpretation of C_1, C_2, C_3 and C_4, the consequences of the accident and normal healing shall be taken into account
	C4	Very many people killed	
Frequency of, and exposure time in, the hazardous zone (F)	F1	Rare to more often exposure in the hazardous zone	3 See comment 1 above
	F2	Frequent to permanent exposure in the hazardous zone	
Possibility of avoiding the hazardous event (P)	P1	Possible under certain conditions	4 This parameter takes into account: • operation of a process (supervised (i.e. operated by skilled or unskilled persons) or unsupervised), • rate of development of the hazardous event (for example suddenly, quickly or slowly), • ease of recognition of danger (for example seen immediately, detected by technical measures or detected without technical measures), • avoidance of hazardous event (for example escape routes possible not possible or possible under certain conditions), • actual safety experience (such experience may exist with an identical EUC or a similar EUC or may not exist).
	P2	Almost impossible	
Probability of the unwanted occurence (W)	W1	A very slight probability that the unwanted occurences will come to pass and only a few unwanted occurrences are likely	5 The purpose of the W factor is to estimate the frequency of the unwanted occurrence taking place without the addition of any safety-related systems (E/E/PE or other technology) but including any external risk reduction facilities
	W2	A slight probability that the unwanted ocurences will come to pass and few unwanted occurrences are likely	6 If little or no experience exists of the EUC, or the EUC control system, or of a similar EUC and EUC control system, the estimation of the W factor may be made by calculation. In such an event a worst case prediction shall be made
	W3	A relatively high probability that the unwanted occurrences will come to pass and frequent unwanted occurrences are likely	

Fig. 15 *Risk parameters (example in IEC/EN 61508)*

The *figure 16* shows the process of risk assessment for a machine.

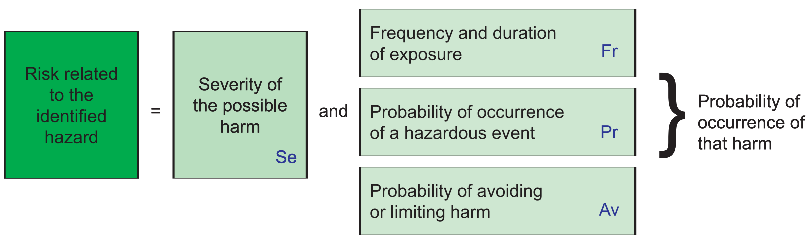


Fig. 16 *Assessment process*

7

7.4 Concept of safe operation

Safe operation is the practice of the principles described above and is a global concept which covers several aspects:

- machine design and production integrating risk assessment,
- installation and implementation with validation,
- operation including training,
- maintenance with periodic proof tests.

It consists of 5 stages.

■ Stage 1: risk assessment (standards EN ISO 1200-1, EN1050)

The objective is to eliminate or reduce risk and select an adequate safety solution to ensure personal protection.

The iterative process described in the *figure 3* is used to facilitate risk assessment. Prior to assessment, the potential hazards must be identified. FMECA (Failure Modes, Effect and Criticality Analysis) provides a stringent exhaustive analysis.

■ Stage 2: decision on risk reduction measures (standard EN ISO 12100-1)

Avoiding or reducing as many potential hazards as possible at the design stage (EN ISO 1200-2).

Use of safeguards to protect persons from hazards which cannot reasonably be eliminated or from risks which cannot be adequately reduced by inherently safe design measures (EN 418, EN 953 guards, EN 574 two-handed controls, EN 1088 locking devices on guards).

Information on using the machine.

■ Stage 3: definition of requirements and categories (standard EN 954-1)

Based on the prior risk assessment, a practical method for selecting a category of a control system is defined by standard EN 954-1.

■ Stage 4: design of safety-related control parts (standard EN 954-1)

It is at this stage that the designer selects the products for the machinery. At the end of this section are some examples based on safety products by Schneider Electric.

■ Stage 5: validation of safety level achieved and categories (standard EN 954-1)

Validation should show that the safety-related parts of the control system meet the defined requirements.

Validation must be done by analysis and testing (standard EN 954-1 clause 9).

An example for such a test is fault simulation on the circuits with the components actually installed, especially whenever there is any doubt about behaviour after the theoretical test.

7.5 Certification and EC marking

There are 6 steps in the process of machinery certification and EC marking:

1. application of all relevant directives and standards,
2. compliance with essential health and safety requirements,
3. technical documentation,
4. compliance inspection,
5. declaration of compliance,
6. EC marking.

Machinery Directive

The Machinery Directive is an early example of the “New Approach” to technical harmonisation and standardisation of products and is based on:

- mandatory essential health and safety requirements (which must be met before machinery is placed on the market),
- voluntary harmonised standards drawn up by the European Committees for Standardisation (CEN) and Electro-technical Standardisation (Cenelec),
- compliance assessment procedures tailored to the type and level of risks associated with machinery,
- EC marking, affixed by manufacturers to signify compliance with all relevant directives. Machinery bearing this marking may circulate freely within the European Community.

The directive has greatly simplified the national laws that preceded it and thus removed many barriers to trade within the EU. It has also reduced the social cost of accidents. New Approach directives apply only to products which are marketed or commissioned for the first time.

Essential health and safety requirements

The EU Machinery Directive in appendix I cover the essential health and safety requirements for marketing and commissioning of machines and safety components in Europe.

- If the requirements of the directive are fulfilled, no member state of the EU may prevent the product from circulating.
- If the requirements are not fulfilled, marketing may be forbidden and a call back may be demanded.

This affects the manufacturers or their authorised representatives in the EU as well as the importers and retailers who market or commission machines.

Harmonised standards

The easiest way to prove compliance with the Directive is to comply with Harmonised European Standards.

When, for products in appendix 4, there are no Harmonised Standards, existing standards are not relevant for covering all essential safety requirements or when a manufacturer considers them inappropriate for his product, he must seek approval by an independent third party, a (Notified Body).

These are appointed by the Member States after having proven that they have the relevant expertise to provide such an opinion. (TÜV, BGIA, INRS, HSE, etc.)

Although a Notified Body has various responsibilities under the Directive, the manufacturer (or authorised representative) always remains responsible for the compliance of the product.

Conformity assessment

According to article 8 of the Machinery Directive the manufacturer (or his authorised representative established in the Community) must draw up an EC declaration of conformity for all machinery (or safety components). This must be done to certify that machinery and safety components comply with the Directive.

Before a product goes on the market, the manufacturer, or his authorised representative, must draw up and submit a file to the Notified Body (⇨ *Fig. 14*).

EC marking

The manufacturer or his authorised representative established in the Community must affix EC marking to the machine. This marking has been mandatory since 1 January 1995 and can only be applied if the machine complies with all relevant EU Directives such as:

- machinery Directive 98/37/EC,
- electromagnetic Compatibility Directive (EMC) 89/336/EEC,
- low Voltage Directive 73/23/EEC.

There are other directives e.g. for personal protective equipment, lifts, medical devices which may also be relevant.

The EC marking on a machine is like a passport for the European countries, because such machines can be sold in all EU member states without considering their respective national rules.

The EC marking process is described (⇨ *Fig. 17*) below.

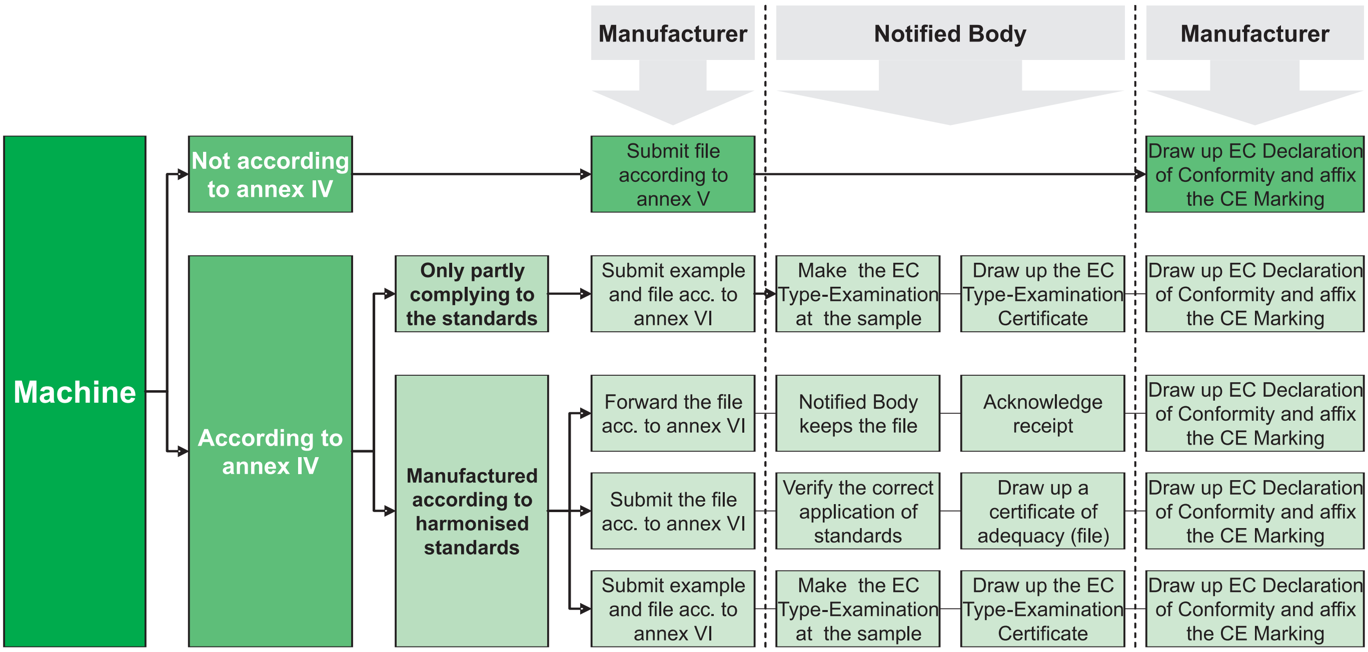


Fig. 17 *EC marking process*

7.6 Safety principles

Fig. 18 Some of tested devices

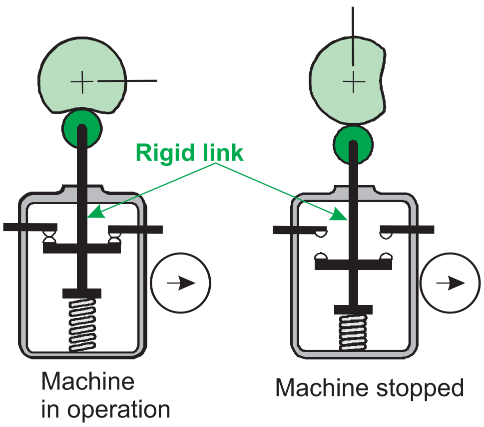


Fig. 19 Principle of positive actuation

Fig. 20 Symbol for direct opening contact

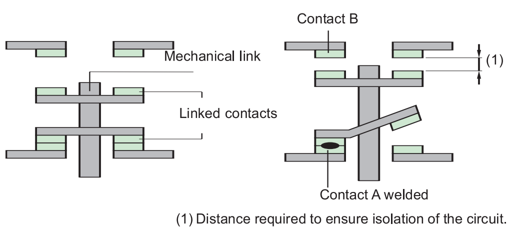


Fig. 21 Mechanically linked contacts

Guidelines for building a safety control

Standard EN 954-1 defines the safety requirements for safety related parts of a control system.
It defines 5 categories and describes the specific properties of their safety functions, which are:

- basic safety principles,
- tried and tested safety principles,
- tried and tested components.

To illustrate the tried and tested safety principle, here is an extract from the list in EN954-2:

- mechanically linked contacts,
- cables with only one conductor to prevent short circuits,
- gaps to prevent short circuits,
- no undefined conditions: build deterministic control systems,
- positive mode actuation,
- over-sizing,
- simplified control system,
- components with defined failure modes,
- timers without power supply using energy from a capacitor,
- redundancy (double critical components).

Below are examples of devices for electrical systems (⇨ Fig.18):

- switches with positive mode actuation,
- emergency stop equipment (according to EN 60947-5-5),
- power switch,
- main contactor (only when the additional requirements of the norm are fulfilled),
- auxiliary contactors with mechanically linked contacts (only when the additional requirements of the norm are fulfilled),
- electromagnetic valve.

Below are some explanations of technical principles which are usually the province of experts.

Positive actuation

This is direct opening (IEC 60947-5-1) whereby contacts are separated as the result of switch movement by a non-resilient (rigid) device.

The *figure 19* shows how opening of N/C contacts is ensured by the rigid link and is independent of the springs.

Every element of direct opening contact must be indelibly and legibly marketed on the outside with the symbol the *figure 20*.

Mechanically linked contacts

Relays, contactors and switches usually consist of a set of contacts. For safety applications, the position of every safety related contact in the circuit must be known in all possible switching conditions.

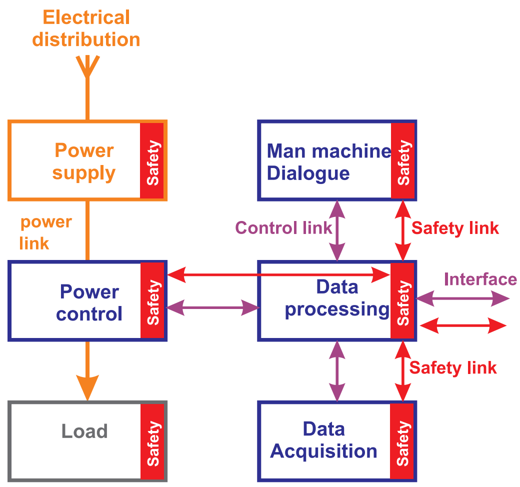
This makes it possible to determine the behaviour of the circuit under fault conditions. Mechanically linked contacts are an answer to this requirement (⇨ Fig.21).

Definition of mechanically linked contacts (IEC/ EN 60947-5-1):

“[…] a combination of n N/C contact element(s) and b N/O contact element(s) designed so that they cannot be closed simultaneously.

When an N/C contact is maintained in the closed position a minimum gap of 0.5mm between all N/O contacts is ensured when the coil is activated. When an N/C contact is maintained in the closed position a minimum gap of 0.5mm between all N/O contacts is ensured when the coil is de-energised.

7.7 Safety functions



↑ *Fig. 22* *Adaptation of existing control functions*

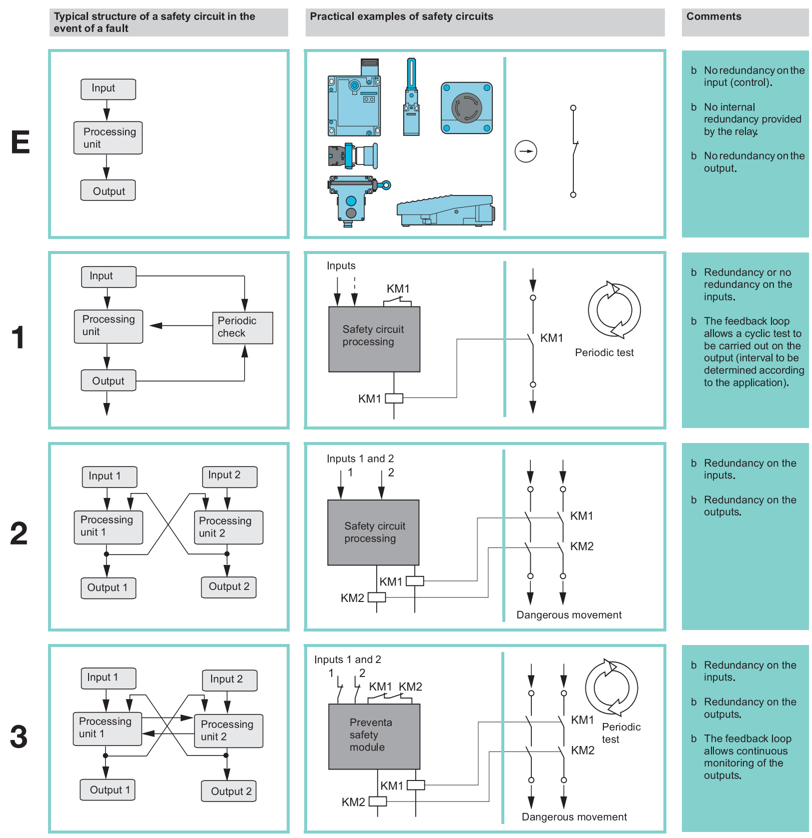
Based on the risk assessment, safety can be ensured by adapting existing functions *(⇨ Fig.22)*.

As previously explained, this can be done in one of two ways:
- redundancy or self-testing,
- increased component safety.

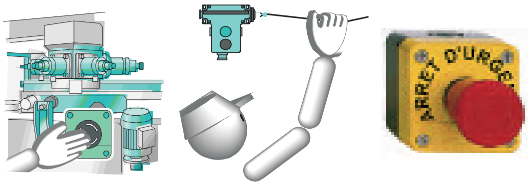
Unlike the classical approach where automation systems are divided into functions and treated individually, safety needs to be viewed holistically. To make it easier to build an automation system, component manufacturers offer specific certified products with integrated sets of functions.

The *figure 23* shows the generic solutions for the first four categories (B,1,2,3). We shall describe their use in standard applications and then give a more complex one.

An example of a safety module designed for the requirements of category 4 is given at the end of the section.



↑ *Fig. 23* *Generic safety solutions*



↑ Fig. 24 *Emergency stop*

Emergency stop

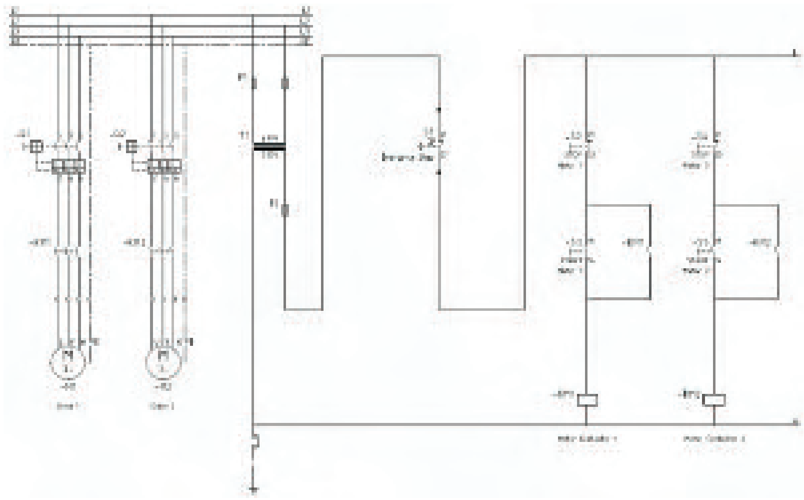
The emergency stop (⇨ Fig.24) is designed to warn or reduce the effects of a potential hazard on humans, the machine or the process.
The emergency stop is manually enabled.

Requirements for the emergency stop:
- for stop category 0: immediately stop the machine actuators or disconnect mechanically. If necessary, non-controlled stopping can be used (e.g. mechanical brake),
- for stop category 1: controlled stop at the power rate of the actuators concerned then power disconnection when standstill is reached.

The type of control component and its actuator must be positive mechanical (standard EN 292–2).

The emergency stop function must be available and operational at all times whatever the operating mode.

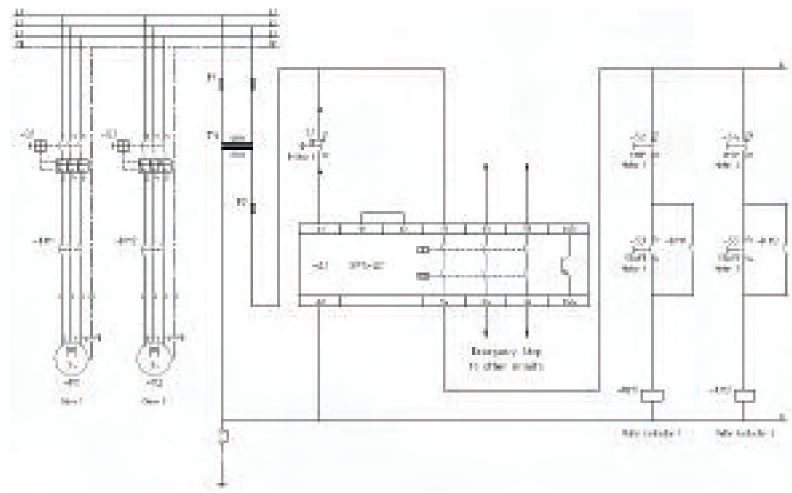
The diagram (⇨ Fig.25) shows a typical case of emergency stop:



↑ Fig. 25 *Typical emergency stop diagram*

If the emergency stop device has to work on more than one circuit, the safety diagram is much more complex. This is why it is advisable to use a safety module.

The diagram (⇨ Fig.26) represents an emergency stop function for 2 circuits.



↑ Fig. 26 *Emergency stop for 2 circuits*

The diagram *(⇨ Fig.27)* shows how an emergency stop is linked to a speed controller (stop category 1).

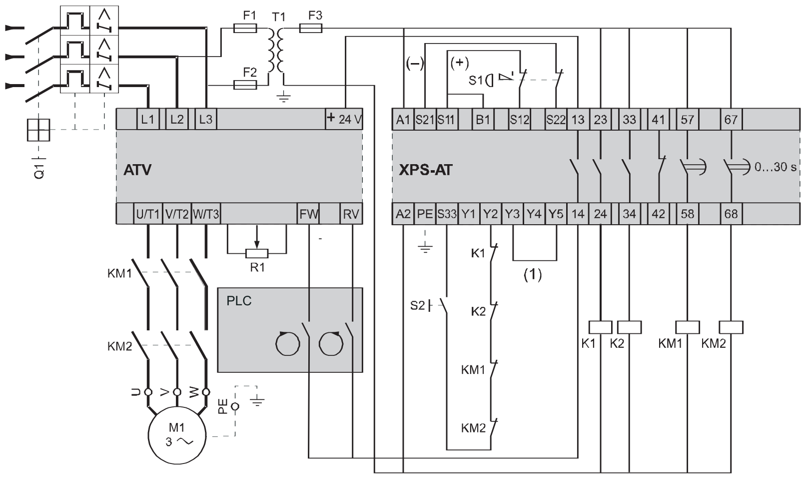


Fig. 27 *Emergency stop category 1*

7.8 Network safety

Technological progress, improved reliability and new standards have helped to change industrial networks so they can be used for applications with high safety demands.

Most networks have a secured version; here we shall describe the ASI network used for components. For more information on networks, *(see the section on Industrial networks)*.

■ AS-Interface (ASI)

The Actuator-Sensor Interface (AS-Interface), a system which can be connected with the power on, is the successor to conventional wiring. This network is easy to use and extend.

Speed, shorter installation time, cost saving, simplified maintenance and high availability are the defining features of this standardised network.

The ASI network is ideal for fast sure transmission of small amounts of data in a hostile industrial environment.

□ Data integrity

Invulnerability to interference in data transmission is an important feature in a network of sensors and actuators in the industrial environment. By using specific APM coding (alternating pulse modulation) and permanent monitoring of the signal quality, the ASI network delivers the same data integrity as other field buses.

□ Components used in ASI networks

The ASI logo is affixed to components which have been approved by the independent ASI test centre. It certifies that products from different manufacturers will work with no problem on an ASI network.

↑ *Fig. 28* Two-handed control on a press

◻ Master and gateway, power supply, repeaters

The heart of the ASI system is a Master or gateway with diagnostic capacities. Regular PLCs and PC software can still be used, because the component connected to the ASI bus is seen as a remote input or output.

The special power supply also ensures data splitting. Repeaters can be used to extend the network beyond 100m and thus ensure the primary and secondary electrical circuits are isolated to increase safety in the event of a short circuit.

■ Application: monitoring of two-handed control with ASI bus (Safety at work)

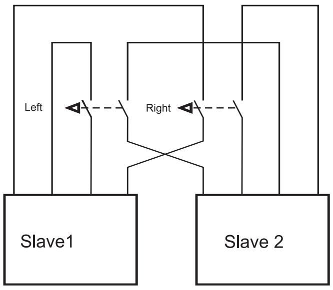
Operators of hazardous machines can be exposed to serious injury. Such machines are found in all means of production and are most common in the hydraulic press group: presses, punching machines, folding machines, etc.

The machine is often manually fed by an operator. At this stage in the work, the risk is heightened by familiarity and routine.

Two-handed controls *(⇨ Fig.28)* are devices that require the operator to start the hazardous process by using two distinct controls simultaneously with each hand. These two-handed controls include the controls themselves and an emergency stop device.

The four output contacts are monitored *(⇨ Fig.29)* to control their interdependence.

The time lapse between the actions on the two controls must not exceed 0.5 seconds and the controls must be in operation throughout the entire length of the hazardous machine process.

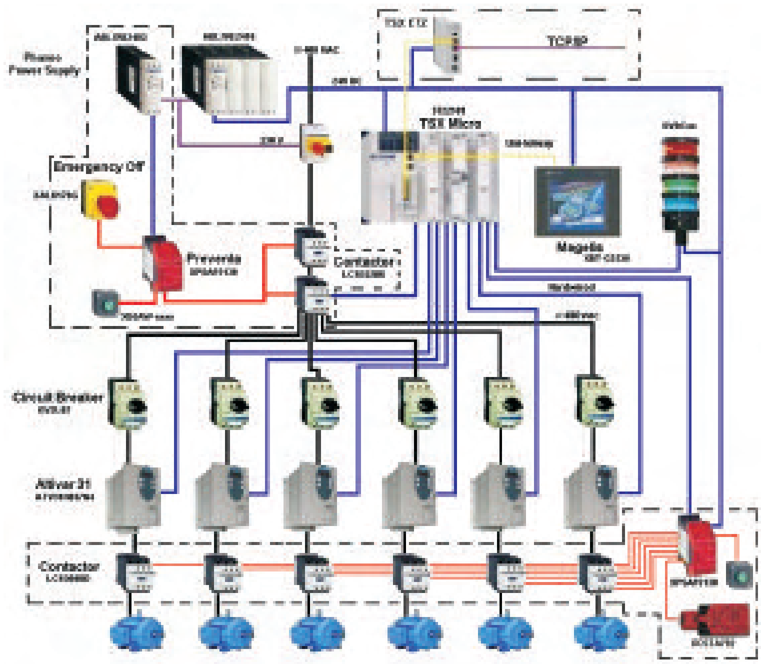


↑ *Fig. 29* *Two-handed control with ASI bus*

7

7.9 Example of application

The application described and illustrated *(⇨ Fig.30)* is a practical example of some safety functions.



↑ *Fig. 30* *Example of application*

7.9 Example of application

The system has a mid-range PLC which controls up to 6 speed controllers, each of which powers a motor. Every speed controller is protected by a circuit breaker and every motor has its own contactor.

The speed controllers can run with the factory settings or else be reconfigured with Power Suite software.

Power supply: 3-phase 400V and single-phase 230V distributed to the components (3-phase 400V for the speed controllers and 230V for the Phaseo supply). All the speed controllers are hard-wired to the PLC.

The speed controllers are monitored via a graphic touch-screen terminal and programmed with VijeoDesigner software. The graphic terminal is connected to the PLC via a Uni-Telway link. The PLC is configured and programmed with PL7 Pro software.

An illuminated indicator bank gives the actual status of the system (power on or off, motor(s) running, awaiting confirmation, and emergency stop).

The main switch is connected so that if the system is disconnected the PLC will still be powered and enable diagnostic operations to be run.

As the speed controllers are used with the factory settings, the application program in this example is at its most basic. The equipment however was chosen to control further inputs/outputs.

Options:

The system reaches safety level 4 with the Preventa module to drive the speed controller contactors. This module not only protects the controllers but also keeps account of the emergency stop.

The system also has another safety option for safety level 3 which automatically stops the motors if any box is open.

Note: the speed controller safety module has its own power supply. If there is a safety stop, starting again will require confirmation.

A gateway (TSX ETZ) to the next level up can be added to communicate via TCP/IP.

The options are framed with dotted lines.

This diagram can be used for the following typical applications:
- small and medium automatic machines,
- packaging machines, textile machines, conveyor belts, water distribution, wastewater treatment, etc,
- automated standalone subsystems relating to medium to large machines.

7.10 Safety-related functions and products

Schneider Electric has a wide range of safety-related products

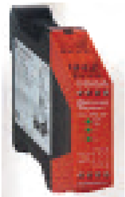
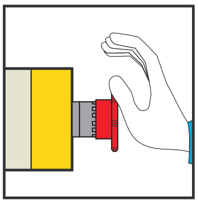
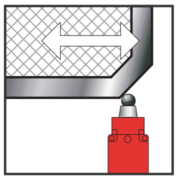
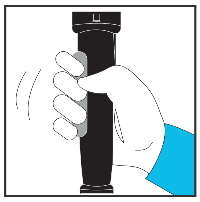
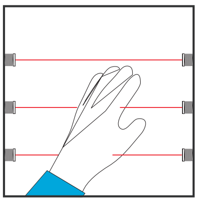
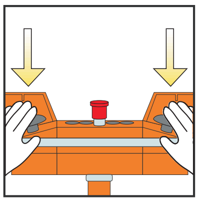
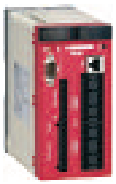
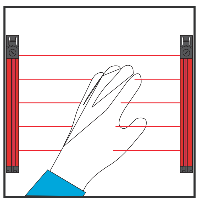
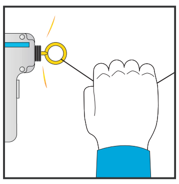
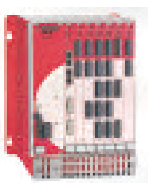
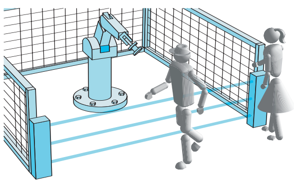
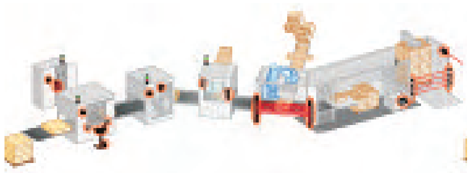
Below is a brief overview of the solutions, illustrated by examples.

Depending on how complex the machine is, the solution can be built with:
- a configurable single-function controller,
- a multi-function controller which can simultaneously handle two functions out of 15 predefined ones,
- a multi-function controller which uses software to configure predefined functions,
- a software-driven safety-related PLC for building a complete solution.

Links can be hard wired or made by an ASI safety network.

The table (⇨ *Fig.31*) shows some examples.

Fig. 31 Safety-related controllers

Type of controller	Examples of solution The controller governs the following functions		
XPS family Single-function 	Emergency stop  Category 4	Protection of persons by protective barrier  Category 4	Positioning movement  Category 4
XPS MP Selection of 2 amongst 15 predefined functions 	Protection of fingers and hands in danger zone  Category 2	Tow-handed control  Category 4	
XPS MC Software-configured function 	Protected operator access in danger zone  Category 4	Dangerous movement stopped in any part of the work zone  category 4	
XPS MF Safety-related PLC Programmable software 	Protection of operator accessing a danger zone  Category 4	Protection of operator accessing a series of danger zones  category 4	

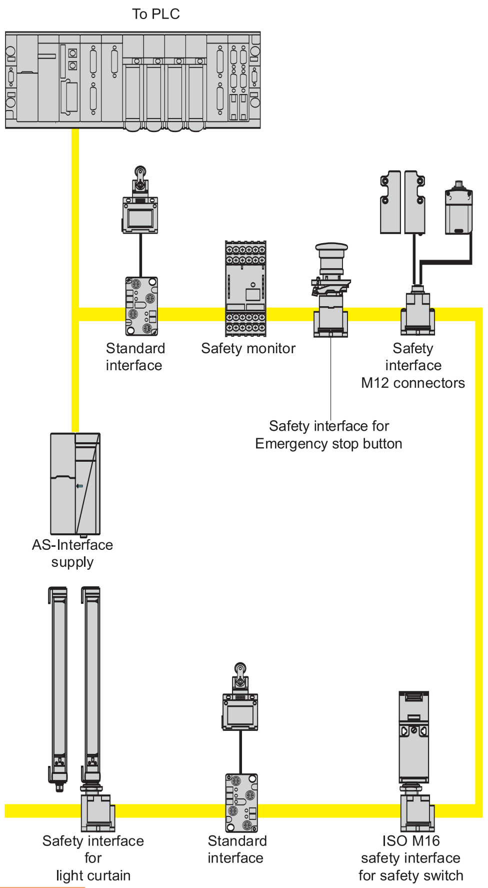


Fig. 32 *ASI Safety at work*

■ ASI "Safety at work" network

In addition to information on the process, safety information can now transit via the same cable to comply with safety requirements up to level 4 of standard EN-954-1.

The AS-Interface "Safety at work" system covers most needs with regard to safety applications such as:

- emergency stop monitoring with instant opening contacts (category 0),
- emergency stop monitoring with delay opening contacts (category 1),
- switch monitoring with or without interlocking,
- light barrier monitoring, etc.

The safety options chosen, such as ON button monitoring, can be configured for all predefined certified functions.

Safety functions can be built into the ASI network by adding a safety controller and safety interfaces to be connected indifferently to the same "yellow cable" as standard components.

Safety information is only exchanged between the safety controller and the safety interfaces. This exchange is transparent for all the other standard components, so an existing ASI network can be upgraded with safety components without having to change the components that are already installed (e.g., masters, inputs/outputs, power supplies etc.).

The safety circuits are interrogated immediately without any additional wiring by the standard ASI master communicating with the safety controllers via the ASI network ("yellow cable").

"ASI Safety at work" configuration and safety function selection is straightforward and intuitive. The requisite information on this topic is provided in the manufacturers' documentation.

7.11 Conclusion

Machine safety is an essential requirement in the European Union and a precondition for circulation of the products in member states. Designers would be well advised to use analysis tools such as FMECA to help find the most appropriate and cost-saving solutions.

If this analysis is done, risk assessment to comply with standards in force will be faster and further-reaching.

The methodical approach described above will help guarantee successful risk assessment.

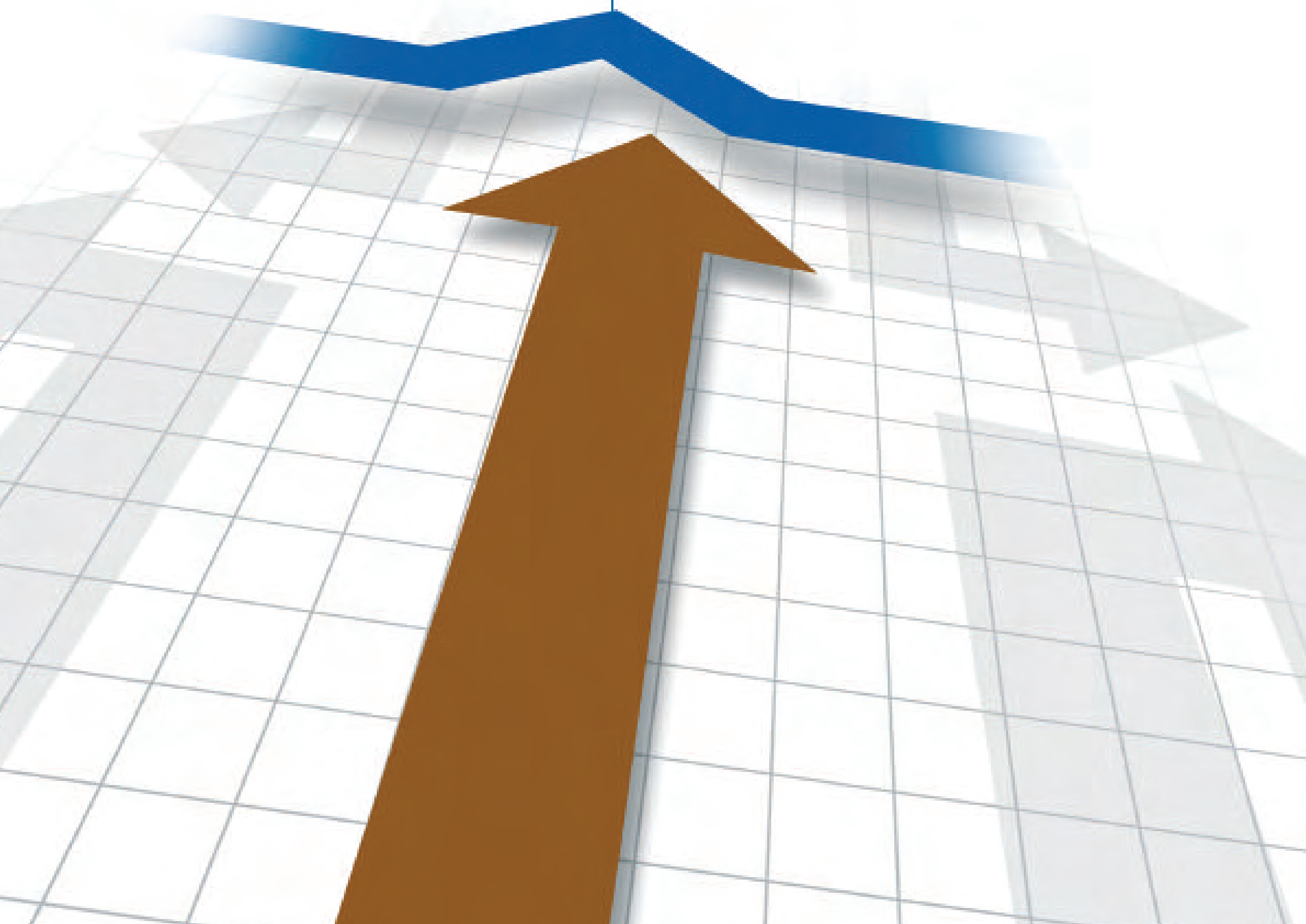
It will lead to the best-devised safety diagram and the best choice of components to perform the function.

Suppliers such as Schneider Electric offer a full range of products and solutions perfectly designed for building safety functions. If required, experts can step in to help find solutions for difficult cases.

8 chapter
Human-machine interface

Presentation :

- *Man machine dialog according to machine operation*
- *Command and interface solutions (push buttons or terminals)*
- *Screens configuration software*

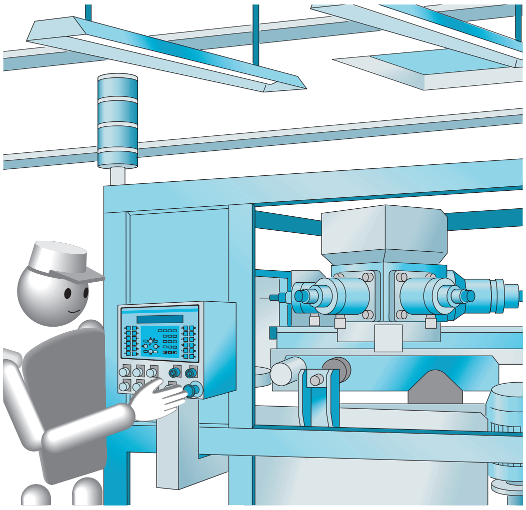


8. Human-machine interface

Summary

Operators play an important part in the human-machine dialogue. They must use the information they have to perform actions that make the machines and installations run properly without endangering safety and availability. It is therefore crucial that the interfaces and dialogue functions are designed to ensure that operations can be performed reliably in all circumstances.

8.1 Human-machine interface setup



↑ *Fig. 1* *Human machine interface*

Information flow in the human-machine interface

A human-machine interface (⇨ *Fig. 1*) uses two information flows in two directions:

- Machine –> Human
- Human –> Machine

These flows are independent yet linked.

Independent

Because their content can be on different levels.

The levels are defined by the designer of the automation system according to the requirements of the process and what the user wants, such as discrete signals from the operator to the machine, alphanumerical or animated diagram messages from the machine to the operator.

Linked

Because the automation system interprets an operator action on a control interface as a specifically defined action and, in return, emits information that depends on whether the action was properly performed or not. The operator can either act by his own decision (stop production, modify data, etc.) or in response to a message from the machine (alarm, end of cycle, etc.).

Role of the operator

The operating interface includes all the functions required for controlling and supervising the operation of a machine or installation.

Depending on the requirements and complexity of the process, the operator may have to perform.

Regular process run tasks

- stop and start the process; both steps may include start and stop procedures that are automatic or manual or semi-automatic and controlled by the operator;
- operate the controls and make the adjustments required for regular process run and monitor its progress.

Tasks to deal with unexpected events

- detect abnormal situations and undertake corrective action before the situation disturbs the process further (e.g. for early warning of motor overload, restoring normal load conditions before the overload relay trips);
- deal with system failure by stopping production or implementing downgraded operation using manual controls instead of automatic ones to keep production running;
- ensure safety of people and property by operating safety devices if necessary.

8.1 Human-machine interface setup

The scope of these tasks shows how important the operator's role is. Depending on the information he has, he may have to take decisions and perform actions that fall outside the framework of the regular procedures and directly influence the safety and availability of the installation. This means the dialogue system should not be confined to mere exchange of information between human and machine but should be designed to facilitate the task of the operator and ensure that the safety of the system in all circumstances.

Quality of interface design

The quality of the operating interface design can be measured by the ease with which an operator can **detect and understand** an event and how efficiently he can **respond**.

Detect

Any change in a machine's operating conditions is usually seen by a change in or display of information on an indicator, display unit or screen. The operator must, above all, be able to detect the event in any environmental conditions (ambient lighting, etc.).

Different means can be employed to attract attention: flashing information, colour change, sound signal, anti-reflection devices, etc.

Understand

To prevent any action that might endanger safety, the information the operator sees must be legible and accurate enough to be immediately understood and used.

This is as much a matter of the ergonomics of the components as of the function design:

- for a pilot light: use of the standard colour, fast and slow flashing clearly differentiated, etc.;
- for a display unit: clear texts in the language of the user, adequate reading distance, etc.;
- for a screen: use of standard symbols, zoom giving a detailed view of the area the message involves, etc.

Respond

Depending on what message the machine sends, the operator may have to act swiftly by pressing one or more buttons or keys. This action is facilitated by:

- clear markings to identify buttons and keys easily, such as standard symbols on buttons;
- clever ergonomics with large buttons, touch keys, etc.

8.2 Human-machine interfaces

The human-machine interface has made outstanding progress over the last few years. The basic function of the push button has been enhanced by interfaces using electronics to improve and customise the dialogue and add new features, such as custom settings and diagnostics.

The table *(⇨ Fig. 2)* shows the offer and functions of human-machine interfaces

	DESIGN	COMMISSIONING	OPERATING	MAINTENANCE
Product				
PB		YES	YES	YES
Integrated dialogue		YES	YES	YES
Operator Dialogue	CAD software	YES	YES	Possible
Supervision	CAD software	YES	YES	Possible
Function				
Operation		PB, Supervision, Operator dialogue	PB, Supervision, Operator dialogue	
Diagnostic				Integrated dialogue (Supervision and Operator dialogue possible)
Adjustment			Integrated dialogue (Supervision and Operator dialogue possible)	
CAD software and others	Integrated dialogue Operator, Supervision software			PC adjustment software

Fig. 2 *Offer and functions of human machine interfaces*

8.3 Discrete control and indicator units

■ Push buttons and pilot lights

□ Standard ranges

These interfaces are perfectly adapted to situations where the operator and the machine exchange little information which is limited to discrete signals (run orders and status indications).

They are rugged and reliable electromechanical components that are easy to implement, ergonomic and not vulnerable to ambient conditions. They can be fitted with a wide range of round or square control heads.

They have a standard colour code which makes them easy to identify (see note).

They are intuitive or reflex devices (e.g. for emergency stops).

For this reason, they are used for safety operations which require controls that are as simple and direct as possible.

↑ *Fig. 3* *Push buttons Harmony design*

Note : the IEC 60204-1 standard stipulates the colour codes that pilot lights and push buttons must be:
- *red light: emergency – hazardous situation requiring immediate action (pressure not within safety limits, over-travel, broken coupling, etc.);*
- *yellow light: abnormal – an abnormal situation likely to lead to a hazardous situation (pressure not within normal limits, tripping of protection device, etc.);*
- *white light: neutral – general information (supply voltage, etc.);*
- *red push button: emergency - action to counter danger (emergency stop, etc.);*
- *yellow push button: abnormal - action to counter abnormal conditions (intervention to restore an automatic cycle run, etc.).*

The push button interface is used for general stop and start control and safety circuit control (emergency stops).

They exist in diameters of 16, 22 and 30mm (NEMA standards) and different designs *(⇨ Fig 3)*:
- chromium-plated metal bezel, for all heavy-duty applications in harsh industrial environments;
- plastic for harsh environments: chemical and food industries.

- **Operating head**

There is a wide range of control heads:
- flush, protruding, recessed or booted;
- mushroom;
- double-headed;
- mushroom with latching;
- “emergency stop”;
- switch with toggle, handle, key, 2 or 3 set or pull-off positions;
- metal pin (multidirectional control);
- flush, protruding or booted pilot lights.

The modular design of control and indicator units offers great flexibility of use.

Pilot lights and illuminated buttons are fitted with filament lamps or LEDs. They are mains powered and have a voltage reducer or built-in transformer.

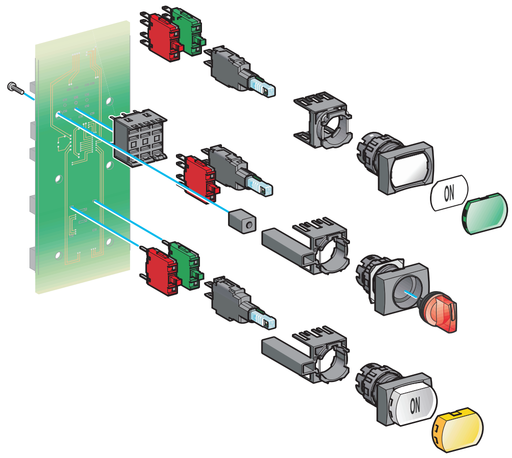
The control units can hold 1 to 6 NO or NC contacts compatible with 24V PLC inputs.

- **Ruggedness and reliability**

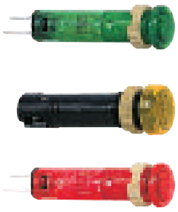
Push buttons and pilot lights are subject to harsh environmental conditions. Life time of a push button is around 1 million of operations. They must be designed to withstand shock tests according to the IEC 60947-5-5 standard. As an example, according to the standard, an emergency stop button must withstand 5.5 Joules without failure, the Harmony push button range can withstand 17 Joules.

◻ Buttons and pilot lights for printed circuit connection *(⇨ Fig. 4)*

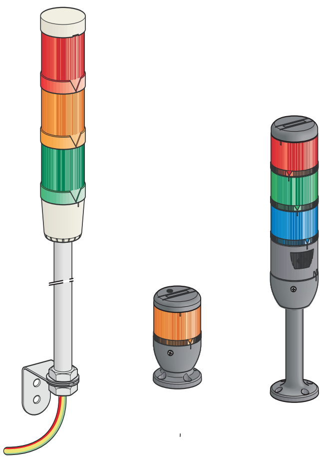
The 22mm diameter range exists in a version for "printed circuit connection". These products are designed for repeated dialogue media with an identical diagram. The control and indicator units are from the standard range. The electrical blocks specific to these versions have output contacts to weld them to printed circuits.



↑ *Fig. 4* *Push button and pilot light for printed circuit board*



↑ Fig. 5 *Led's pilot lights*



↑ Fig. 6 *Illuminated beacons and banks*

↑ Fig. 7 *Telemecanique joysticks*

- **Square-headed key buttons and pilot lights**

These devices are mounted at intervals of 19,05 mm (3/4 ") in holes 16 mm in diameter. They are used to make compact control units when space is at a premium and they can be linked to input keyboards.

Key buttons are touch-sensitive. They can have a silver or gold contact.

- **LED pilot lights** (⇨ *Fig 5*)

LED's for 0.8 and 12 mm mountings are especially recommended when space is limited or when there are a lot of indicating elements (low power dissipation).
They have many advantages:
- excellent resistance to shocks, vibrations and voltage surges,
- long lifetime (>100,000 hrs),
- low consumption making them directly compatible with PLC's outputs.

☐ Illuminated beacons and banks (⇨ *Fig. 6*)

Beacons and banks are optical or sound indicators to view machine and alarm statuses over great distances and through 360°.

- **Beacons**

These have a single illuminated lens or flash unit, which is colourless, green, red, orange or blue.

- **Banks**

These have a variable composition made up of lens units, flash units or sound signals. These elements are slotted together. Electrical connection is made automatically as they are stacked together.

- **IEC 60204-1 standard**

The IEC 60204-1 standard stipulates the colour codes corresponding to displayed messages :

Light signalling
- Red: urgent (immediate action required)
- Yellow / Orange: anomaly (checking and/or intervention required)
- Green: normal condition (optional)
- Blue: obligatory action (action required from the operator)
- White: monitoring (optional)

Flashing lights
- For distinction or specific information:
- Attract more attention
- Call for immediate action
- Indicate discordance between the instruction and the actual status
- Indicate a change in cycle (flashing during transition).

Flash and rotating mirror beacons
- A more powerful signal for top priority information or longer distance signalling (conforming to IEC 60073).

Buzzer and sirens
- Recommended in environments subject to considerable light or sound interference or when the presence of the operator is of higher importance.

☐ Joysticks (⇨ *Fig. 7*)

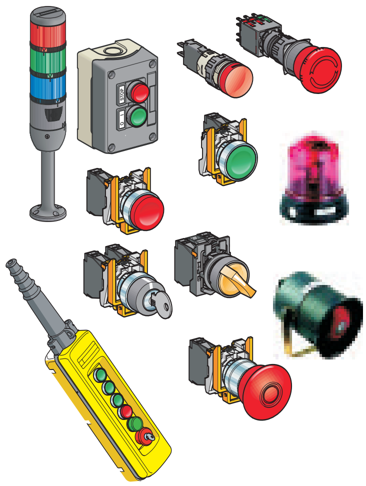
Joysticks usually use contactors to control movement through one or two axes, such as travel/direction or raising/lowering on small hoisting equipment.

They usually have 2 to 8 directions, with 1 or 2 contacts per direction, with or without return to zero.

Some joysticks have a "dead man" contact at the end of the lever.

8. Human-machine interface

8.4 Schneider Electric Discrete Control and Indicator Unit offer



↑ *Fig. 8* *Harmony offer*

Harmony range (Telemecanique)

The illustration above shows part of the Harmony range of discrete control and indicator units. These products are noted for their:

- **simplicity:** the elements clip together for safe and easy assembly;
- **ingenuity:** LED technology used for all light functions;
- **flexibility:** modular design to upgrade the products along with the automation system;
- **ruggedness:** mechanical performances well above standard;
- **compactness:** overall dimensions are the smallest on the market;
- **multiple connection options:** 2.8 x 0.5 Faston lugs, welded lugs, tags, screw-in terminals or terminal clamps.

8.5 Advanced human-machine interfaces

Progress in electronics and communication systems has led to the development of human-machine interfaces with enhanced user-friendly functions.

These interfaces make it possible to set product parameters, obtain information on actuators, such as current consumption, temperature, speed, etc.

The operator can also choose the working language by setting it in advance.

↑ *Fig. 9* *ATV71 embendded control panel*

↑ *Fig. 10* *Example of ATV71 messages*

Special embedded control panel

Special dialogue tools built into products offer performance tailored to the needs of operating adjustment and efficient diagnostics.

The panel *(⇨ Fig. 9)* is from an **Altivar ATV 71** Telemecanique.

Main features

- Graphic screen with custom display.
- Plain text entry with 6 languages available (Chinese, English, French, German, Italian and Spanish) and others on option.
- Browse button to navigate the menus easily.
- “Simply Start” menu for a quick start to get the most from Altivar 71 performance immediately.
- “Function” keys for shortcuts, online help or to configure for applications.
- Permanent display of motor operation settings.

Main advantages

- **Clear** display with text on 8 lines and graphic views. Legibility up to 5 m *(⇨ Fig. 10)*.
- **Flexibility** through remote operation: on a cabinet door avec with IP 54 or IP 65 protection for multipoint connection to several speed controllers.
- **Storage** 4 configurations can be stored for transfer to other speed controllers.

- **Ease to use** with function keys for shortcuts, direct access and online help, maximum and minimum parameter display.
- **Ergonomic** browse button. Navigate the dropdown menu quickly and easily with just one finger.
- **Custom** parameters, viewing screens, monitor bar, user menu creation, etc.
- **Protection** of parameters, visibility control, password protection for safe and easy access to custom configurations.

Many macro-configurations already integrated. They ared designed for a wide range of uses and applications: handling, hoisting, general use, connection to field bus, PID regulation, master, slave, etc.

They are easy to modify.

A wealth of varied services is available through the graphic terminal to help tune and diagnose machines.

Screen/keyboard terminals

Unlike embedded terminals, screens and keyboards are generic products that adapt to any application.

As we saw in the table above *(⇨ Fig.2)*, screen terminals are used in both commissioning and operation.

Depending on their type and software, they can play an important part in maintenance operations.

Terminals communicate with the process via the appropriate communication bus and are an integral part of the dialogue and data chain.

To illustrate what screen/keyboard terminals can do, we shall take a look at the Telemecanique Magelis offer.

These graphic terminals (with an LCD touch screen of 5.7" to 12.1" and keyboard or touch screen of 10.4") provide simple access to graphic solutions for controlling and/or supervising automated units. Communication performance are guaranteed by a direct connection to an Ethernet TCP/IP network.

Important features

- **Designed for harsh industrial environments**
  - rugged and compact;
  - reliable ergonomic control by keyboard or touch screen;
  - highly contrasted screens for excellent legibility.
- **Maintenance & diagnostics via the web**
  - remote control via Internet Explorer;
  - access to operator console diagnostic information via HTML pages;
  - remote diagnostics;
  - automatic emailing.
- **Compatible and upgradeable**
  - API connection available (several manufacturers);
  - OPC communication (several manufacturers (OPC server);
  - TCP/IP network integration;
  - Embedded VB Script.
- **Innovating HMI concepts**
  - decentralised control stations;
  - centralised access to local stations, small control rooms;
  - usable throughout the world over as many languages are supported.

XBT-F

XBT-G

↑ *Fig. 11* *Terminal device family*

Terminal device family *figure 11*.

Magelis XBT R, S

Compact matrix operator terminals:

- 4 to 8 lines with 5 to 20 prints,
- semi-graphic symbols,
- touch pad and password.

« ZENSHIN »

Touch screen graphic terminals available in 5.7 - 7.5 - 10.4" dimensions.

Magelis XBT GK

Graphic man machine operating terminals available in 5.7 - 7.5 - 10.4" dimensions.

Magelis XBT GT

Touch screen colour graphic terminals available in 3.8-5.7-7.4-10.4-12.1-15” dimensions.

- Magelis XBT G touch screen graphic terminals
  - **Display** LCD screen size 5.7” 7.4” 10.4” 12.1”
  - **Functions**
    - representation of variables: alphanumeric, bitmap, bargraph, gauge,
    - button, light, clock, flashing light, keypad;
    - curves with log;
    - incorporated alarm log.
  - **Communication**
    - embedded Ethernet: 10BASE-T (RJ45);
    - downloadable protocols: Uni-Telway, Modbus, Modbus TCP/IP.
  - **Compatible with Schneider Electric controllers and PLC’s:** Twido, Nano, Modicon TSX Micro, Modicon Premium, Modicon Quantum.
  - **Configuration software** Vijeo Designer **VJD SPU LFUCD V10M** (on Windows 2000 and XP).
  - **Compact Flash card slot**
  - **Supply voltage** 24V =
- Magelis XBT F graphic terminals
  - **Display** LCD screen size 10.4”
    Format 256-colour TFT
  - **Data entry keypad**
    - 10 dynamic function keys with LED’s;
    - 12 static function keys with LED’s + legends;
    - 12 service keys;
    - 12 alphanumeric keys + 3 alphanumeric access.

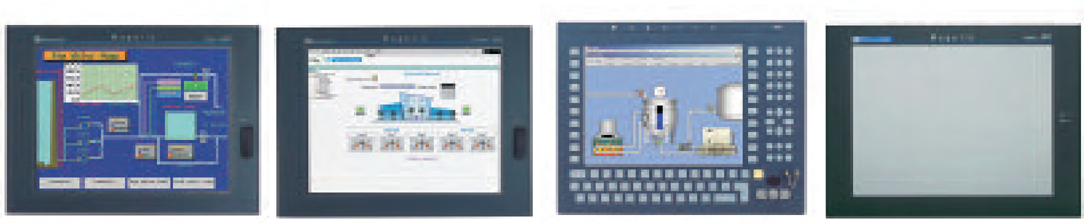
- **Touch screen data entry option**
- **Functions**
  - representation of variables: alphanumeric, bitmap, bargraph, gauge, potentiometer, selector;
  - recipes: 125 records maximum with 5000 values;
  - 16 curves;
  - alarm log.
- **Communication**
  - embedded Ethernet: 10BASE-T/100BASE-TX (RJ45);
  - buses and networks: Fipway, Modbus Plus, and third-party protocols;
  - downloadable protocols: Uni-Telway, Modbus, Modbus TCP/IP.
- **Compatible with Schneider Electric controllers and PLCs**
  Twido, Nano, Modicon TSX Micro, Modicon Premium, Modicon Quantum
- **Configuration software XBT L1003M** (on Windows 98, 2000 and XP)
- **Supply voltage** 24 V =

Industrial PC's

Characteristics

Industrial PC's are characterised by their rugged design enabling them to work without failure in industrial environments with electromagnetic interference and harsh climatic conditions. Industrial PC's can be compact or modular to fit closely the user's needs.

The illustrations *(⇨ Fig. 12a)* shows part of Schneider Electric offer.



	Magelis Smart i PC		Magelis Compact i PC		Magelis Modular i PC	Magelis i Display
Integrated screen	**12" SVGA**	**15" XGA**	**12" XGA**	**15" XGA**	**Without or 15" XGA**	**External screen 15" XGA***
Front panel interface	Touch screen		Touch screen		Touch screen and/or function keypad	Touch screen
	1 x USB	-	1 x USB	1 x USB	1 x PS2	-
Processor	Celeron M @600MHz	VIA @667MHz	Celeron M @1.3GHz	VIA @667MHz Pentium 4 M @1.7GHz	Celeron M @1.3GHz or Pentium M @1.6GHz	- -
Memory	CF 1GB		HDD 20 GB		HDD 40 GB	-
Reader	-	-	-	FDD, CDROM	FDD, CDROM, DVD-CD-Writer (Option)	-
Extension cards	1 PCMCIA		1 PCI and 2 PCMCIA		1 or 4 PCI and 2 PCMCIA	-
Ethernet ports	2	1	2	1	1	-
Integrated video port					1	
Power supply	AC	DC	AC	AC	AC or DC	AC
Operating system	Windows XPe		Windows 2000 or XP Pro		Windows 2000 or XP Pro	
						* 12" and 19" available soon

↑ *Fig. 12a* *Partial Industrial Magelis PC offer*

↑ Fig. 12b *Industrial modular PC - Magelis I Display*

□ **Magelis Modular iPC industrial PCs**

The modularity and flexibility of the Magelis Modular iPC range *(⇨ Fig. 12b)* offer solutions for the perfect choice of human-machine interface on a PC base, with easy upgrading and fast maintenance.

Magelis Modular iPC

Easy commissioning with 12” or 15” colour TFT LCD screens, with or without touch screen, with or without a QWERTY keyboard.

Magelis IDisplay

12, 15, 19” touch screen with a USB port optimising the man / machine interface.

8.6 Exchange modes

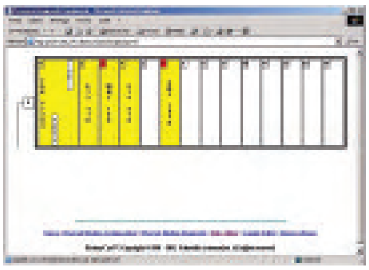
Conventional communication modes such as serial and bus links are naturally used on most products. They work through drivers embedded in the configuration software. Networks can also be used.

■ Protocols supported

All the core protocols in the =S= offer can be used:
- Uni-TE (Uni-Telway), Modbus, Modbus TCP-IP, FipWay, Modbus Plus;
- third-party protocols are also available;
- features: control graphic and ergonomics, types of automation system action.

□ **FactoryCast (on PLC Ethernet plug-in)** *(⇨ Fig. 13)*

Remote diagnostic functions via an ordinary internet browser:
- secure access to system diagnostics and application;
- numerical or graphic data display and adjustment;
- Emailing;
- open to customisation and web page creation for diagnostics suited to user needs.



↑ Fig. 13 *Example of a remote diagnostic*

□ **FactoryCast HMI**

Same diagnostic functions as FactoryCast + new HMI functions embedded in a PLC module:
- real-time database and PLC data acquisition (1000 variables);
- calculations for pre-processing data;
- advanced alarm management with emailing;
- data archived in relational databases (SQL, Oracle, MySQL);
- a web server the user can customise for an interface suited to requirements.

□ **FactoryCast Gateway**

New offer of intelligent “all-in-one” web gateways in a standalone box containing:
- network communication interfaces and Modbus or Uni-Telway serial links;
- remote access server (RAS);
- alarm notification by email;
- a web function the user can customise.

8.7 Development software

In addition to the terminal hardware, software is also offered to configure and adapt the terminals to their requisite application.

Below is a description of the Telemecanique Magelis offer. Hardware and software are combined in a consistent package enabling the user to build the requisite application in the shortest possible time.

The software can also be used to communicate with third-party products to gain optimal flexibility and open-endedness.

■ XBT L1003M configuration software

For Magelis terminal displays running under Microsoft Windows 98, 2000 an XP.

The XBTL1001/L1003 configuration software is provided to build an interface in order to run or operate a machine. It is applicable to:
- all XBTN/R/H/HM displays, XBTP/PM/E screens with the XBTL1001 software;
- all XBTN/R/H/HM displays, XBTP/PM/E screens et F with the XBTL1003 software.

Application generated with the XBTL1001/L1003 software are independent of the protocol being uses. Same dialog application ca be used on PLC's coming from any major providers.

□ Configuration

The XBTL1001/L1003 configuration software is an user friendly package to create several family of pages:
- application pages (eventually linked to each other);
- alam pages;
- help pages;
- recipe pages.

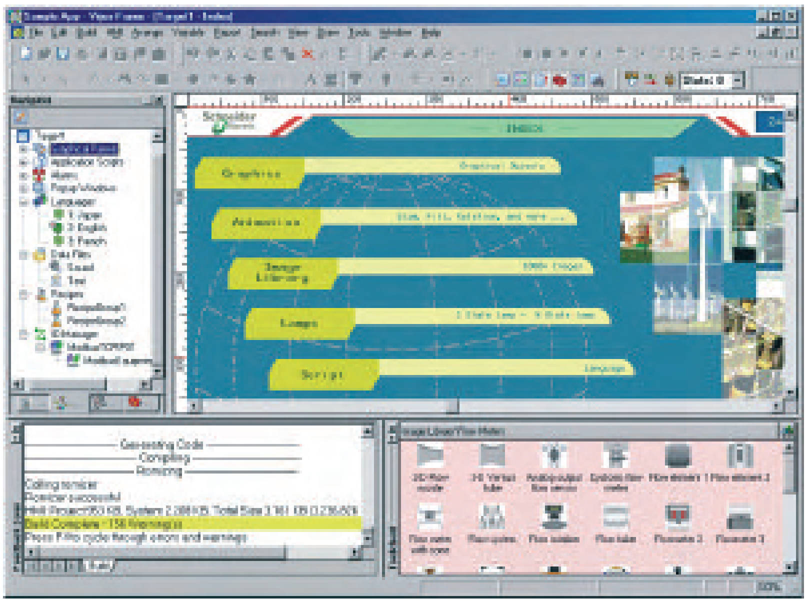
■ Vijeo Designer, MMI interface software for XBTG / XBTGT

Vijeo Designer is a software workshop for the "Build Time" part and a run time software which is downloaded into the XBTG / XBTGT (⇨ *Fig. 14*).

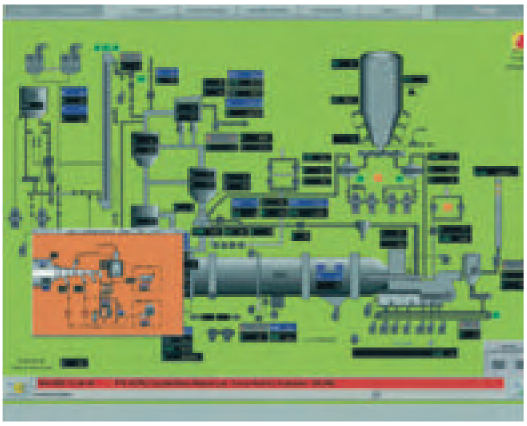
The 'Build Time' part is similar to Visual Studio. The supported operating systems are Microsoft Windows 2000 et XP Professionnal.

The run time software, the key point of the solution is as user friendly as possible. It is available in two formats:
- a PC format which runs automatically any time a user wants to emulate the application on a PC;
- a user's format which can be downloaded in the background when debugging has bee made and the application is ready to run on the XBTG / XBTGT.

Additional information are available in the Schneider Electric documentation.



↑ *Fig. 15* *Screen shot of Vijeo designer*



↑ *Fig. 14* *Screen shot of Vijeo designer*

■ Vijeo Citect

Vijeo Look 2.6 a SCADA (Supervision ControlAnd Data Acquisition) aimed to stand alone terminals *(⇨ Fig.15)*. If offer a perfect symbiosis between Web and MMI (Man Machine Interface).

Information are available in the Schneider Electric documentation.

8.8 Conclusion

Human-machine interface is probably the sector in automation which has made the greatest progress in the last few years.

This progress is due to increasingly sophisticated and user-friendly electronics and signal processing.

With the right choice of interface and its configuration, users can control processes with ever greater exactness and undertake diagnostics and preventive maintenance to increase productivity by reducing downtime.

9 chapter
Indutrial networks

Presentation:
- *Needs and available components*
- *Technologies*
- *Schneider Electric policy*

Summary

9. Industrial networks

In this part we discuss the electrical links required for operating automation equipment. These usually involve two categories:

- ***High current** links connecting the power components between the mains supply and the load. We shall not be dealing with this topic here but refer the reader to the sections on power supply and implementation.*
- ***Low current** links connecting all the capture, dialogue, processing and power control components with the machine and process environment.*

9.1 Introduction

Electrical equipment systems are traditionally hard wired.

The international machine standard IEC 60 204-1 and individual country standards have precise stipulations for sections, the quality of the insulating agent and colour markings. Most of these links are made from flexible wire units with a section of 1.5-2.5 mm^2 (AWG 16 and 14), protected at each end.

Until a decade ago, these solutions covered all requirements, both for discrete signals and analogue signals for servocontrol, the latter sometimes requiring shielded cables to prevent electromagnetic interference.

Influenced by IT and automotive industry standards, the advent of digital technologies in other industries has had a considerable impact on the design and construction of electrical equipment.

Digital data exchange entails links by communication networks requiring the use of connectors and ready-made connections. This makes it much simpler to build electrical equipment as wiring errors are reduced and maintenance is more straightforward.

As conventional link technologies are already well known, we shall devote this section to the communication networks used in industry.

9.2 History

In 1968, the company Modicon invented the concept of the programmable logic controller, a single unit to handle a wide range of needs and provide economies of scale. Its high flexibility in use offers many advantages throughout every stage in the lifetime of a plant. Networks came in gradually, initially as serial links. Exchanges were formalised by protocols, such as Modbus (1979, short for MODicon Bus), which has become a standard by its very existence.

Within the last few years, many applications have adopted the field bus. This backbone of automation system architecture is an extremely powerful means of exchange, visibility and flexibility in the devices connected to it. The field bus has gradually led to an overhaul in architecture:

- input/output wires eliminated;
- input/output interfaces superseded or decentralised;
- intelligence decentralised and distributed;
- Internet interconnection.

The 1970s saw the emergence of the Xerox PARC Ethernet – a contraction of ether and net(work) – which 10 years later became the international standard native equipment in practically all computers. Its initial applications were file and message transfer and web page transmission. The spread of information technology to all parts of industry by the 1990's led to the need for industry-wide connection.

The World Wide Web invented by the CERN in 1989 was originally developed to enable different work teams scattered throughout the world share information. The WWW system involves sharing documents and links using HTTP, a simple protocol used by a browser to access web pages stored on a server. These pages are programmed with languages such HTML or XML. The World Wide Web Consortium (W3C) was set up in 1994 to manage technical web developments (see the site http://www.w3.org).

In 1996 Schneider Electric promoted the industrial Ethernet to connect the "management" and "shop floor" sides of businesses by PLC's and then developed the "Transparent Ready" concept based on the addition of industrial tools and protocols, including Modbus, to existing standard Ethernet elements.

9.3 Market requirements and solutions

With the combined effects of user, technological and standards requirements, architectures are now structured into four separate levels interconnected by networks *(⇨ Fig. 1)*.

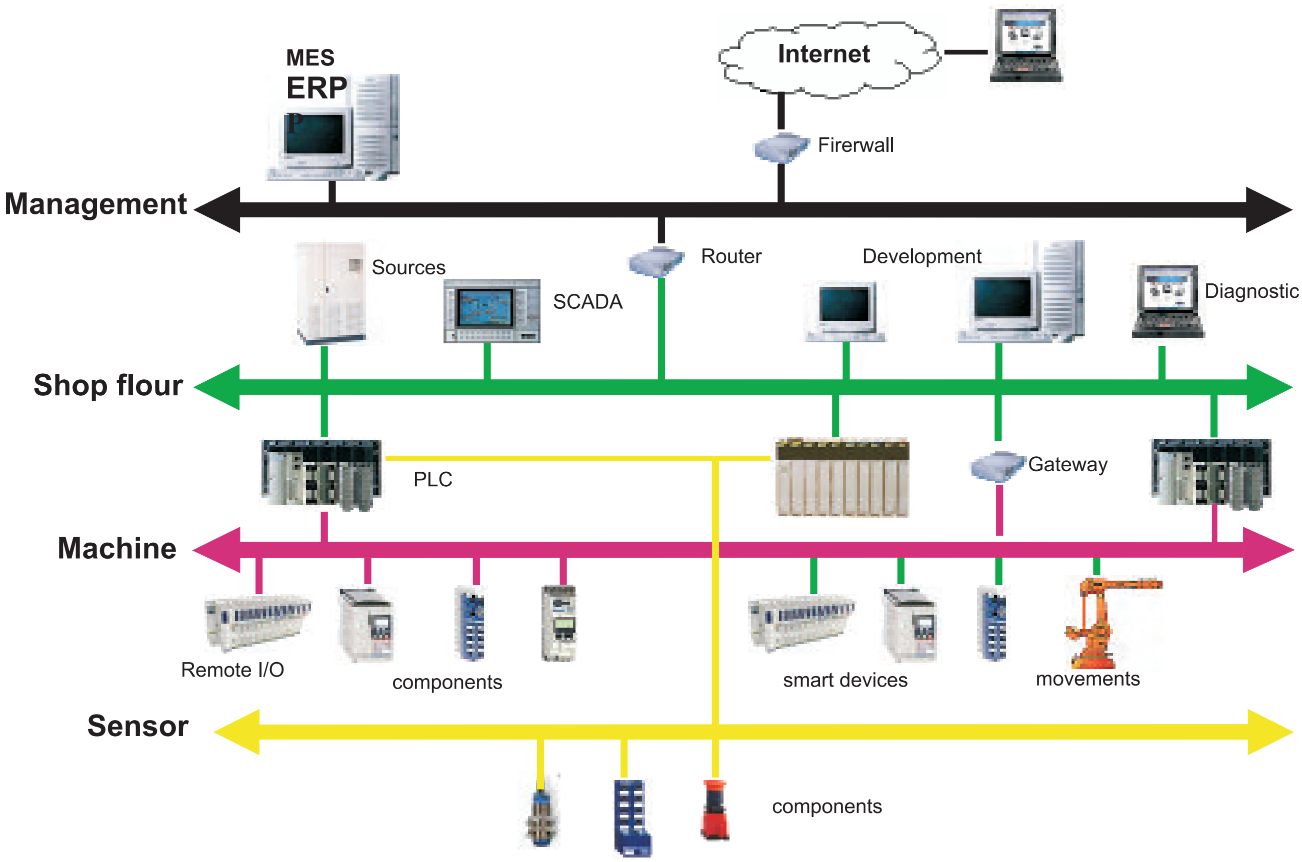


Fig. 1 *Example of architecture levels*

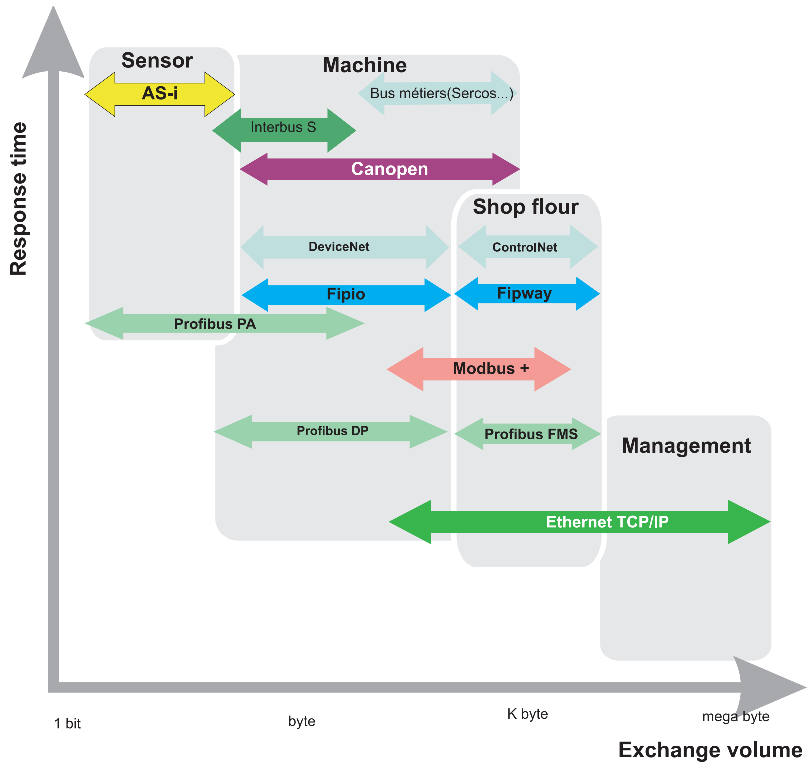
Before analysing communication network technologies, there should be a breakdown of the main requirements for which these levels provide a relevant solution. The characteristics in the table in *fig. 2* are detailed in the paragraphs which follow.

Level	Requirement	Volume to data to transmit	Response time	Distance	Network topology	Number of addresses	Medium
Management	Data exchange. Computer security . Standards between software packages.	Files Mbits	1 min	World	Bus, star	Unlimited	Electrical, optic, radio
Shop floor	Synchronisation of PLC's in the same data exchange automation cell in client/server mode with the control tools (HMI, supervision). Real-time performances.	Data Kbits	50-500 ms	2-40 Km	Bus, star.	10-100	Electrical, optic, radio
Machine	Distributed architecture. Embedded functions and exchange. Transparency. Topology and connection costs.	Data Kbits	5-100 ms (PLC cycle)	10 m to 1K m	Bus, star	10-100	Electrical, optic, radio
Sensor	Simplification of distribution wiring for power supply to sensors and actuators. Optimised wiring costs.	Data Bits		1- 100m	No constraint	10-50	Electrical, Radio

↑ *Fig. 2* *Communication requirements and constraints*

An initial approach is to adopt the two main focuses from this table of requirements:
- the amount of information to transmit;
- the response time needed.

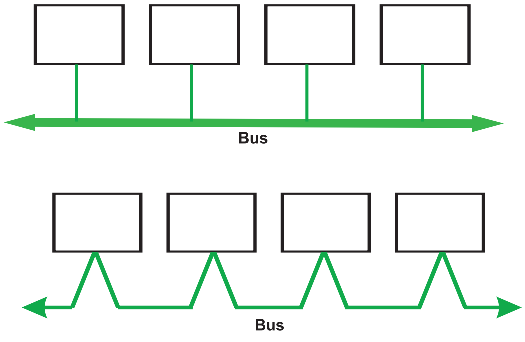
This helps to position the main networks (⇨ *Fig.3)*.



↑ *Fig. 3* *Main industrial networks*

9.4 Network technologies

The concepts are described in brief; for further reading, there are many works devoted to this subject.



↑ *Fig. 4* *Network topology*

■ Network topology

An industrial network is made up of PLC's, human-machine interfaces, computers and I/O devices linked together by communication links such as electric cables, optic fibres, radio links and interface elements such as network cards and gateways. The physical layout of a network is the hardware topology or network architecture.

For the circulation of information the term used is **software topology.**

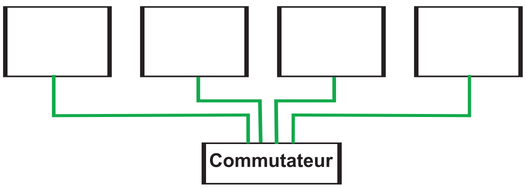
Topologies are usually divided as follows:
- bus,
- star,
- tree,
- ring,
- hub.

• Bus topology

This is one of the simplest layouts; all the elements are wired together along the same transmission line. The word bus refers to the physical line. This topology is easily implemented and the failure of a node or element does not prevent the other devices from working.

Machine and sensor level networks, otherwise known as field buses, use this system.

The bus topology is implemented by linking devices together in a chain or to the main cable via a connection box (TAP) *(⇨ Fig. 4)*.

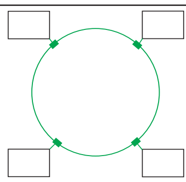
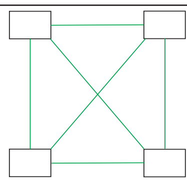


↑ *Fig. 5* *Star network topology*

• Star topology

This is the Ethernet topology, the most common at management and shop floor levels *(⇨ Fig. 5)*. It has the advantage of being very flexible to run and repair. The end stations are linked together via an intermediate device (repeater, switch). Failure of a node does not prevent the network as a whole from working, though the intermediate device linking the nodes together is a point of weakness.

• Other topologies *(⇨ Fig. 6)*
- **The ring topology** uses the same hardware layout as the star topology but ensures greater network availability.
- **The hub topology** is not very widespread in industry and has the disadvantage of a large number of links.

Ring	Hub
	
The ring topology uses the same hardware layout as the star topology but ensures greater network availability.	The hub topology is not very widespread in industry and has the disadvantage of a large number of links.

↑ *Fig. 6* *Other topologies network*

9

Protocol

A communication protocol specifies a set of rules for a given type of communication. Initially, protocol was the word meaning what was used to make dissimilar devices communicate on the same level of abstraction. The term now extends to the rules of communication between two layers on the same device.

The OSI (Open System Interconnection) model was created by ISO (International Standards Organisation) which published standard ISO 7498 to provide a common basis for all computer network descriptions. In this model, the suite of protocols in a network is divided into 7 parts called OSI layers, numbered 1 to 7. OSI layers work on the following principles:

- every layer supports a protocol independently of the other layers;
- every layer provides services to the layer immediately above it;
- every layer requires the services of the layer immediately below it;
- layer 1 describes the communication medium;
- layer 7 provides services to the user or an application.

In a communication, the network user calls on the services of layer 7 via a program. This layer formats and enriches the data the program gives it according to its protocol and sends it to the layer below it when a service is requested. Each layer formats the data and adds to it according to the protocols used. Finally it is sent to the medium and received by another network node. It goes back through all the layers of this node and ends up in the correspondent's program, divested of all the protocol-related additions.

The OSI 7-layer model (⇨ *Fig. 7*) has been implemented by several manufacturers but was never a commercial success as the market preferred the 4-layer TCP/IP model which is easier to understand and use and which had already been implemented in the mobile domain. The model does however have a certain theoretical advantage, even though the frontiers of the 4 TCP/IP layers do not have an exact equivalent in OSI. These layers will be described in the subsection on Ethernet.

N°	OSI layer	Function of layer	Examples
7	**Application**	The interface with the user; sends requests to the presentation layer.	HTTP, SMTP,POP3, FTP, Modbus.
6	**Presentation**	Defines how data will be represented. Converts data to ensure that all systems can interpret it.	HTML, XML.
5	**Session**	Ensures correct communication and links between systems. Defines session opening on network devices.	ISO8327, RPC, Netbios.
4	**Transport**	Manages end-to-end communication, data segmentation and reassembly, controls flow, error detection and repair.	TCP, UDP, RTP, SPX, ATP.
3	**Network**	Routes data packets (datagrams) through the network.	IP, ICMP, IPX, WDS.
2	**Data-link**	Creates an error-free link from the hard medium.	ARCnet, PPP, Ethernet, Token ring.
1	**Physical**	Defines the protocols for the bit stream and its electrical, mechanical and functional access to the network.	CSMA, RS-232, 10 Base-T, ADSL.

↑ *Fig. 7* *OSI layers*

Frame

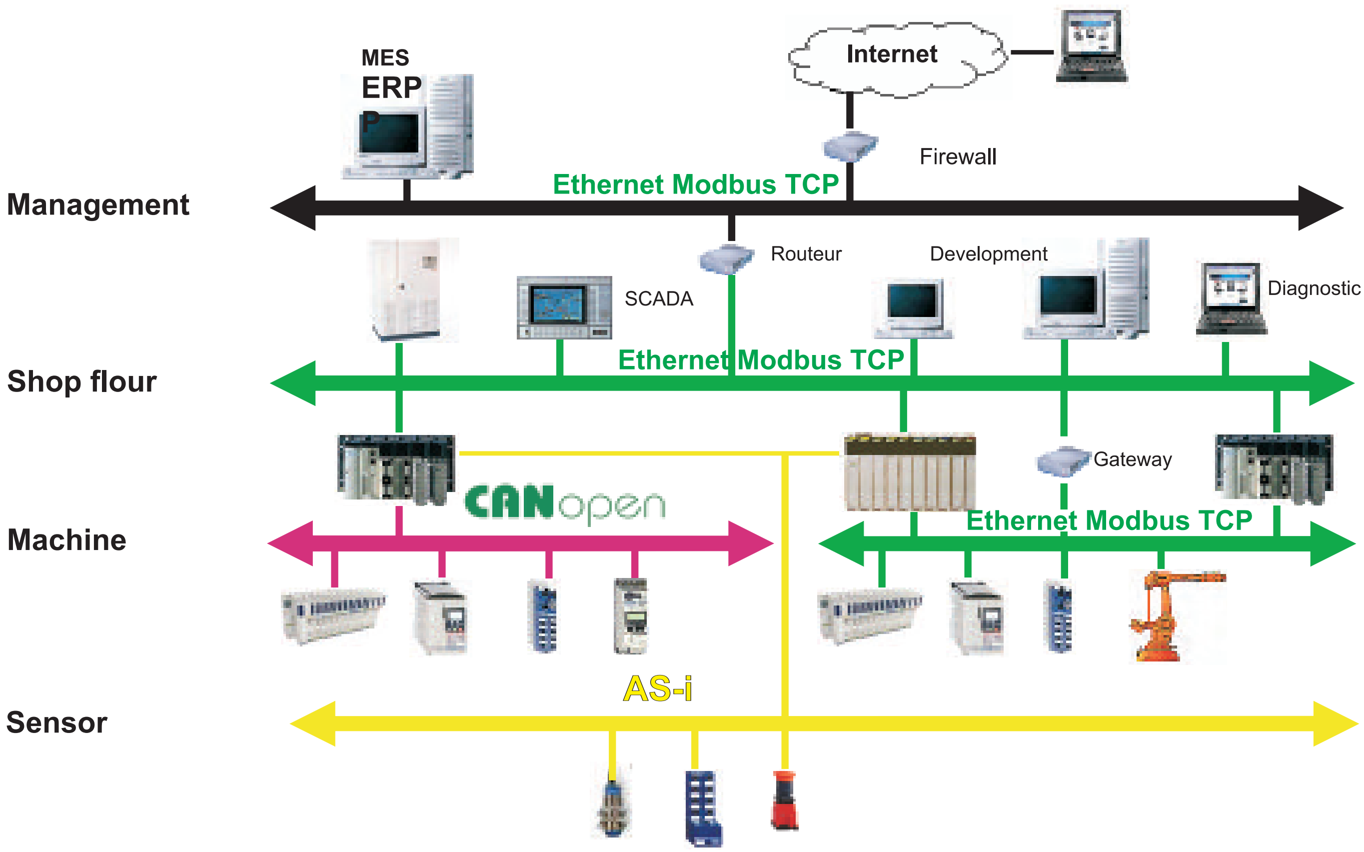
A frame *(⇨ Fig.8)* is a set of data sent via a network in a single block. It is also known as a packet. Every frame has the same basic layout and contains control information such as synchronisation characters, workstation addresses, an error control value and a variable amount of data.

Header	Frame delimiter	Target address	Source address	Data size	Data	Frame sequence control

↑ *Fig. 8* *Format of a frame*

9.5 Networks recommended by Schneider Electric

To answer all requirements with a rational offer, the company has selected three communication networks *(⇨ Fig.9)* to implement the preferred systems described in the introduction to this document.



↑ *Fig. 9* *Communication levels chosen by Schneider Electric*

Ethernet Modbus TCP

The widespread use of Ethernet in business and on the Internet has made it a more or less mandatory communication standard. It helps to cut connection costs and enhance performance, reliability and functionality. Its speed does not slow down applications and its architecture makes upgrading easy. Products and software are compatible, so systems are durable. The "Modbus" protocol, standard usage in industry, provides a simple cost effective application layer.

CANopen

CANopen is the industrial version of the CAN bus developed for automotive purposes. This network has proved its flexibility and reliability for over 10 years in a wide range of applications such as medical equipment, trains, lifts and many machines and plant installations. Schneider Electric's choice of this network is upheld by its widespread distribution.

As-Interface

Modern machines have a great many actuators and sensors and often have safety constraints as well. AS-Interface is the network at sensor level which meets industrial automation requirements. It has the advantage of fast connections and a single cable to convey data and power.

9.6 Ethernet TCP/IP

General description

Ethernet works on the principle of media access controlled by a collision detection mechanism. Each station is identified by a unique key, or MAC address, to ensure that every computer on an Ethernet network has a different address. This technology known as Carrier Sense Multiple Access with Collision Detection (CSMA/CD) ensures that only one station can transmit a message on the medium at a time.

Successive Ethernet upgrades have given rise to the IEEE 802.3 standard (see www.ieee.org) which only defines the characteristics of the physical layers; the way the data accesses the network and the data frame must be defined by further layers. As these notions often get confused, *figure 10* places them and the protocols mentioned are explained in the following paragraphs.

For many years, Ethernet was present in industry but had little success. Suppliers and customers felt it was non-deterministic. Their need for real-time control made them prefer proprietary networks. It was the combination of industry and Internet protocols that finally led them to accept it.

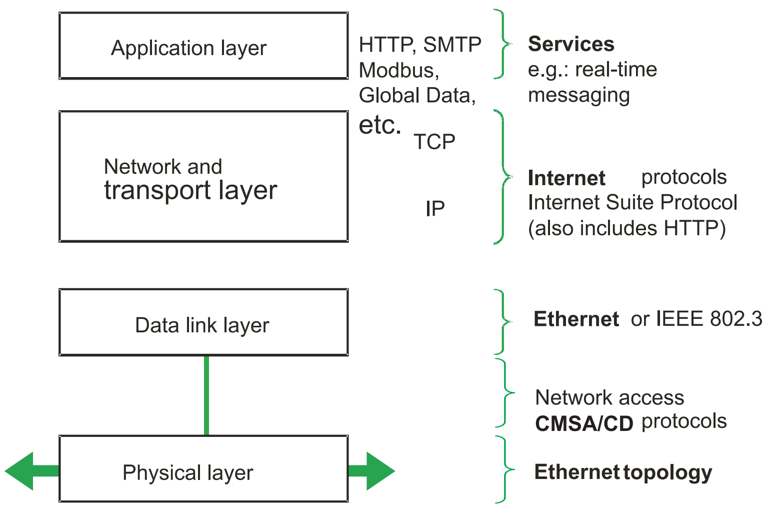


Fig. 10 *Ethernet topology*

Physical layer

The physical layer describes the physical characteristics of communication such as the type of medium conventionally used (electric cables, fibre optic or radio links) and all related details like connectors, types of encoding and modulation, signal levels, wavelengths, synchronisation and maximum distances.

Data link layer

The data link layer specifies media access control and how the data packets are conveyed on the physical layer, in particular the frame structure (i.e. the specific sequences of bits at the start and end of the packets). For example, Ethernet frame headers contain fields indicating which machine on the network a packet is to go to.

Network layer

In its original definition, the network layer solves the problem of conveying data packets across a single network. Further functions were added to it when networks became interconnecting, especially data transmission from a source network to a target one. In general this means that packets are routed across a network of networks, otherwise known as Internet.

In the suite of Internet protocols, IP transmits packets from a source to a target anywhere in the world. IP routing is made available by defining an IP addressing principle to ensure and enforce the uniqueness of every IP address. Each station is identified by its own IP address. The IP protocol also includes other protocols, such as ICMP used for transferring IP transmission error messages and IGMP which manages multicast data. ICMP and IGMP are located above IP but join in the functions of the network layer, thereby illustrating the incompatibility of the Internet and OSI models.

The IP network layer can transfer data for many higher level protocols.

Transport layer

The transport layer protocols can solve problems such as the reliability of data exchange ("Did the data reach the target?"), automatic adaptation to network capacity and data stream control. It also ensures that the data arrive in the right order. In the suite of TCP/IP protocols, transport protocols determine which application each data packet is to be delivered to.

TCP is a connection-oriented transport protocol which delivers a reliable stream of bytes ensuring the data arrive unaltered and in order, with retransmission in the event of loss and elimination of duplicate data. It also handles "urgent" data to be processed in random order (even though they are not technically emitted out of band). TCP tries to deliver all the data correctly and in order – this is its purpose and main advantage over UDP, even though it can be a disadvantage for real-time transfer applications, with high loss rates in the network layer. UDP is a simple, connection-free, "unreliable" protocol. This does not mean it is actually unreliable, but that it does not check that the packets have reached their target and does not guarantee they arrive in order. If an application requires these guarantees, it has to ensure them itself, or else use TCP. UDP is usually used for broadcasting applications such as Global Data or multimedia applications (audio, video, etc.) where there is not enough time for managing retransmission and packet ordering by TCP, or for applications based on simple question/answer mechanism like SNMP queries, where the higher cost of making a reliable connection is disproportionate to needs.

TCP and UDP are used for many applications. Those that use TCP or UDP services are distinguished by their port number. Modbus TCP uses TCP services. UDP can be used for the Factorycast plug-in.

Application layer

Most network application functions are located in the application layer.

These include HTTP (World Wide Web), FTP (file transfer), SMTP (messaging), SSH (secured remote connection), DNS (matching IP names and addresses) and many others.

The applications generally work below TCP or UDP and are usually linked to a well-known port. Examples:
- HTTP port TCP 80 or 8080;
- Modbus port 502;
- SMTP port 25;
- FTP port 20/21.

These ports are allocated by the Internet Assigned Numbers Authority.

The HTTP protocol (HyperText Transfer Protocol)

It is used to transfer web pages between a server and a browser. HTTP has been used on the web since 1990.

Web servers embedded in Transparent Ready automation devices provide easy access to products anywhere in the world via an Internet browser such as Internet Explorer, Netscape Navigator or others.

BOOTP/DHCP

It automatically provides product IP address settings. This avoids having to find the individual address of each device by offloading the task onto a dedicated IP address server.

The DHCP protocol (Dynamic Host Configuration Protocol) automatically allocates device configuration parameters. DHCP is an extension of BOOTP. The BOOTP/DHCP protocol has 2 components:
- the server to provide the IP network address;
- the client which requests the IP address.

The Schneider Electric devices can be:
- BOOTP/DHCP clients which automatically retrieve the IP address from a server;
- BOOTP/DHCP servers for the device to distribute the IP addresses to network stations.

The standard BOOTP/DHCP protocols are used to provide the faulty device replacement service (FDR).

File Transfer Protocol (FTP)

It provides the basic means for file transfer. FTP is used by many systems to exchange files between devices.

TFTP: Trivial File Transfer Protocol

It is a protocol to simplify file transfer and download codes to devices. For example, it can be used to transfer the boot code in a workstation without a drive unit to connect and download firmware updates for network devices. Transparent Ready devices implement FTP and TFTP to transfer certain data between devices.

- **NTP (Network Time Protocol)**

It is used to synchronise the time on devices (client or server) via a provider server. Depending on the network used, it provides universal time (UTC) with a precision of a few milliseconds on a local area network (LAN) to several dozen milliseconds on a wide area network (WAN).

- **SMTP (Simple Mail Transfer Protocol)**

It provides an e-mail transmission service. It is used to send e-mails from a sender to a recipient via an SMTP server.

- **SNMP (Simple network management protocol)**

The Internet community developed this standard to manage different network components via a single system. The network management system can exchange data with SNMP agent devices. This function enables the manager to view the status of the network and devices, alter their configuration and return alarms in the event of a fault. Transparent Ready devices are SNMP-compatible and can integrate naturally into a network administered via SNMP.

- **COM/DCOM (Distributed Component Object Model) or OLE (Object Linking and Embedding)**

It is the name of the Windows object component technology used for transparent communication between Windows applications. These technologies are used in OFS data server software (OLE for Process Control Factory Server).

9.7 Web services and Transparent Ready

As already explained, as universal services are not suited to industrial usage, component manufacturers have completed the Internet universal service offer with specific functions for automation systems.

Schneider Electric has developed an offer for “transparent” communication between the web and all the levels described above, defining it as web technology embedded in products and services. This offer has a dual basis:

- Industrial Ethernet;
- WEB components.

The aim is to offer **"Services"** with functions enabling the customer to perform specific tasks such as sending data from one PLC to another or trigger an alarm.

"Web technology" means the same as "Internet technology" and comprises: Internet protocols, programming languages such as Java, html, xml, etc. and the tools which have completely changed the ways of sharing information.

Industrial Ethernet services

In addition to universal Ethernet services (HTTP, BOOTP/DHCP, FTP, etc.), eight other types of Ethernet communication services can be provided with:

- Modbus TCP messaging service;
- remote I/O exchange service: I/O Scanning;
- faulty device replacement service: FDR;
- network administration service: SNMP;
- global Data distribution service;
- bandwidth management service;
- time synchronisation service: NTP;
- event notification service: SMTP (e-mail).

Table 11 shows the position of these services in relation to the layers on the network.

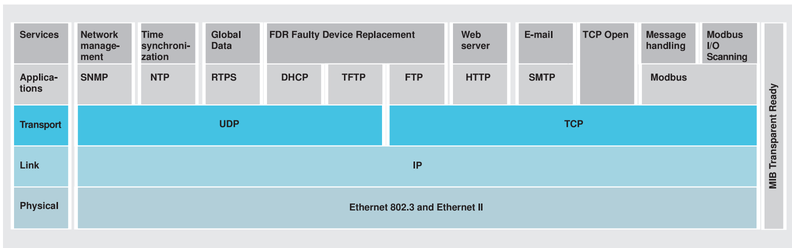


Fig. 11 *Position of Ethernet communication services*

These communication services are divided into three classes:

- Class 10: basic Ethernet communication;
- Class 20: Ethernet communication management (network and device levels);
- Class 30: advanced Ethernet communication.

Table 12 gives a brief summary of the services.

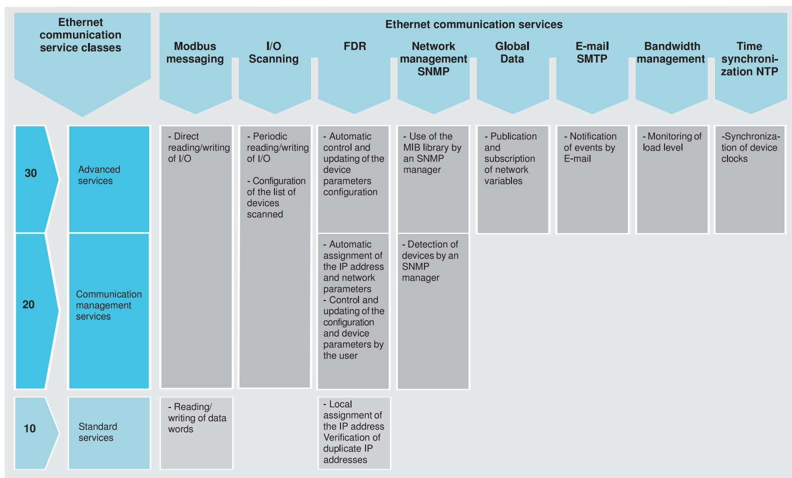


Fig. 12 *Summary of Ethernet services*

Messaging service: Ethernet Modbus TCP

Modbus, the industrial communication standard since 1979, has been applied to Ethernet TCP/IP to make Ethernet Modbus TCP, a fully open Ethernet protocol. Developing an Ethernet Modbus TCP connection does not require any proprietary component or licence purchase. The protocol can be applied to any device that supports a standard TCP/IP communication stack. Specifications are available free of charge from the website: www.modbus-ida.org.

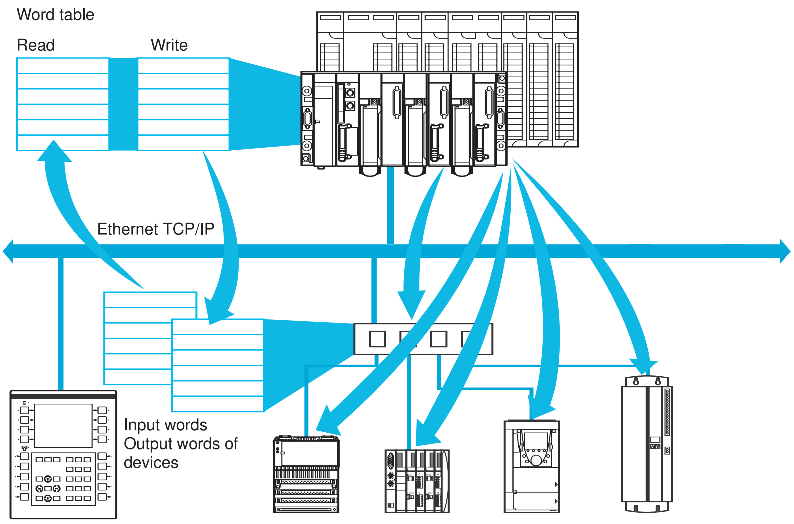
Its simplicity enables any field device, such as an I/O module, to communicate via Ethernet without requiring a powerful microprocessor or a lot of internal memory. Ethernet Modbus TCP has a very simple protocol and high output of 100 Mbps which guarantee its excellent performance enabling this type of network to be used for real-time applications such as I/O scanning.

As the application protocol is identical on Modbus serial link, Modbus Plus and Ethernet Modbus TCP, messages can be routed from one network to another without having to change protocols. Modbus is implemented above the TCP/IP layer, so users also benefit from IP routing which enables devices anywhere in the world to communicate regardless of the distance between them.

IANA (Internet Assigned Numbers Authority) has assigned the Ethernet Modbus TCP with the fixed port TCP 502, thus making Modbus an Internet group standard. The maximum data size is 125 words or registers in read mode and 100 words or registers in write mode.

■ Remote I/O exchange service: I/O Scanning

This service is used to manage status exchange between remote I/Os via Ethernet. After simple configuration with no specific programming, I/Os are transparently scanned by read/write queries using the Ethernet Modbus TCP client/server protocol. This scanning method via a standard protocol is used to communicate with any device that supports Ethernet Modbus TCP. The service offers definition of two word zones, one to read inputs and the other to write outputs *(⇨ Fig.13)*. The refresh periods are independent of the PLC cycle.



↑ Fig. 13 *Remote I/O exchange service: I/O Scanning*

In operation, the module ensures:

- management of TCP/IP connection IP with each remote device;
- product scanning and I/O copying in the configured word zone;
- feedback of status works to monitor service operation from the PLC application:
- use of preconfigured default values in the event of communication problems.

An offer for hardware and software to implement the I/O Scanning protocol on any device that can be connected to Ethernet Modbus TCP can be found on the Modbus-IDA website (www.modbus-ida.org).

Faulty Device Replacement service (FDR)

The faulty device replacement service uses standard address management technology (BOOTP, DHCP) and the FTP or TFTP (Trivial File Transfer Protocol) file management service. This facilitates maintenance of devices connected to Ethernet Modbus TCP.

It replaces a faulty device by a new device and ensures its detection, reconfiguration and automatic restart by the system. The main steps in replacement are:

- a device using the FDR service has a fault;
- a similar product is taken from the maintenance stock, preconfigured with the device name of the faulty device and reinstalled on the network. Depending on the device, it can be addressed with rotary selectors (e.g. Advantys STB distributed I/Os or Advantys OTB) or with the device's integrated keyboard (e.g. Altivar 71 speed controller);
- the FDR server detects the new device, assigns an IP address to it and transfers the configuration parameters;
- the substitute device checks that all the parameters are compatible with its own characteristics and switches to operation mode.

Network administration service: SNMP

SNMP (Simple Network Management Protocol) monitors and controls all the Ethernet architecture components from a network management workstation to make a quick diagnostic of problems that arise. It is used to:

- interrogate network components such as computers, routers, switches, bridges and terminal devices to view their status;
- obtain statistics on the network the devices are connected to.

This network management software uses the traditional client/server model. However, to prevent confusion with other communication protocols using the same terminology, it is referred to as a network manager or SNMP agent.

Transparent Ready devices can be managed by any SNMP agent, including HP Openview, IBM Netview and, of course, the Transparent Ready ConnexView network management tool. The standard SNMP protocol (Simple Network Management Protocol) provides access to the configuration and management object in the device MIB's (Management Information Bases). MIB's must comply with certain standards to make them accessible for all management tools, though depending on the complexity of the devices, manufacturers may add some objects to the private MIB. The Transparent Ready private MIB has specific management objects for Transparent Ready communication services such as Modbus, Global Data, FDR, etc. These objects facilitate device installation, implementation and maintenance.

Transparent Ready devices support 2 SNMP network management levels:

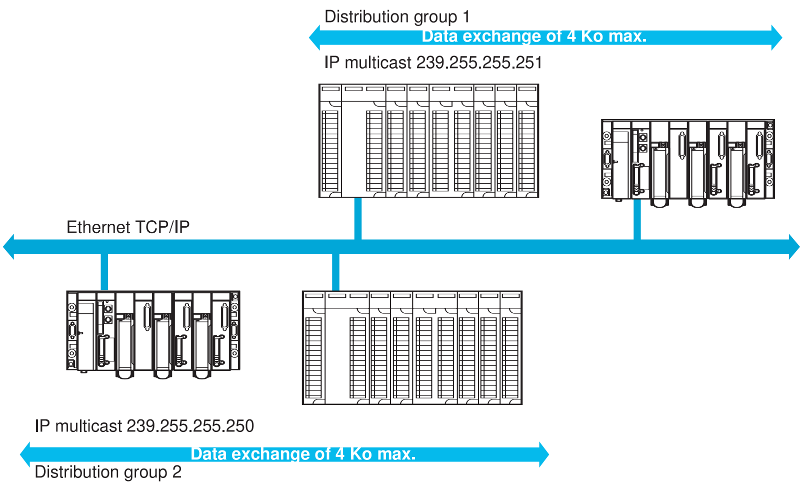
- MIB II Standard interface: a basic network management level is accessible via this interface. The manager uses it to identify architecture component devices and retrieve general information on the configuration and operation of Ethernet TCP/IP interfaces;
- Transparent Ready MIB interface: this interface enhances Transparent Ready device management. The MIB has a set of information enabling the network management system to supervise all the Transparent Ready services. It can be downloaded from the FTP server of any Transparent Ready Ethernet module on a PLC.

Global Data distribution service *(⇨ Fig.14)*

The Global Data service ensures multicast data distribution in real time between stations in the same distribution group. It can synchronise remote applications or share a common database amongst distributed applications. Exchanges are based on a standard Publisher/Subscriber protocol guaranteeing optimal performance with a minimum network load. The RTPS protocol (Real Time Publisher Subscriber) is promoted by Modbus-IDA (Interface for Distributed Automation) and is already a standard adopted by several manufacturers. 64 stations can take part in exchanges via Global Data within the same distribution group. Each station can:

- publish a variable of 1024 bytes. The publishing period can be configured for 1 to n periods of the processor master task;
- subscribe from 1 to 64 variables.

The validity of each variable is controlled by Health Status bits linked to a refresh timeout configurable from 50 ms to 1 s. Access to a variable element is not possible. The total size of subscribed variables reaches 4 contiguous Kbytes. To optimise Ethernet performance even further, Global Data can be configured with the multicast filtering option which, combined with the switches in the ConneXium range, multicasts data only on the Ethernet ports with a station subscribing to the Global Data service. If the switches are not used, Global Data are multicast on all the switch ports.



↑ Fig. 14 *Global Data distribution service*

NTP time synchronisation service

The time synchronisation service is based on NTP (Network Time Protocol) to synchronise Ethernet TCP/IP client or server time from a server or any other time reference source (radio, satellite, etc.).

The Ethernet Modbus TCP communication modules: – 140 NOE 771 11 on the Modicon Quantum Unity V2.0 (or higher) automation platforms; TSX ETY 5103 on the Modicon Premium Unity V2.0 (or higher) automation platforms – have an NTP client component. These modules can connect to an NTP server using a client query (unicast) to set their local time. Every so often (1 to 120 seconds), the module clock is updated with an error of less than 10 ms for regular processors and 5 ms for high-performance processors. If the NTP server cannot be contacted, the Ethernet Modbus TCP module uses a standby NTP server.

SMTP e-mail notification service

This simple e-mail notification service can be programmed. The PLC application uses it to notify an event with conditions. The PLC creates the e-mail automatically and dynamically to alert a defined local- or remote-connected recipient. It should be noted that this service is available with the latest Ethernet communication modules for Modicon Premium and Modicon Quantum PLC's, and with the latest processors with Ethernet connection on the same PLC's used with Unity Pro software. There is also a more complete service independent of the PLC application available with the active Web server module FactoryCast HMI.

The mechanism is simple and effective: predefined message headers are linked to the e-mail body which is created dynamically from the latest information from the PLC application. The PLC application prepares the message according to preset conditions. A function block is used to select one of the 3 predefined headers, create the e-mail with the variables and text (up to 240 bytes) and send it directly from the PLC. The three headers each contain the following predefined elements:

- list of e-mail recipients;
- name of sender and subject.

This information is defined and updated by an authorised administrator using configuration web pages.

Web services *(⇨ Fig.15)*

The level of a Web Server service is defined by 4 service classes identified by a letter:

Class A

Transparent Ready devices with no web services.

Class B

Basic web level for managing static web pages pre-configured in a Transparent Ready device. It offers device diagnostic and monitoring services using a standard web browser.

Class C

Configurable web level for customising the website of a Transparent Ready device with web pages defined by the user for the needs of an application. The client procedure diagnostic and monitoring can be run from a standard web browser. The Factorycast offer includes this level of web functionality as well as tools to facilitate management and modification of embedded websites:

Class D

Active web level for running specific processes in the Transparent Ready Web Server device itself. This processing capacity can be used for pre-calculation, real-time database management, communication with relational databases and sending e-mails. Communication between the browser and the server is thus reduced and optimised. The Factorycast offer includes this level of web functionality as well as tools to configure processes to run in the Web Server device.

Web server class		Web services: Maintenance	Web services: Monitoring and IT link	Web services: Diagnostics	Web services: Optional
D	Active Web server	- User website update	- Autonomous execution of specific services (e.g. alarm notification by E-mail, exchange with databases, calculations, ...) - SOAP/XML (client/server)	- User-defined states	- User documentation
C	Configurable Web server		- PLC variables editor - Remote commands - User Web pages - SOAP/XML (server)	- Communication service diagnostics - State of internal device resources	
B	Standard Web server	- Remote device software update - Remote auto-tests	- Device description - Data viewer	- Device status - Device diagnostic	- Configuration of network parameters and Ethernet communication services - Device documentation
A	No Web server	- No Web service			

↑ Fig. 15 *Web services*

Transparent Ready devices

These are identified by a letter defining the level of web services followed by a number defining the level of Ethernet communication service. E.g.:

- Class A10: a device with no web service and with basic Ethernet services;
- Class C30: a device with a configurable Web Server and advanced Ethernet communication services.

The services offered by a higher class include all those supported by a lower one. The range of Transparent Ready devices is divided into 4 major families:

- field devices (simple or intelligent) like sensors and pre-actuators.
- controllers and PLC's;
- HMI (Human/Machine Interface) applications;
- dedicated gateways and servers.

The selection table in *figure 16* can be used to choose Transparent Ready devices according to the requisite service classes.

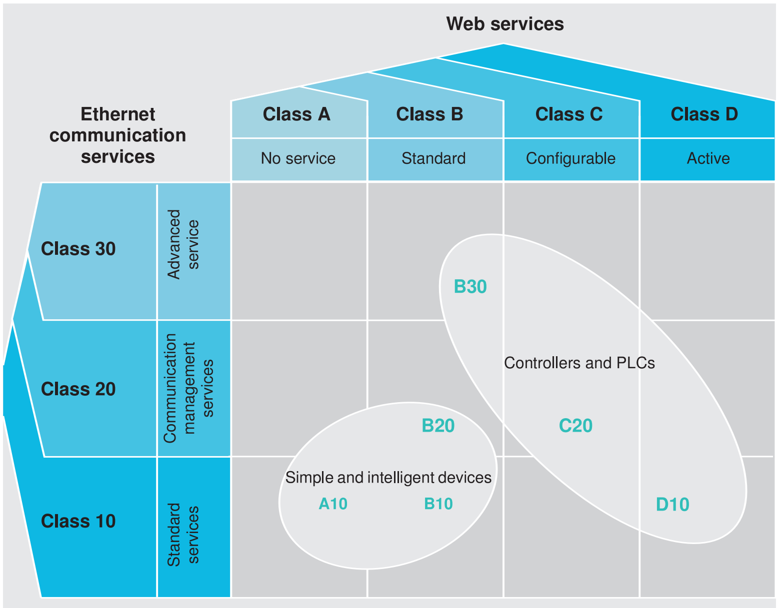


Fig. 16 Selection table

9.8 CANopen bus

General description

CAN (Controller Area Network) is a serial system bus developed by Bosch for the automotive industry. It was presented with Intel in 1985 and designed to reduce the amount of wiring in a vehicle (there can be as much as 2 km of wires in a car) by making control organs communicate via a single bus rather than dedicated lines, thereby reducing the weight of the vehicle.

High immunity to electromagnetic interference combined with reliable real-time transmission caught the attention of industrials. In 1991, the CiA (CAN in Automation) consortium was set up to promote the use of CAN in industry (see the site: http://www.can-cia.de/).

In 1993 the CiA published the CAL (CAN Application Layer) specifications describing transmission mechanisms without giving details on when and how to use them. In 1995 the CiA published DS-301 communication profile: CANopen.

Several applications level 7 layers as in *figure 17* are defined to the CAN standard:

- CANopen;
- DeviceNet;
- CAL;
- SDS;
- CAN Kingdom.

In 2001 the CiA publication of DS-304 enabled integration of level 4 safety components on a standard CANopen bus (CANsafe).

A description of CANopen technical features follows.

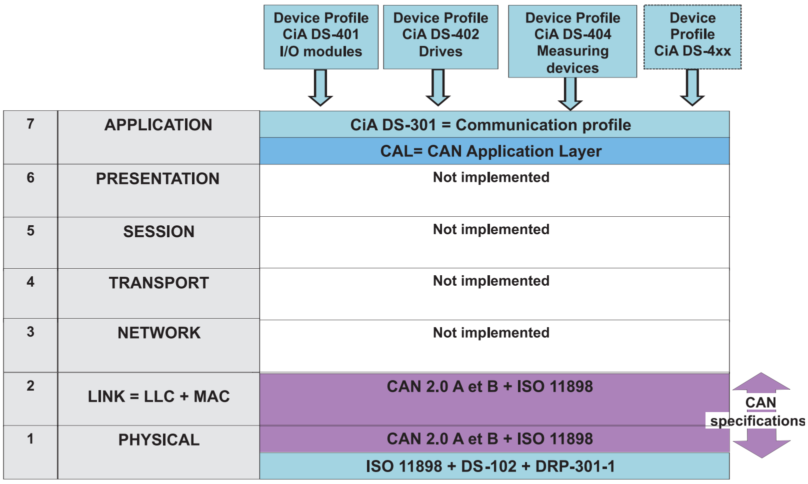


Fig. 17 *CAN bus layers*

Advantages of CANopen

CANopen uses short frames

Because it has high immunity to electromagnetic interference (EMI), CANopen enables a machine or plant to work with precision, even in an atmosphere of high interference. The short CANopen frames and CANground connection offer the same capacities for every device connected to the network and protect them from electromagnetic interference (EMI).

CANopen for reliable transmission

When a CANopen device transmits data, the system generates and automatically prioritises the message. A telegram cannot be lost because of a collision problem and time is not lost waiting for the network's next idle status. With CANopen data transmission is absolutely reliable. This is one reason why CANopen is used in medical equipment requiring reliable networks.

CANopen eliminates time loss

Time losses always waste time and money. CANopen is designed to cut time losses to an absolute minimum. With a Hamming bit length of 6, CANopen has a high error detection capacity and a very good correction mechanism. An undetected error probability of 1000 years makes CANopen the most reliable network for machines and plants.

1 bit of error every 0.7s at 500Kbps, 8hrs a day, 365 days a year.

When the network detects an error condition, first device status monitoring feature is the watchdog. Each diagnostic message contains the source and cause of the error, thus enabling a rapid response and a less time lost.
A further diagnostic is developed to improve complex CANopen device diagnostics and uphold the network. In addition, there is an error log to help detection of random errors.

9

CANopen: Performance and flexibility

The main reason for using a network is its performance and flexibility in adapting exactly to the needs of the application. CANopen offers a unique device for data transmission adaptation. Based on the consumer / producer model, CANopen can transfer data in general broadcast, point-to-point, status change and cyclic modes. This means data are transferred only if necessary or on a specific time scale. Process data objects (PDO) can be configured individually. Parameters can be changed at any time.

• Performance

Though CANopen is highly flexible, the network response is very fast. 256 digital I/O points can be processed at 1 Mbps in less than 1 ms Source: Grid Control. Profibus-DP typically requires about 2 ms at 12 Mbps for the same data transfer. In addition to fast response, message priority control can be changed.

With CANopen, data transmission can be adapted to suit application requirements.

CANopen cuts costs

CANopen offers ease of installation and low-cost devices. It does not require an equipotential link between devices like many field buses do. A poor connection not only causes communication errors, it also damages field bus devices.

Furthermore, CANopen components are produced in great quantity and this lowers their cost. Schneider Electric passes this advantage on to customers.

Prices of 10 to 20% less than for other field buses can be expected.

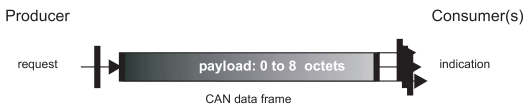
How CAN works

CAN is a serial bus based on a publisher/subscriber model in which a publisher sends a message to subscribers. CAN was developed with broadcast architecture.

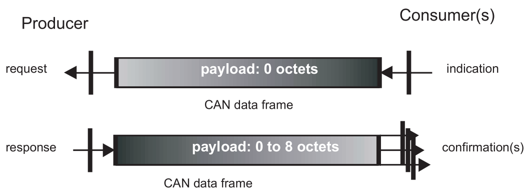
The sender (publisher) sends the message with an identifier. The recipients (subscribers) filter messages from the bus based on their send criteria so if a message is intended for them, they read and process it. The recipient then becomes a sender (⇨ *Fig. 18*).

The diagram shows the push (send) mode of the publisher/subscriber model. CAN also supports its pull (receive) mode. A client can send a message based on a remote transmission request (RTR), which is a CAN frame with RTR flags (status bits). When the producer receives such a request, it transmits the related answer (⇨ *Fig. 19*).

In a broadcast architecture, the network nodes can transmit at the same time. CAN has 2 mechanisms to deal with this: first, a sender surveys the communication artery to check if another node is already transmitting. If the artery is free, the node starts to transmit. Several nodes can start transmitting but never at the same time. This problem is overcome by a priority system.



↑ *Fig. 18* *CAN operation*



↑ *Fig. 19* *CAN push / pull (publisher/subscriber model)*

A CAN frame (⇨ *Fig.20*) starts with a start of frame bit (SOF) followed by eleven identification bits, from the most to the least significant. The next bit is the remote transmission request bit, followed by 5 control bits and up to 8 bytes of working data. The control bits are: ID extension (IDE), a reserve bit and 3 bits of working data length code (DLC) in bytes. A frame check sequence (FCS) of up to 8 bytes follows the working data. The transmitter sends a recessive acknowledgement bit (ACK) which is replaced by a dominant bit by receivers which have received the frame with no error.

Fig. 20 *CAN Frame*

The end of frame (EOF) bit denotes the end of frame transmission.

The bus's intermission frame space (IFS) bit must be recessive before the next frame starts. If no node is ready to transmit, the bus stays as it is. Bit codes have 2 values, dominant and recessive. If 2 nodes transmit at the same time, the receiver will only see the dominant value. In binary code, '0' is dominant and '1' is recessive. When a node transmits, it is always heard on the bus. If it transmits a recessive bit and receives a dominant one, it stops transmitting so it can continue receiving the dominant bit. This simple system prevents collisions on the CAN bus. The message with the smallest identifier has priority on the bus.

CAN is a system bus with carrier sense multiple access, collision detection and arbitration of message priority (CSMA/CD+AMP). As collisions never occur, the CAN bus is often said to be CSMA/CA (carrier sense multiple access and collision avoidance).

The message frame described in *figure 21* is the base frame. For applications requiring more identifiers, there is the CAN extended frame format. The extended frame has 18 extra identifier bits in the header, after the control bits. This extends the range from 211 to 229 different identifiers. The two frame types can coexist in a single bus.

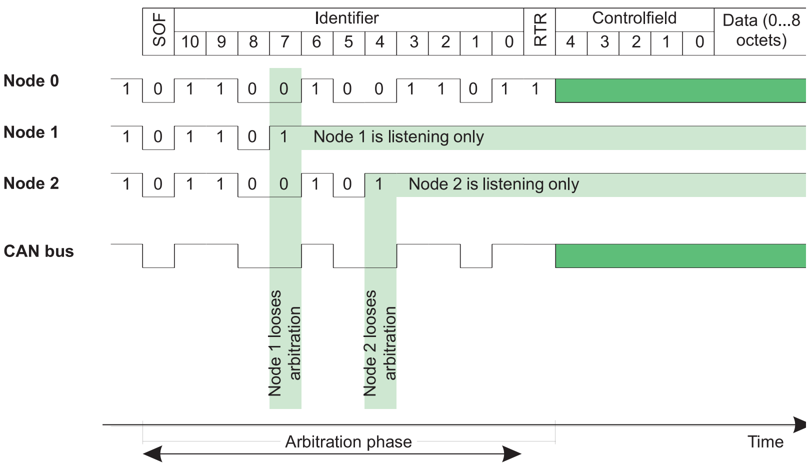


Fig. 21 *Typical CAN message*

CAN has several means of detecting wrong messages:

- the frame check sequence (FCS) contains the frame's cyclic redundancy check (CRC). The receiver checks the frame's CRC and compares the result against the FCS. If they are not the same, the frame has a CRC error;
- the receiver detects errors in the frame structure. If the frame structure is faulty, the frame has a format error;
- the receiver of a frame publishes a dominant acknowledgement bit (ACK) if it has received an error-free frame. If the transmitter does not receive this bit, it sends an error acknowledgement;
- CAN uses non return to zero (NRZ) coding with bit stuffing. If the sender has to transmit 5 consecutive bits of the same type, it inserts another bit of the opposite type. Bit stuffing enables the receiver to synchronise with the bit chain. The receiver removes the stuffing bits from the data frame. If there are more than 5 consecutive bits of the same type, the receiver detects a stuffing error.

There are several levels of protocol application that can be used with CAN, such as DeviceNet and CANopen. CAN itself does not define a protocol application level.

Overview of CANopen

CANopen defines an application layer and a communication profile based on CAN.

CANopen defines the following communication objects (messages)

- process data object (PDO);
- service data object (SDO);
- network management object (NMT);
- special function object (SYNC, EMCY, TIME).

Properties

- serial data transmission based on CAN;
- up to1 Mbps;
- efficiency approx. 57%;
- up to 127 nodes (devices);
- several masters allowed;
- interoperability of devices of different brands.

Object dictionary

The object dictionary *(⇨ Fig.22)* is an interface between the application program and the communication interface.

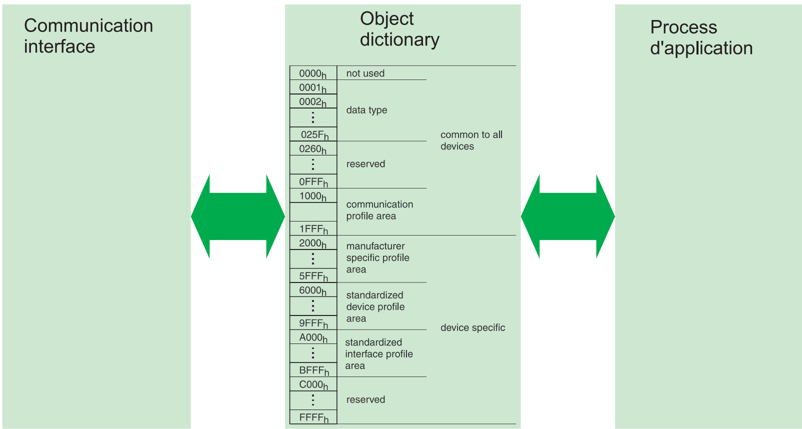


Fig. 22 *Object dictionary*

Schneider Electric

• **Process data object (PDO)**
Process data objects (PDO) are used for their speed of process data transmission. A PDO can carry up to 8 bytes of working data, the maximum for a CAN frame. PDO transmission uses the CAN producer/consumer model extended by synchronised transfers. Synchronised PDO transfer relies on SYNC message transfer on the CAN bus. A PDO is sent in cyclic mode after a number (configurable from 1 to 240) of SYNC messages received. It is also possible to await availability of application process variables and send a PDO after the next SYNC message is received. This is called **acyclic synchronised transfer.**

• **Service data objects (SDO)**
Service data objects (SDO) transmit parameters. SDOs give remote devices access to the object dictionary. There is no limit for the length of an SDO. If the working data cannot adapt to the CAN frame, they are divided into several CAN frames. Each SDO is acknowledged.

SDO communication uses the point-to-point mode, with one point acting as server and the others as clients.

• **Network management (NMT)**
Network management objects (NMT) change or check the status of CANopen devices *(⇨ Fig.23)*. An NMT message has a CAN 0 identifier. This gives NMT messages top priority.

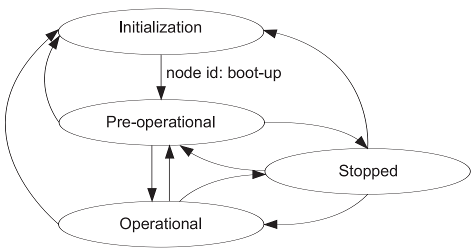


Fig. 23 *Network management*

An NMT message always has 2 bytes of working data in the CAN frame. The first byte contains the encoded NMT command and the second the ID of the addressed node.

A CANopen device starts at initialisation status when the ON button is pressed. When the device has completed its initialisation, it delivers a starting NMT object to notify the master.

The collision detection protocol for monitoring device status is implemented with NMT objects.

• **Special function objects (SYNC, EMCY, TIME)**
CCANopen must have a SYNC producer to synchronise CANopen node actions. The SYNC producer periodically transmits the SYNC object. The SYNC object identifier is 128. This can lead to a delay caused by the priority of this message.

An internal device error can trigger an emergency message (EMCY). The response of EMCY clients depends on the application. The CANopen standard defines several emergency codes. The emergency message is transmitted in a single CAN frame of 8 bytes.

A CAN frame with the ID CAN 256 and 6 bytes of working data can be used to transmit the time to several CANopen nodes.

The TIME message contains the date and time in an object of Time-Of-Day type.

• **Watchdog systems**
CANopen has 2 device status monitoring methods. One is a network manager which regularly scans every device at configured intervals. This method is called "Node guarding" and has the drawback of consuming a lot of bandwidth.

The other is a message sent regularly by each device. This method uses up much less bandwidth than node guarding.

• **Network length and output rate**

The length is restricted by the output rate due to the bit priority procedure *(⇨ Fig.24)*.

Output (Kbps)	1000	800	500	250	125	50	20	10
Max. length (m)	20	25	100	250	500	1000	2500	5000

Fig. 24 *Network length and output rate*

In documents on CANopen, the most common maximum length mentioned for an output rate of 1 Mbps is 40 metres, calculated without electrical insulation such as is used in Schneider Electric CANopen devices. When this insulation is included, the minimum bus length is 4 metres at 1 Mbps. However, experience shows that, in practice, the maximum length is 20 metres.

Baud rate (kbps)	**1000**	**800**	**500**	**250**	**125**	**50**	**20**	**10**
L max. (m) (1)	0,3	3	5	5	5	60	150	300
ΣL max. (m) local star (2)	0,6	6	10	10	10	120	300	600
Interval min. (m) 0,6 x ΣL local (3)	□	3,6	6	6	6	72	180	360
ΣL max. (m) on all bus (4)	1,5	15	30	60	120	300	750	1500

Fig. 25 *Length limitations for branching devices*

Limitations on branching devices must be taken into account and are set by the parameters in *figure 25*.

(1) L max.: maximum length of branching device.
(2) EL max. local star: maximum value of total length of branching devices at the same point when a multiport distribution box is used to create a local star topology.
(3) Interval min.: Minimum distance between 2 distribution boxes. Maximum length of branching devices at the same point. This value can be calculated individually for each device: the minimum interval between two branching devices is 60% of the total length of devices at the same point.
(4) EL max. (m) of total bus: maximum value of the total length of all intervals and branching devices on the bus.

Combinations according to compliance classes

Schneider Electric has defined compliance classes for CANopen master and slave devices similar to Ethernet Modbus TCP and web services classification. The compliance classes specify which systems a device can support and ensure the upward functional compatibility of each class *(⇨ Fig.26)*.

Characteristics					
Conformance classes			**M10**	**M20**	**M30**
Layer settings	Slave ID		1-16	1-63	1-127
	Data rate	**kbps**	125, 250, 500	M10 + 50, 1000	M20 +10, 20, 800
	LSS		–		Master
Devices supported			16	63	126
NMT (Network Management object)	NMT Master		NMT Master , according to DS301		–
	CANopen Manager		–		NMT master, according to DS301. Configuration Manager according to DSP302
	Boot-up procedure		according to DSP302		
	Time stamp		–		Producer
	Auto configuration		–		support
SDO (Service Data Object)	SDO Client		1	1	2
	SDO Server		–	1	1
	SDO Manager		–		1
	SDO data transfer		Expedited, segment transfer		Expedited, segment block transfer
PDO (Process Data Object)	COB-ID		ReadOnly	Read/Write	Read/Write
	PDO TT		254, 255	M10 +0, 1-240	
	PDO Inhibit Time		–	TPDO's (Read/Write)	
	PDO Event Timer		–	TPDO's (Read/Write)	RPDO's & TPDO's (Read/Write)
SYNC	SYNC		–	producer	producer/consumer
	TRIGGER		–		producer
EMCY			consumer	producer/consumer	
HEALTH	Heartbeat		16 consumers 1 producer	63 consumers 1 producer	126 consumers 1 producer
	Node guarding		no	yes	yes
Parameters	Store parameters		no	yes	yes
Conformance classes			**S10**	**S20**	**S30**
Layer settings	Slave ID		1-63	1-127	1-127
	Data rate	**kbps**	125, 250, 500	S10 + 50, 1000	S20 +10, 20, 800
	LSS		–		Slave
Diagnostic devices	Diagnostic local		–	LED or display	
NMT (Network Management object)	NMT slave		b Start remote node b Stop remote node b Enter pre-Operational b Reset node b Reset communication		
	Time stamp		–		consumer
SDO (Service Data Object)	SDO Client		–		1
	SDO Server		1		2
	SDO data transfert		Expedited, segment transfer		Expedited, segment, block transfer
PDO (Process Data Object)	COB-ID		ReadOnly	Read/Write	Read/Write
	PDO TT		254, 255	S10 +0, 1-240	
	PDO mapping parameters		FIX (Read)		–
	Connection set		Predefined connection set	Free	
	PDO Inhibit Time		–	TPDO's (Read/Write)	
	PDO Event Timer		–	TPDO's (Read/Write)	RPDO's & TPDO's (Read/Write)
SYNC	SYNC		–	consumer	producer/consumer
	TRIGGER		–		consumer
EMCY			producer	producer	consumer/producer
HEALTH	Heartbeat		1 consumer 1 producer		
	Node guarding		no	yes	yes
Parameters	Store parameters		no	no	no

Nota : S00 and M00 are for products not 100% compliant to the conformance class.

↑ Fig. 26 *CANopen compliance*

Table 27 shows the best possible product combinations based on the compliance classes.

Compliance class	S10	S20	S30
M10	Possible combination	Usage restriction	
M20			
M30			

Fig. 27 *Product combinations*

It is however possible to use a slave device with a master of a lower compliance class (e.g. S20 with M10) or a master device with a slave of a higher compliance class (e.g. M10 with S20), by using only devices supported by the lower compliance class.

9.9 Ethernet and CANopen synergy

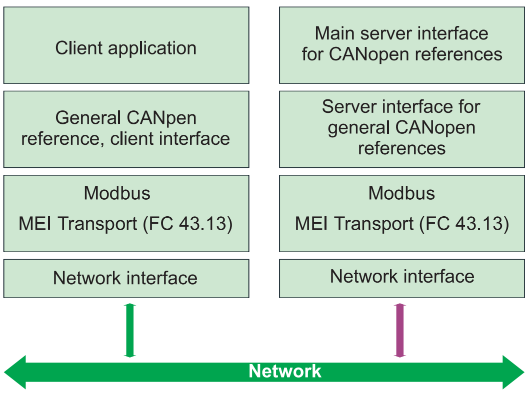


Fig. 28 *Ethernet / CANopen synergy*

A common communication profile (DS-301) defines amongst other things assignment of COB-ID identifiers for every type of message.

Profiles specific to each product family such as discrete I/Os (DS-401), analogue I/Os, speed controllers (DS 402) and encoders describe the combined objects.

CAN in Automation and Modbus-IDA have worked together to create a standard for complete transparency between CANopen and Ethernet Modbus TCP. The result of this collaboration is the CiA DSP309-2 specification defining the communication standard between an Ethernet Modbus TCP network and a CANopen bus. The specification defines mapping services enabling CANopen devices to communicate in an Ethernet Modbus TCP network via a gateway *(⇨ Fig. 28)*.

Access to information on a CANopen device is available in read/write mode for a great many device control functions.

9.10 AS-Interface (AS-i) Bus

General description

Today, machine are fitted with many sensors and actuators. Upgrading possibility, maintenance and safety must be taken into consideration. AS-Interface is the floor level network filling the needs of industrial automatism's.

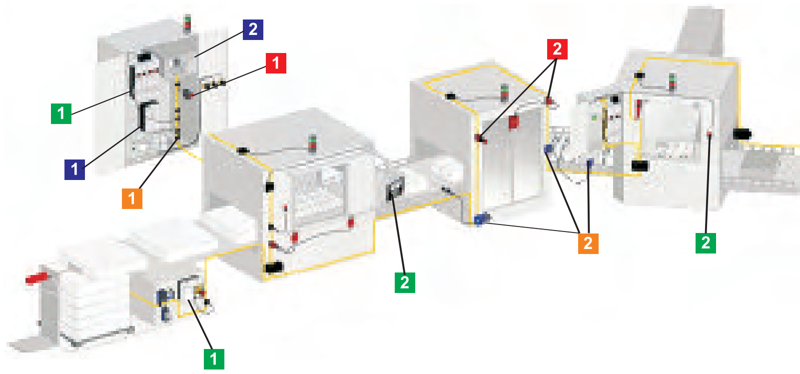
AS-Interface carry data and power in a two wire single cable. Components connected to the network can easily be replaced for maintenance purposes. The new device receives automatically the address of the former product.

AS-Interface is a highly efficient networking alternative to the hard wiring of field devices, like sensors, actuators and PLC's.

All Schneider Electric offer complies with the AS-i standard as defined by the AS-International association. It is an "open" technology supported by leading automation vendors which guaranty interchangeability and interoperability between products.

AS-Interface, as shown *(⇨ Fig. 29)*, is a mature protocol which, from more then 10 years, has proven to be a user friendly and reliable system in hundreds of thousands of applications, including conveyors, process control, bottling plants, electrical distribution systems, airport carousels, elevators and food production.

9.10 AS-Interface (AS-i) Bus



↑ *Fig. 29* *AS-Interface*

- 1 Interface IP20
- 2 Interface IP67
- 1 Control component
- 2 Dialog component
- 1 Safety monitor
- 2 Safety interface
- 1 Power supply
- 2 AS-i Master

AS-Interface is identify by a yellow cable *(⇨ Fig.30)* of a particular shape which makes inversion impossible. This cable is self sealing and sensors / actuators are equipped with punch through connectors allowing tool less connection or displacement.

AS-Interface is exclusively a field bus of the master / slave type, master being a PC, a PLC or a controller which receives information form sensors and controls the actuators thorough the installation. AS-Interface has other benefits as a free topology which allows to operate in a star , point to point, line, tree, ring technology network.

↑ *Fig. 30* *AS-Interface components*

During 10 years, AS-Interface was only suitable for discrete I/O. A few vendors had slow analogue devices i.e. temperature sensors; level sensors, but any time these were proprietary products and the number of addresses 0 to 31 was a major restriction.

AS-Interface consortium has launched a new version (V2). With this one, the number of addresses has doubled with a possibility of 62 discrete I/O's per master. But the major change is the capacity to connect any analogue sensors / actuators to any master, trough an AS-Interface. Its is also possible to mix discrete and analogue devices. Although the number of slaves will be reduced, operation is still manageable.

This new version introduced changes at the diagnostic level. The former version was only able to detect faults of the network. V2 version takes into account all defects including defects into the devices.

Obviously, V2 and V1 operating on the same network are compatible.

AS-Interface benefits (⇨ Fig.31)

Simplicity	**The simplicity of the wiring system is due to:** • a single cable to connect all actuators and sensors in an automation system; • built-in communication management.
Cost reduction	**Cost can be cut by up to 40% by:** • shorter design, installation, commissioning and upgrade times; • smaller housings due to more compact devices and elimination of intermediate housings now that most functions are controlled ex-machine; • elimination of control cable ducts.
Safety	**AS-Interface helps increase reliability, operational availability and safety:** • wiring errors are impossible; • no risk of poor connections; • high immunity to electromagnetic interference (EMC); • machine safety functions can be fully integrated into AS-Interface.

↑ *Fig. 31* *AS-Interface benefits*

AS-Interface components

These are grouped into families (⇨ Fig.32) For more information, please refer to the Schneider Electric product catalogues.

Generic device interfaces	These enable any standard device (sensor, actuator, starter, etc.) to be connected to the AS-Interface. They offer wide freedom of choice and are especially suited to machine modifications and improvements previously done by conventional wiring. These interfaces are available for mounting in housings (IP20) or directly on the machine (IP67).
Dedicated interfaces and components	Dedicated interfaces (communication modules, etc.) are used for communication with the AS-Interface cable. Dedicated components are embedded in an interface and can be connected directly the AS-Interface cable. This makes short work of wiring but the choice is not as wide as with generic components.
Master	This is the central component in the system; its function is to manage data exchanges with the interfaces and components (also called slaves) throughout the plant. It can take: - 31 interfaces or components in version V1 (cycle time 5 ms); - 62 interfaces or components in version V2 (cycle time 10 ms). The master is: - either embedded in a PLC, e.g. as an extension, - or connected the field bus, where it acts as a gateway.
AS-Interface power supply	Extra-low voltage of 29.5 to 31.6V for interfaces and components powered via the AS-Interface cable. It is protected against over-voltage and short circuits. This is the only type of supply that can be used on an AS-Interface line. As the AS-Interface cable has restricted current, it is sometimes necessary to add a further supply for some circuits, in particular for actuators.
Flat cable	The yellow cable connected to the power supply ensures two functions: - data transmission between master and slaves; - powering sensors and actuators. The black cable connected to the auxiliary 24V supply powers the actuators and the sensors with insulated inputs. The mechanical profile of the cables makes polarity inversion impossible; the materials used allow for fast reliable connection of the components. When a device is disconnected, e.g. for alteration purposes, the cable recovers its initial shape by self-sealing. These cables support 8A maximum and are available in two versions: - rubber for standard applications; - TPE for applications where the cable may be splashed with oil.
Safety solutions AS-Interface (See section 6 on safety)	Standard process information can be transmitted at the same time and by the same media as information safety up to level 4 of standard EN 60954-1. Integration into AS-Interface by adding a monitor and safety-related components connected to the yellow AS-Interface cable. Safety information is only exchanged between the safety monitor and its components and is transparent for the other standard functions. This means a safety system can be added to an existing AS-Interface network.
Addressing terminal	As the components are connected in parallel on the AS-Interface bus, a different address must be assigned to each. This function is ensured by a terminal connected individually to each components.

↑ *Fig. 32* *AS-Interface components*

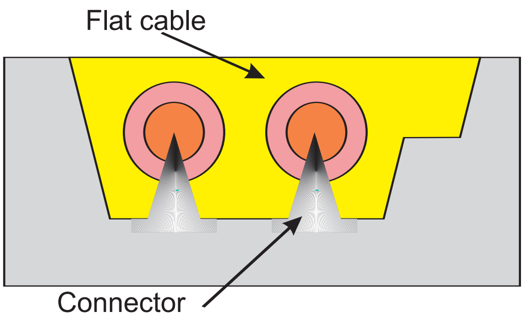


Fig. 33 AS-Interface connection

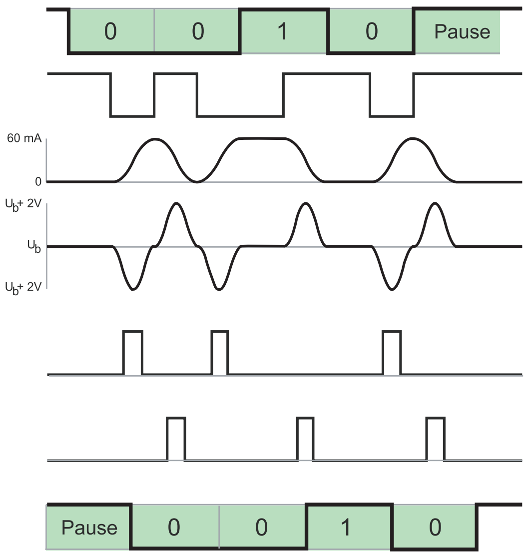


Fig. 34 Voltage and current waveforms

Operating principles AS-Interface network

Connection

Connection hardware uses punch trough connector also named “vampire connector”. The connector has two pins which make the connection through the insulating material of the cable. The two halve parts of the connector are then screwed together to make a reliable connection.

This system (⇨ Fig. 33) is standardised and any type of installation can be made up to IP67 protection.

Signal modulation

AS-Interface has been designed to run without a terminal plug in any configuration. Operation principle uses current modulation based on Manchester encoding. Two chokes, inserted in the power supply convert this current in a sine wave. The shape of the generated signal avoid the use of shielded cables (⇨ Fig.34).

Length of the network

Length is linked to signal distortion and voltage drop. Maximum length between two slaves shall not exceed 100 m (⇨ Fig.35). On can increase this distance by the use of repeaters with the following limits:

- no more than two repeater per line,
- maximum distance to the master shall not exceed 300 m,
- a passive terminal extends the distance from 100 m to 200 m,
- an active terminal extends the distance to 300 m.

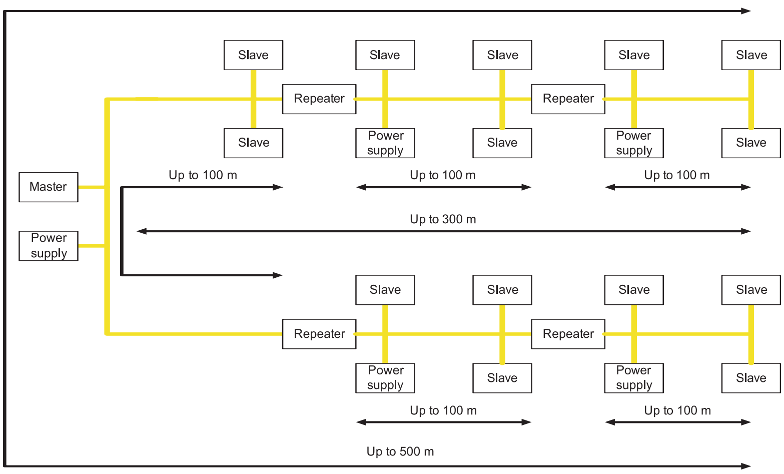


Fig. 35 AS-Interface limits

Protocol principle

Protocol principle is base on a single master protocol. The master send a request to all slaves in a row, these ones send the requisite data (⇨ *Fig.36*). When all slaves have send an answer, a new cycle begins and so on. Cycle time depends upon the number of slaves and is easy to calculate.

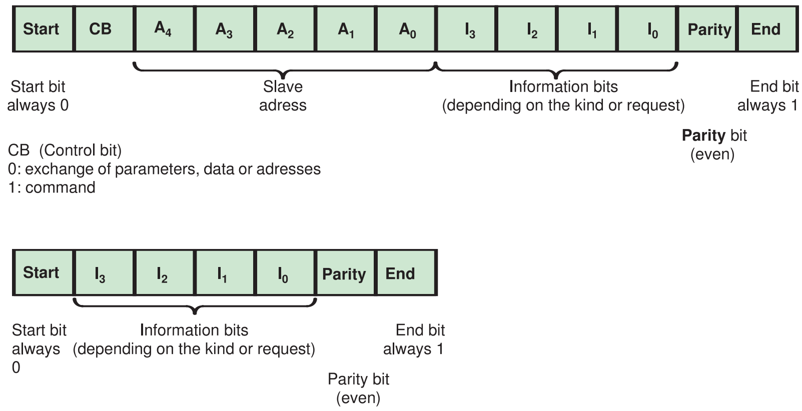


Fig. 36 *Master slaves frame*

AS-Interface use several means to guaranty the dependability of the data transmission. The signal is checked by the receiver; if the form is incorrect, the message is discarded. A check sum bit, added to a short message (7 and 14 bits), secure the logic content of the information. The master dead time causes the acknowledgement (⇨ *fig.37*).

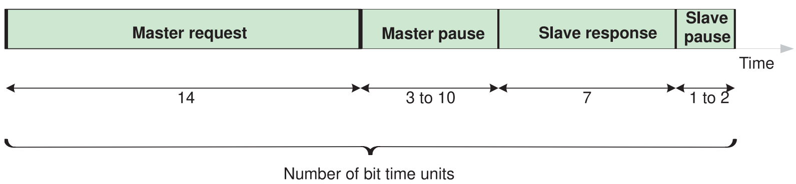


Fig. 37 *Response time constitution*

Length of a bit is 6 ms. At a rate of 166.67 Kbits/s, adding all the dwell bits, the cycle time cannot exceed 5082 µs.

- **Each cycle can be divided in 3 parts**
  - data exchange,
  - system supervision,
  - updating / slave insertion.

Master's AS-Interface profile tailors its actual capabilities. In general, it has the following functions:
- initialise the system,
- identify the connected slaves,
- send the slaves parameters to the slaves,
- check the integrity of the process data with the slaves,
- monitor the system diagnostics (status of the slaves, status of the power supply etc.),
- transmit all detected fault to the system supervisor (PLC, etc.),
- reconfigure the system if any modification is made to it.

Slaves decipher requests issued from the master and sent the answer with no delay. However, as slave will not answer to an incorrect or inappropriate request. Functional capacity of a slave is defined by its AS-Interface profile.

Topology and AS-Interface wiring

The absence of restrictions allows for all sorts of system configurations, some of which are illustrated below (⇨ *fig.38*).

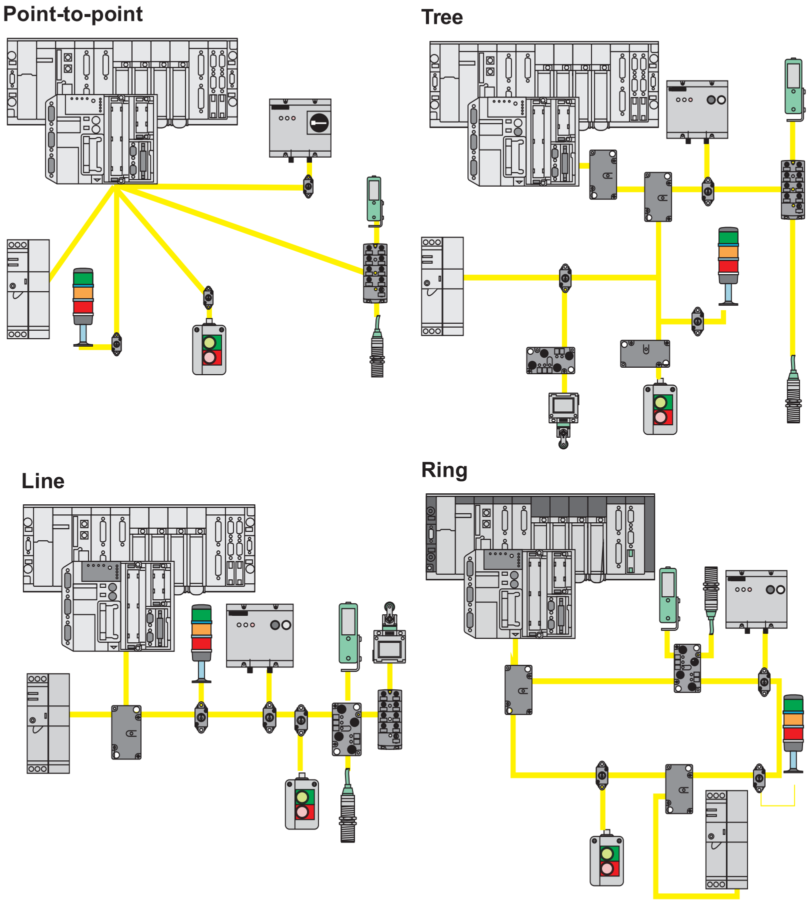


Fig. 38 *System configuration*

AS- interface versions

The fisrt one (V1) has been updated to V2.1 which adds the following improvements:

- capacity to connect 62 slaves (V1 limit is 31);
- capacity to transmit a slave fault message without disconnecting the slave which remains able to communicate when continuity of service is a critical issue;
- support of analogue slaves.

AS- interface profile

AS-Interface equipment profile tailors its capabilities. Two AS Interface devices, made by any manufacturer, having the same function and profile operate identically on the same network. They are interchangeable within the network. Profile is factory set in the electronic of the product by two or three characters and cannot be changed.

Today more then 20 profiles have been defined by the AS-i consortium. They are described hereunder.

Table 39 shows the compatibility between V1 and V2.1.

	Slave V1	Slave V2.1 with standard addressing	Slave V2.1 with extended addressing	Analogue slave
Master V1	Compatible	Compatible but slave defects are not forwarded	Not compatible	Not compatible
Master V2	Compatible	Compatible	Compatible	Compatible

Fig. 39 *V1 / V2.1 compatibility*

◻ Master profiles

Master profiles define individual capacities of every AS-Interface master. There are four profile types: M1, M2, M3, M4, the last one is compatible with the former versions.

◻ Slave profiles

All slaves have a profile, which means they are seen as ASIC equipped AS-Interface peripheral devices. Dedicated products as smart actuators, interfaces connecting traditional devices to the AS-Interface network are in this family. Profiles, similar to ID cards, have been defined to sort actuators and sensors in large categories. This is particularly useful when a slave has to be replaced i.e. tow actuators made by different manufacturers can be installed on the network with no change in the program or the address.

9.11 Conclusion

The use of networks for communication in industrial automation architectures increases their flexibility so they can fulfil the requirements for adapting machines or plants. To do so involves making choices necessitating specific knowledge of the right solutions out of a wide range of communication networks. Simple criteria should be used: products should be open, standardised and suitable.

- An open network, as opposed to a proprietary one, leaves one free to choose suppliers of automation devices.
- An internationally standardised network guarantees durability and upgradeability.
- A suitable choice balanced between machine or plant requirements and network performance is the way to optimise the investment.

The last point is the one which evidently requires exact knowledge of what is offered for communication networks, which have long been thought of as complicated to select, implement and maintain. Schneider Electric has decided to focus its offer on genuinely open networks based on international standards and adapted to requirements at all levels of automation architecture by defining implementation classes which keep choices simple and optimal.

10 chapter Data treatment and software

- *Presentation of actual architecture examples (schematics, products and softwares)*
- *Presentation of an application generator in a collaborative environment*

Summary

10. Data treatment and software

This section deals with the processing function discussed in the first section and includes a description of industrial software and its interaction with automation system processes. Unlike other sections, we shall not go into details about concepts such as systems, programming languages, etc. Many publications are available to the readers.

10.1 Definition

Programmable Logic Controller (PLC) is the name used for a programmable electronic device for controlling industrial systems by sequential processing.

It sends operators (Operating Section or OS) commands based on input data (sensors), setpoints and a program.

A PLC is a device similar to a computer and is used for instance to control machines on an industrial assembly line. A single PLC is enough to do what older automation systems did with hundreds or thousands of relays and cams. The people who program PLC's are called automated systems engineers.

10.2 Introduction

Programmable Logic Controllers (PLC's) were first developed in the 1970s. They were initially designed to deal with the sequential logic required to run machines and processes. At first with, their cost confined them to large systems. Major technological developments have radically restructured the processing function:

- the languages have been unified and standardised; the IEC 61131-3 standard defines the different types;
- the system approach is now widespread and the diagram principle has been superseded by function blocks;
- digital systems are now widely used to process digital values as well as analogue values with prior analogue-to-digital conversion;
- the cost of electronic components has dropped so much that PLC's can now be used instead of relays even in simple systems;
- the communication buses used for data exchange are a competitive alternative to conventional wiring;
- the software technology used in offices and business are increasingly used in industrial automation systems;
- human-machine interfaces have also progressed in becoming programmable for greater flexibility.

10.3 Programming, configuration and languages

An automation program consists of a set of instructions to be run in a specific order by a processor. The word program is often used as a synonym for software. Though software does largely consist of programs, it often requires resource files containing all sorts of data which are not part of the program.

This is where configuration comes in. Configuration is not programming, it completes software by giving it the data it requires to run properly.

As an example, a water treatment system can range from very basic to highly complex, starting with a simple program to maintain the level of water in a reservoir between two limits by opening and closing an electric valve.
A slightly more complex arrangement could involve a flow controller (incoming) and a flow controller (outgoing) to keep the water flowing at a set rate. An industrial application, such as wastewater treatment, will control several reservoirs. Each reservoir must meet a set of conditions, such as:

- level between the minimum and maximum limits;
- pH factor within a given range;
- have a certain output rate, etc.

Standard languages

The International Electrotechnical Commission (IEC) has developed the standard IEC 61131 for Programmable Logic Controllers. Part 3 of this standard (IEC 61131-3) defines the programming languages:

• **IL** (Instruction List) is very similar to assembler language, working in close touch with the processor by using the arithmetical and logical unit, its registers and accumulators;

• **ST** (Structured Text) is similar to C language used in computing;

• **LD** (Ladder Diagram) resembles electrical diagrams and can quickly convert an old electromechanical relay program. This way of programming gives a visual approach to problems;

• **FBD** (Function Block Diagram) is a suite of blocks which can be linked together and perform any type of function from the simplest to the most advanced;

• **GRAFCET** (acronym for “GRAphe Fonctionnel de Commande Etapes/Transitions” or Step/Transition Control Function Chart) is an automation system representation and analysis mode particularly well adapted to sequential systems because it can be broken down into steps. In PLC programming, **SFC** can be used in a very similar way to G (Grafcet IEC848 became an international standard in 1988 with the name of “Sequential Function Chart” (SFC)). Behind each action there is an associated program written in IL, ST, LD or FBD.

10.4 Application categories

Technological progress impelled by user requirements has given rise to a wide range of PLCs which can feature:

- hardware such as processing power, the number and characteristics of inputs/outputs, execution speed, special modules (axis control, communication, etc.);
- software which, apart from the programming language, has higher functions and capacities for communication and interaction with other business software.

These will be described through typical applications to help direct the reader's choice. Our advice is then to refer to the individual documentation of each product.

In the introduction to this guide, we looked at the principle of automation system architecture and implementation based on the customer profile. The solutions described can be divided into four categories.

A - « Electrician » solutions
Applications are simple, standalone and fixed. The choice criteria should be based on products that are easy to use, inexpensive and undemanding in maintenance.

B - « Automated/mechanical systems engineer » solutions
Applications are demanding with regard to mechanical performance (precision, rapidity, movement control, range changes, etc.). Their architecture and processing systems will largely be chosen for performance.

C - « Automated systems engineer » solutions
Automated systems are made complex by the volume and variety of the information to process such as adjustment, interconnections between PLCs, number of inputs/outputs, etc.

D - « Automated/production systems engineer » solutions
Automated production systems must be integrated into the plant's management system architecture. They must interface with each other and exchange data with production and management software, etc.

In *figure 1*, these categories are positioned over the implementations described in section 1 of the Guide to Industrial Automation Systems.

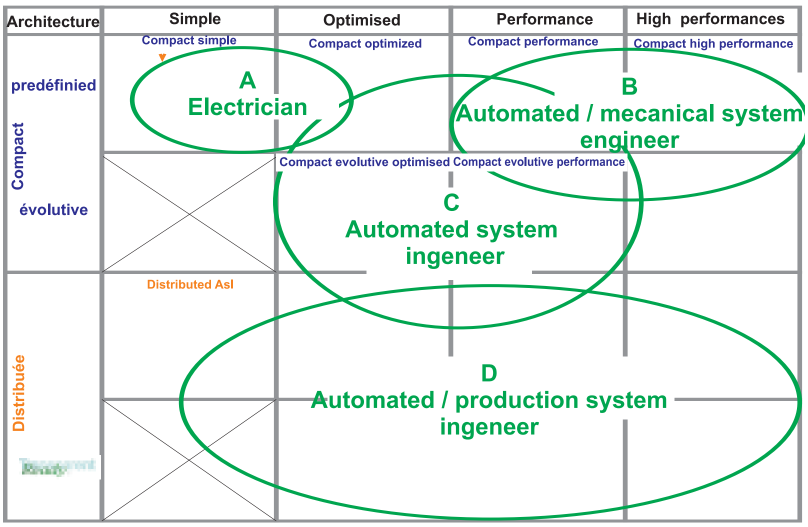


Fig. 1 *Applications categories and users profiles*

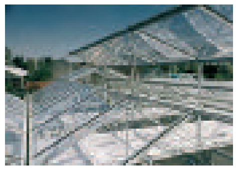
"Electrician" solutions

Simple solutions use a few electromechanical relays to run automation sequences. The latest generation of small PLCs are easy to use, competitively priced starting from a few inputs/outputs and offer new capacities without requiring any expertise in programming.

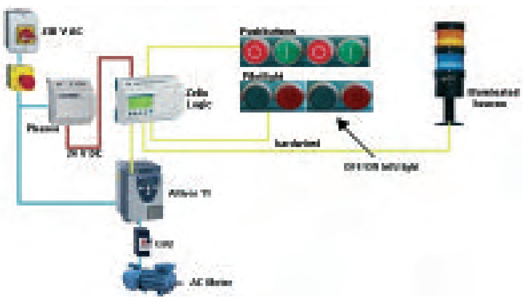
Typical applications are in the following sectors:
- industry: simple machines and additional functions in decentralised systems;
- buildings and services: lighting management, access, control, premises surveillance, heating, ventilation, air-conditioning.

Application with a Zelio PLC

This configuration is suited to the following applications *figure 2*.

Application	Description	Example
Mobile pumping station	An application to fill and empty tanks. Use of a speed controller helps to adjust to degrees of viscosity in fluids.	
Automatic gate	To open and close factory gates.	
Electric window	To control the air in a garden centre.	

↑ *Fig. 2* *Examples with Zelio PLC*



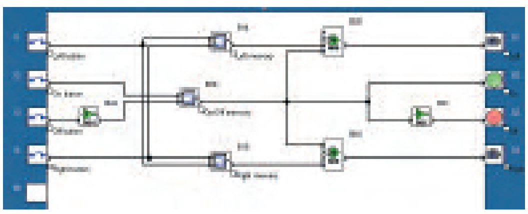
↑ *Fig. 3* *Application based on Zelio PLC*

In the diagram *(⇨ Fig. 3)*, motor operation is governed by a speed controller. For discrete control, all it requires is a contactor linked to its thermo-relay.

This unit comprises:
- a Zelio Logic PLC;
- 24V DC Phaseo power supply;
- an Altivar 11 speed controller;
- a GV2 motor circuit breaker;
- an XVB light tower;
- a Vario VCF switch.

The variables of the speed controller (time, speed, control) can be set directly on the Altivar 11 or with Powersuite software.

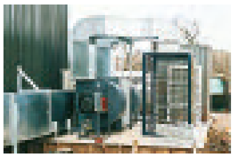
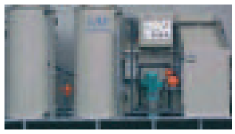
The Zelio can be programmed directly on the module or with Zeliosoft software installed on a PC. The latter option is illustrated by the screenshot in *figure 4* which shows a logical process run by FDB (Function Block Diagram).



↑ *Fig. 4* *Screen shot of a logical FBD*

Application with a Twido PLC

This type of PLC is used to build simple applications which can be monitored or controlled remotely via a modem connected to the telephone network (PSTN). *Figure 5* present some examples:

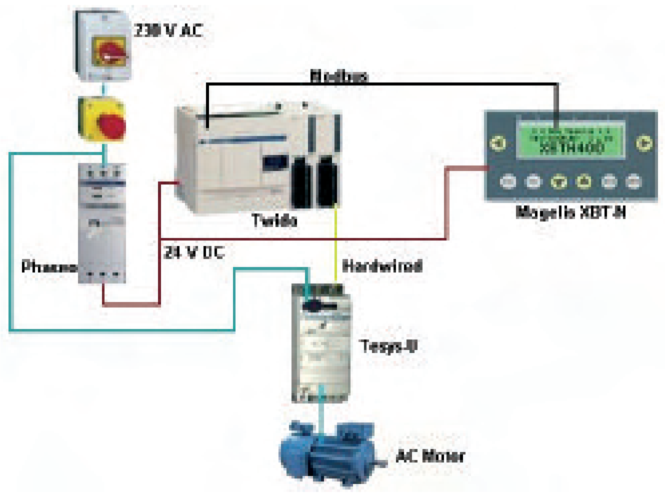
Application	Description	Example
Ventilation	Control of a ventilation system in an industrial building. Temperature measurement governs the starting and stopping of the system.	
Heating	Heating system control in a building.	
Remote control of a fountain	Control of a fountain infrastructure of a service company. The system is remote controlled via a modem.	
Control of filter cleaning in a water distribution plant.	The application controls and cleans the filter in a water distribution plant with an air-cleaning sequence followed by clean water. The system can also be remotely controlled via a modem.	

↑ *Fig. 5* *Examples with Twido PLC*

Typical diagram

The system is developed from a Twido PLC *(⇨ Fig.6)* and controlled and viewed via a Magelis keyboard/screen. Security is ensured by an emergency stop on the main switch.

The system is hardwired and the PLC controls the starter and the messages from the alarm module.



↑ *Fig. 6* *Application based on Twido PLC*

The following components make up the system:
Hardware:

- Twido Modular (PLC);
- Phaseo power supply (PS);
- TeSys-U Starter Controller (SC);
- Magelis XBT-N (HMI);
- Standard 3-phase motor.

Software:

- Twidosoft Version 2.0;
- Magelis XBTL1003M V4.2.

The screenshot in *figure 7* of the Twidosoft program illustrates programming in Ladder which can be switched to List. The software includes a large set of instructions and an embedded browser is used to access all the objects directly.

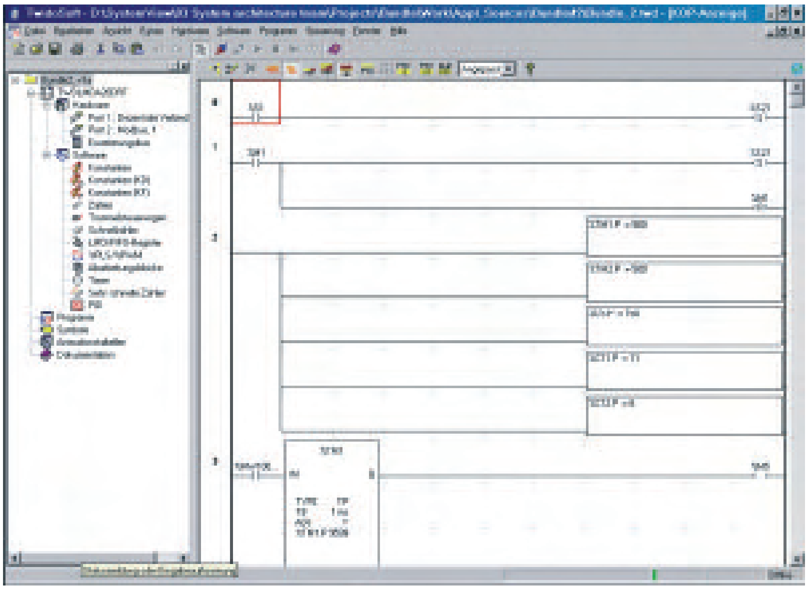


Fig. 7 *Screen shot of Twido Ladder program*

"Automated/mechanical systems engineer" solution

Some applications require performances that are difficult to achieve without their being closely linked to processing, acquisition and power control functions. For this reason, linkage is directly processed by the power control function, either in analogue, by fast bus (CANopen, etc.) or special bus (Sercos, etc.). This type of architecture is found in speed controllers for both asynchronous and synchronous motors (close loop systems).

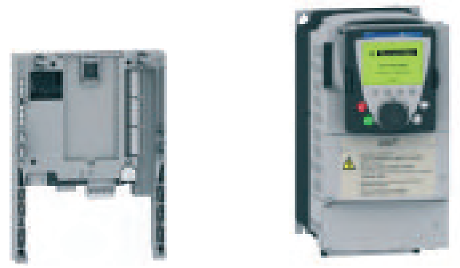
The need to link a sequential process of analogue and discrete variables means that manufacturers have had to add to speed controllers:

- input/output cards;
- communication cards;
- PLC processing cards.

These solutions can be used equally for industrial applications and in infrastructure.

We will illustrate this solution by a speed controller with a built-in PLC.

10.4 Application categories



↑ *Fig. 8* *Altivar 71 with Controler Inside card*

Processing built into a speed controller

A programmable card option *(⇨ Fig. 8)* can be used to convert Altivar speed controllers into proper automation production cells. This card, called "Controller Inside" has all the PLC functions built into to it:

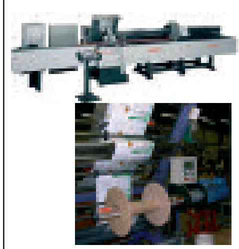
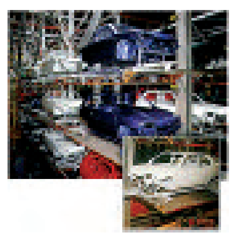
- the Codesys programming software with standardised IEC 61131-3 graphic language capacity;
- processing close to the motor controls for rapidity of movement;
- master CANopen bus to govern other speed controllers (Altivar 31, Altivar 61 and Altivar 71) and exchange all requisite data;
- the card has its own inputs/outputs and access to Altivar I/Os;
- graphic terminal display functions are stored to inform and configure;
- supervision available via Ethernet, Modbus or other communication networks.

CoDeSys is a programming tool used with Windows. It supports the five standard IEC 61131-3 languages. CoDeSys produces a native code for most current processors and can be used on different controller platforms.
It combines the power of advanced programming languages like C and Pascal and PLC programming system functions. The programming kit includes a manual and online help and is available in English, French and German.

Many manufacturers use it and Schneider Electric has chosen it for its Altivar and Lexium speed controllers.

Applications

This configuration is suited to the following applications *(⇨ Fig 9)*.

Application	Description	Exemple
Infrastructure network	Usedin pumping station to feed user's with fresh water	
Dedicated machines	Several applications: - winders - automatic assembly machines - wood working machines.	
Conveyors	Used in combination with hosting equipment's and shuttles.	

↑ *Fig. 9* *Applications for PLC enbended in the Speed drive*

Typical diagram

To make the illustration of this solution clearer, the power section and its supply are not shown *figure 10*.

In the diagrammatic illustration, the system comprises:

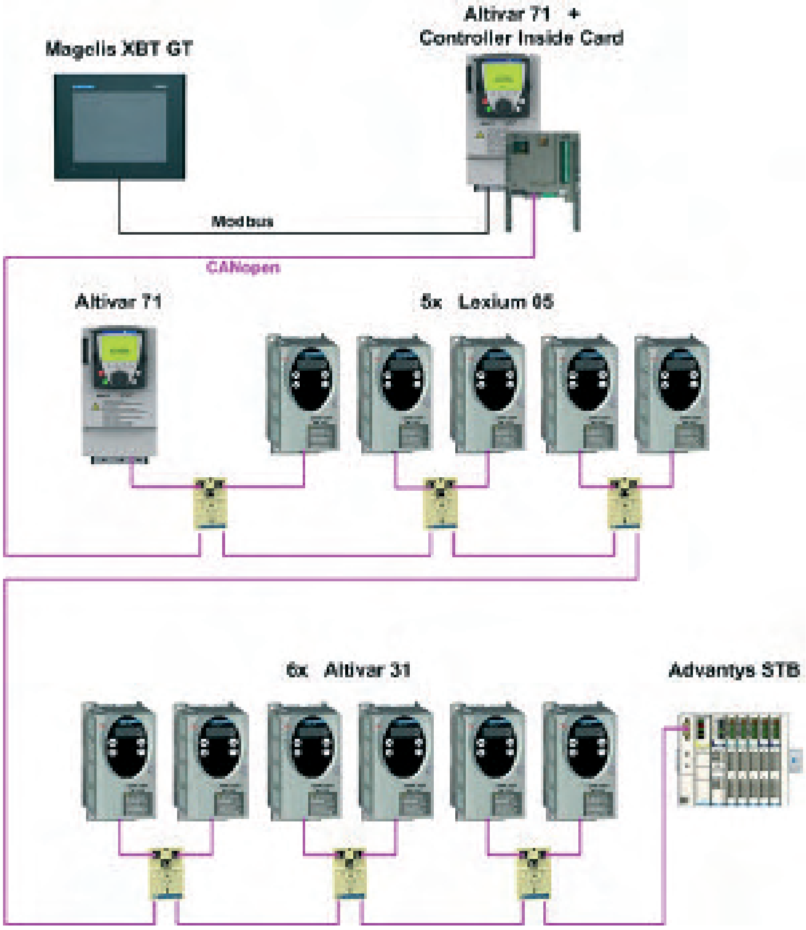


Fig. 10 *Application with a ATV71 + Controler Inside*

Hardware
- Controller Inside card installed in an Altivar 71; the speed controller is the master on a CANopen bus;
- ATV31 and ATV71 speed controllers with built-in CANopen interface;
- Lexium05 servo-drive with built-in CANopen interface. The HMI is managed by a Magelis XBT-GT graphic terminal and linked to the production cell by a Modbus link;
- Advantys STB distributed input/output production cells.

• Software
- PS1131 (CoDeSys V2.3);
- PowerSuite for ATV31, ATV71 and Lexium05;
- Vijeo-Designer V4.30 for Magelis;
- Advantys Configuration Tool V2.0.

"Automated systems engineer" solution

Modern automation systems require a great many inputs and outputs of different types. They must be able to process automation sequences and provide the information needed for management and maintenance.
The complexity of the systems entails lengthy and costly design and implementation. Manufacturers offer a dual approach to help cut costs:
- modular offers of hardware and software to reduce the end cost of learning all the applications;
- software tools to boost productivity, manage logs and ease system maintenance and upgrading.

10.4 Application categories

This type of automation solution is used in industrial processes where several machines are linked together or in infrastructures. Some examples are shown in the table *figure 11*.

Application	Description	Example
Handling equipment.	Used in a process with several conveyor systems and which uses external information.	
Packaging machines, textile machines, special machines.	Used for cutting and folding machines integrated into a production line.	
Pumps and fans.	Used for water circulation and refrigeration systems governed by external measurements such as output rates.	

Fig. 11 *Industrial process applications*

Applications

We do not intend to describe an application from end to end, but to illustrate its working principle we will make a description of a significant part of it.

A Premium PLC is used to control a local production cell *(⇨ Fig. 12)*. This is a platform made up of Advantys STB inputs/outputs, four speed controllers and external input/output modules. Each element is connected to a CAN bus. This implementation can easily be expanded by adding more speed controllers and inputs/outputs. The PLC is linked to the production cell by a Modbus/TCP bus. The controllers and motors are powered from a 230VAC network. Another source is used for a 24VDC supply.

Typical diagram *(⇨ Fig. 12)*

List of system components:
- TSX Premium (PLC),
- Phaseo (24V supply),
- ATV31 (speed controllers),
- Advantys STB (input/output cell),
- Advantys FTB IP67 input/output module,

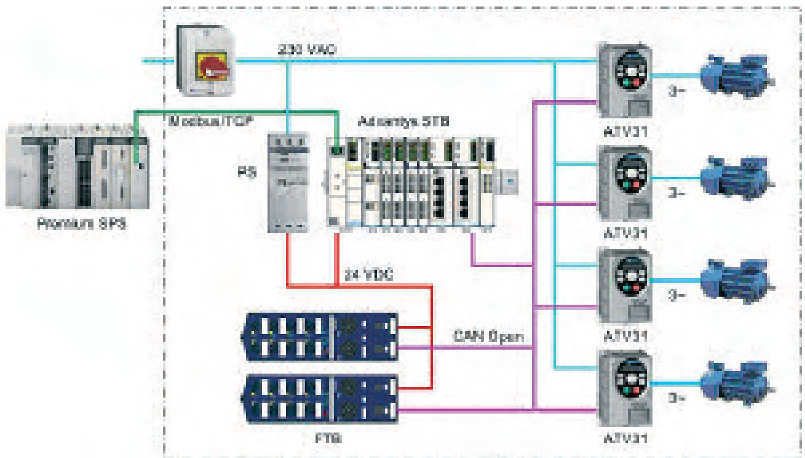


Fig. 12 *Application based on PLC Premium*

- 3-phase squirrel cage motors.

Software:
- Unity Pro V2.0.2 (PLC),
- Advantys configuration software V1.20 (I/O cell),
- PowerSuite V2.0 (ATV31 speed controller configuration).

UNITY PRO software workshop

Unity Pro is the common programming software for debugging and operating Modicon Premium, Atrium and Quantum PLCs. Based on the standards of PL7 and Concept, Unity Pro opens the way to a comprehensive set of new functions (⇨ *Fig. 13*) for a greater productivity and software collaboration.

Fig. 13 *Screen shot of Unity Pro*

- **Main features of Unity Pro**
  - Windows 2000/XP graphic interfaces;
  - “Custom” icons and toolbars;
  - user profiles;
  - graphic design of hardware configurations;
  - integrated PL7 and Concept converters;
  - automatic generation of synchronisation variables on Ethernet (Global Data);
  - 5 native IEC61131-3 languages supported with graphic editors;
  - integration and synchronisation of program editors, data, user function blocks;
  - drag & drop reuse of library objects;
  - XML import/export and automatic data reassignment;
  - automation of repetitive tasks by VBA macros;
  - plug & play Hot Standby redundancy system.

Unity Pro offers a comprehensive set of functions and tools to match the structure of the application to the structure of the process or the machine. The program is divided into functional modules which, assembled with hierarchical priority, form the functional view and contain:
- program sections;
- animation tables;
- operator screens;
- hyperlinks.

The basic functions, used repetitively, can be encapsulated into user function blocks (DFB) in IEC61131-3 language.

To create an application reference database, Unity Pro supports project and application libraries locally or on server.

It has around 800 standard function, and can be enhanced with customer’s standards (variables, data types, function blocks).

10.4 Application categories

It also includes:
- symbolic variables independent of the physical memory;
- structured user-defined data types (DDT);
- DDT and DFB function block version management in the library;
- a library of pre-animated graphic objects for operator screens;
- read/write protection of programming data to prevent any modification;
- function block development available in C++ with the Unity EFB Toolkit option.

Put in libraries on a local PC or a remote server, the application objects and their properties are used and shared by all programs and any changes made to an object in a library is effective in the programs that use it:
- the functional modules can be used in the application or between projects by XML import/export;
- function blocks are instantiated by drag & drop from the library;
- all instances automatically inherit library changes (as the user chooses);
- graphic objects for operator screens are selected and configured by drag & drop.

A PLC simulator on PC is integrated into Unity Pro and is used to fine-tune the application as much as possible before it is commissioned on site. It exactly reproduces the behaviour of the target program. All the debugging tools can be used in simulation:
- step by step program execution;
- sreak and view point;
- dynamic animations to view the status of variables and the logic in execution.

Operating screens facilitate debugging by views representing variable status in graphic object form: indicators, trend curves, etc.

The same as for configuration, application-specific modules have special screens to debug them: the functions available are adapted to the type of module implemented (discrete, analogue, counter, communication I/Os, etc.).

Operator actions are logged and archived in a standard secured Windows file. Hypertext links are used to link the application to all the documents and tools required for operation and maintenance.

- **Diagnostics tools**

Unity Pro provides a library of application diagnostic DFBs. These are integrated into the program and, depending on their function, are used to monitor the permanent safety conditions and the progress of the process.

A viewing window displays any system and application defects explicitly and chronologically in real time from the source. A click on the window opens the editor of the program where the error was triggered (search for conditions missing at the source).

Online changes can be grouped consistently in local mode on a PC and transferred directly to the PLC in one operation to be included in the same cycle run.

Hypertext links integrated into the application give remote or local access to working resources (documentation, additional tools, etc.) to cut stopping time.

There is a full range of functions to control operations:
- unity Pro operator action log in a secured file;
- user profile with a choice of accessible functions and password protection.

10.4 Application categories

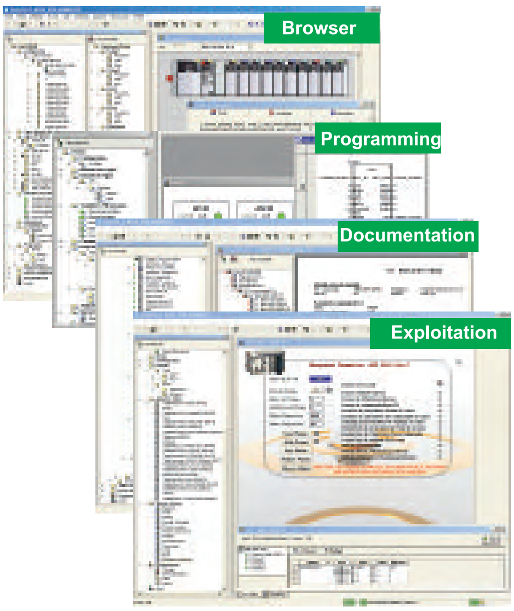


Fig. 14 Screen shot of various Unity Pro vues

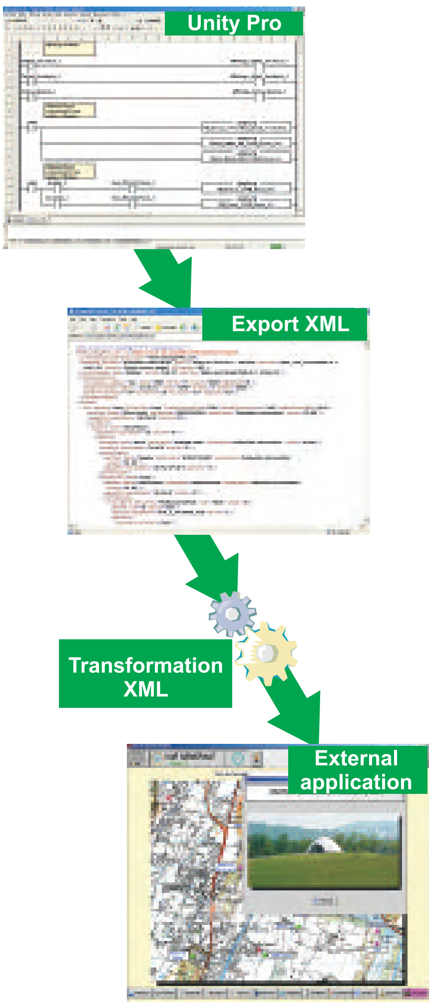


Fig. 15 Screen shot of steps for cross software exchange

Operating screens and functional views for direct graphic access to application elements (⇨ Fig. 14).

The Unity client/server architecture gives access to the software resources via programming interfaces in VBA, VB or C++; here are two examples:
- automation of repetitive tasks (input, configuration, translation, etc.);
- integration of specific applications (code generator, etc.).

• **Cross-software exchange**

The XML format, the universal W3C standard for data exchange via the internet, is used as the source format for Unity applications such as variables, programs, inputs/outputs, configurations, etc. (⇨ Fig. 15).

Simple import/export is used to exchange all or part of the application with other software in the project (CAD, etc.).

Unity Developer's Edition (UDE) and its programming interfaces in C++, Visual Basic and VBA can be used to develop custom solutions such as interfaces with electrical CAD, a variables generator, a PLC program or repetitive design task automation. Many software publishers use UDE to simplify data exchange with Unity Pro; here are some examples (⇨ Fig. 16).

Domain	Company	Product
Electrical CAD	ECT	Promise
Electrical CAD	EPLAN	EPLAN
Electrical CAD	IGE-XAO	SEE Electrical Expert
Electrical CAD	AutoDesk	AutoCAD Electrical
Electrical CAD	SDProget	SPAC Automazione
Process Simulation	Mynah	Mimic
Change Management	MDT Software	AutoSave
Application Generator	TNI	Control Build
SCADA/Reporting	Iconics	GENESIS BizViz Suite
SCADA	EuropSupervision	Panorama
SCADA	Arc Informatique	PCVue32
Graphical User Interface	ErgoTech	ErgoVU
SCADA	Areal	Topkapi
SCADA	Afcon	P-CIM
MES	Tecnomatix/UGS	XFactory
Historian/RtPM	OSISoft	PI
Web Services	Anyware	PLC Animator

Fig. 16 Sofware publisher using UDE

• **Compatibility with existing applications**
PL7 and Concept IEC61131 applications are imported into Unity Pro by an integrated converter as a standard feature. Operating system update provided with Unity Pro is available for most Premium and Quantum PLC processors.

Existing I/O peripherals, application-specific, communication and field bus modules remain compatible with Unity Pro.

"Automated/production systems engineer" solutions

Here we discuss complex architectures implementing several PLCs which communicate with each other and with supervisory workstations (SCADA). These architectures also interface with corporate management systems.

System optimisation requires a global approach to interrelate all the business departments, partners and means. We can distinguish two types of interaction:

- real time: in the operating stage, this characterises the link with customer relationship management systems (CRM), stock and production management (MES) and accounts management for optimising flows;
- collaborative: software tools support the relationship between the relevant players in the design, building, operating and maintenance stages to cut the time and cost of the production tool and improve its quality.

Applications are so diversified that it is not easy to grasp their individual positions in their environment. The need for cross-software exchange leads to a collaborative approach throughout the business.

Real time and corporate software

The illustration *figure 17* shows the most common software used in a workshop or factory. It can be separated into four levels:

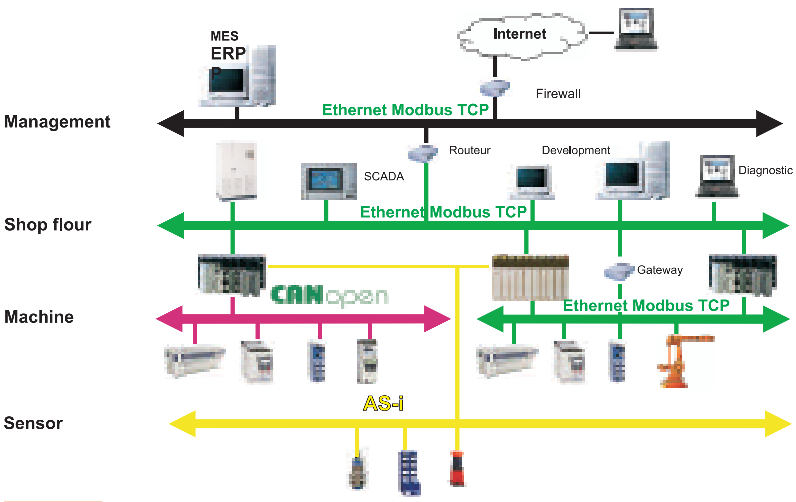


Fig. 17 *Software used in a factory*

• the **corporate level** is characterised by a very large flow of information. Office automation and internet standards are now basic requirements. The software is run on PC or on more powerful servers;

• the **shop floor** level is mainly characterised by supervisory tools and the PLCs which govern the process. Ethernet is now the standard means of communication between the computer and PLC domains;

• the **machine level** where the principle of real time conditions the choice of communication tools. Tasks are allotted to industrial PC's and PLC's, links are made by field buses (CANOpen for Schneider Electric) or by Ethernet associated to specific application layers;

• the **sensor level** where hardwired links compete with the ASi bus which is particularly well suited to this kind of use.

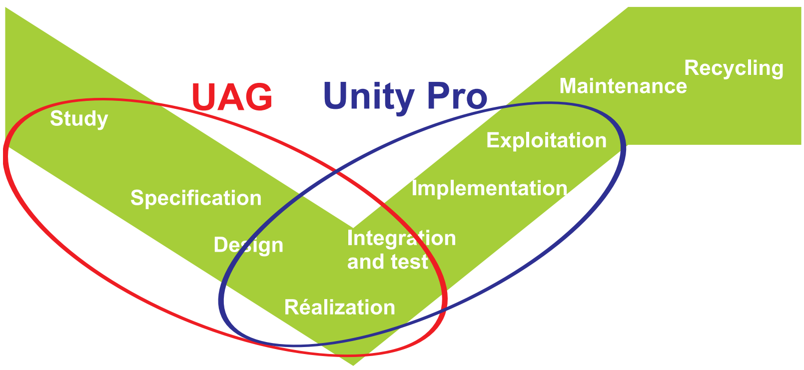
□ Collaborative design and building

The PLC software described above is confined to the control of assemblies designed separately to work as standalone units, even though communication links are sometimes required.

New tools have been developed around the programming software to deal with the constraints of working in parallel on design and building. These help developers to simplify and speed up their work, keep track and reduce the number of errors.

Consider the cycle from the study stage to the end of the life of a machine or process *(⇨ Fig. 18)*. The range of different types of work involved in this lifecycle requires collaboration between departments. This collaboration is made possible by tools such as mechanical and electrical CAD, ERP, MES, SCADA and others.

Unity Pro and UAG (application generator) at the core of the Schneider Electric offer provide a software and hardware automation platform based on openness and collaboration between the tools which cover the range of needs from the study stage right up to system maintenance *(⇨ Fig. 18)*.



↑ Fig. 18 *The two platforms UnityPro and UAG*

The Unity Pro software workshop has already been described so we will devote the next paragraph to UAG and how it works.

10.4 Application categories

Several additional software tools have been developed to ensure collaboration. The table *figure 19* describing their functions is followed by a brief explanation of how they work.

The main computing standards such as Ethernet TCP/IP, Web, OPC, SOAP, XML, etc. are used to facilitate vertical collaboration at every corporate level and offer:

- more visible information in real time;
- interoperability between the process and the information systems (MES, ERP, etc.);
- exchange with design tools such as CAD.

Components	Function
Unity Pro	Single PLC application development workshop in a collaborative environment
UAG Unity Application Generator	Object-oriented multiple PLC application development and SCADA Complies with standard ISA S88
UDE Unity Developer Edition	Software for development in VBA, VB and C++ programming languages
OFS OPC Factory System	Schneider OPC server to interrelate the desktop and PLC environments
Factory Cast Web Environnement	Ensure that information passes between a PLC environment and a desktop environment
CITEC SCADA	SCADA software
AMPLA	MES software
Ethernet card	Cards using Factory Cast services
Organisation of additional configuration and setting software	
XBT L1000	HMI creation
Vijeo designer	HMI creation
Vijeo Look	Mini SCADA
Power Suite	Configuration of Altivar speed controllers and Altistart and Tesys U starter units

↑ *Fig. 19* *Complementary software tools*

UDE: Unity Developer's Edition

The Unity range is enhanced with Unity Developer's Edition (UDE), specialist software for programmers in VBA, VB or C++. It provides access to all the object servers in Unity Pro software for developing custom solutions such as interfaces with an electrical CAD or an automatic application generator.

UAG: Unity Application Generator

UAG is a design tool based on a reusable module approach (PID, valve, motor, etc.) and is compliant with standard ISA 88. UAG generates the code of the PLCs in the architecture and the SCADA graphics. In addition, with a single input it manages a database, common to all the elements, to ensure application consistency.

Single data input ensures speed and consistency between the two environments.

With this structured modular design approach, UAG offers significant savings in development costs and facilitates validation and maintenance of automation projects.

OFS: OPC Factory System

OFS, OPC (OLE for Process Control) adapted to the Schneider Electric environment, is a program for communication between the desktop environment and the industrial automation systems. It originated with Microsoft and derives from DDE, then OLE to OLE Automation using Windows COM/DCOM.

A foundation made up of software providers and publishers manages OPC upgrades and guarantees upward compatibility and interoperability between different software products.

Upgrades are conditioned by the following industrial requirements:

- application interfaces based on open standards offering simple common access to shop floor data;
- greater interoperability between automation and control applications, site equipment and IT applications;
- multiple Client/Server architecture;
- access to a local or remote server;
- information flow in real time.

Factory Cast: Web environment

A set of tools to enable applications to communicate via internet and meeting the following requirements:

- communication between applications;
- web and internet compatibility;
- standard-based non-proprietary solutions;
- easier implementation.

The applications must be able to communicate whatever:

- language they were developed in;
- operating system they run on.

The internet-compatible technology is based on a standard XML SOAP protocol (S*imple Object* Access *Protocol*) cohabiting with HTTP and enables applications to communicate with each other.

A standard description of services and interfaces is provided by a WSDL application (W*eb* S*ervice* D*escription* L*anguage*) which is a library of standard and self-documented data access functions.

The combination of these technologies is known as 'WEB SERVICES' and is independent of platforms, languages and operating systems.

SCADA: supervision software

SCADA (Supervisory Control And Data Acquisition) is industrial software designed to optimise production management. It is used to run a production workshop in real time, based on production requirements and the means available.

Ethernet cards

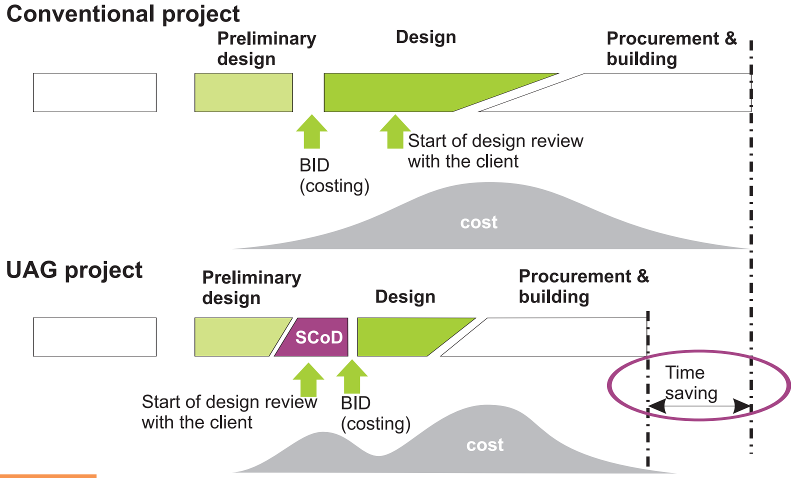
The ranges of Ethernet cards offer modern architectures open to different current software technologies and provide users with tools to build their own functions. This makes it possible to organise objects in a way fully compatible with MES and ERP IT environments.

10.5 UAG: Application generators

Unity Application Generator (UAG) is both design software and a generation tool to integrate PLCs and supervisory systems (SCADA) or human-machine interfaces (HMI). To do this, it uses the basic single database technique of hybrid control systems combining DCS and PLC functions. Though UAG is used for single PLC applications, it is especially useful in multiple PLC architectures. It uses the full power of UNITY Pro which it closely associates with supervisory systems such as Monitor Pro, I-Fix and so on.

Significant savings in development time

UAG and its underlying concepts enable developers to get involved with the customers at a very early stage. Reusable objects and easy updating and testing can cut project time by 20 to 30% *(⇨ Fig. 20)*, which can mean several months for big projects.



↑ Fig. 20 *Time and cost reduction*

Main features of UAG

- A single input for the PLC/HMI database (SCADA);
- use and reuse of library objects;
- process application configuration;
- incremental generation for SCADA;
- global resource mapping;
- PLC application (code, variables, configuration, communication, etc.);
- SCADA application (symbols, mimic diagrams, variables, attributes, alarms, etc.);
- communication management (Ethernet, ModBus+);
- generic interface in XML.

Note: "Generic Plug-in Interface" is an open interface for other SCADA systems.

10.5 UAG: Application generators

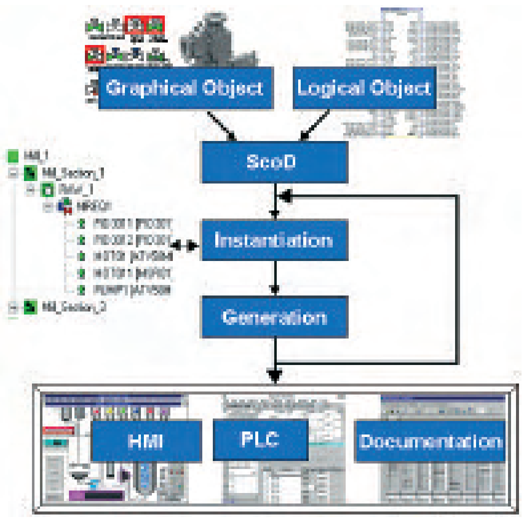
UAG operation

Unity Application Generator is made up of three tools (⇨ *Fig. 21*).

Tool	Field	Library
SCoD Editor.	Libraries.	Specification of control modules, DFB or EFB import, attribute specification and screen configuration definition (within UAG).
UAG Customisation	Customisation	Definition of user profiles in a project including: naming rules, hardware specification catalogues, libraries.
Unity Application Generator	Projet	Project design, functional analysis and application generator.

↑ *Fig. 21* *UAG tools*

The links between tools is summed up in *figure 22*.



↑ *Fig. 22* *UAG synoptic*

ScoD object editor

Unity Application Generator (UAG) is an object-oriented tool based on control modules. A control module describes a process unit and covers all aspects of the automation task:

- PLC logic;
- representation for the operator in the supervision system;
- mechanical and electrical properties of the unit;
- maintenance and troubleshooting;
- multi-facet representation of these elements in UAG is called Smart Control Device -(SCoD), the equivalent of control modules in standard ISA 88.

Control instantiation has an equivalent physical representation which can be:

- an actual component, which can be held and inspected, such as a motor, a valve, a temperature transmitter, etc.;
- a control element used to adjust other functions such as a PID loop, timer or counter.

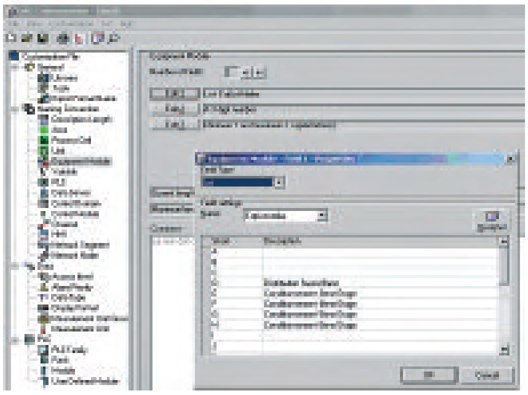
Control modules are defined and used in type libraries; the SCoD editor is the tool which creates, updates and groups specific customer controls in the objects (Smart Control Device).

Definition of rules and properties in the SCoD editor based on the DFB/EFB interface includes:

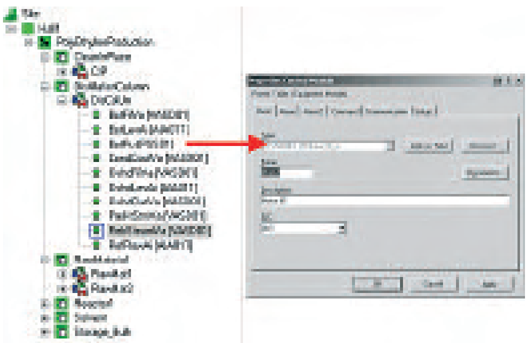
- graphic user interface (GUI);
- mandatory configuration of the SCoD instance;
- optional configuration of the SCoD instance;
- SCoD instance inheritance;
- simple and complex relations inherited by the selected module and other ScoDs;
- definition of data transmitted to and from the HMI;
- definition of data related to the topological model;
- specific HMI information such as alarm texts, measurement units;
- access levels:
  - per module reference to specific HMI information such as ActiveXs and symbols;
  - per module reference to specific PLC information such as DFBs/EFBs;
- SCoD documentation.

10.5 UAG: Application generators

↑ Fig. 23 *Screen shot of UAG editor*



↑ Fig. 24 *List elements description*



↑ Fig. 25 *Screen shot UAG physical model and control model parameter setting*

An example of a Smart Control Device could be a valve. A valve is generally used as a cut-off device to prevent or allow the flow of a fluid or gas in a pipe. It is usually linked to three digital signals:
- limit switch open or closed (2 signals);
- the signal for the actuator.

There are many different standard valves ranging from the smallest actuated by solenoids to the largest actuated by motors.

The properties are assigned for the type of valve from the PLC interface (API).

The default valve insert mode is “Energise-to-Open”, though the user can specify “Energise-to-Close”.

The “Travel Time-out” operating time must be within the [min Value.. max Value] interval.

Figure 23 shows a screenshot of the editor.

□ UAG Customisation Editor

This editor *(⇨ Fig. 24)* is used to define a common language for different people (operation, automation, maintenance). It describes the list of elements used and their definition, objects (SCoD) and human-machine interfaces (HMI).

Customisation starts with:
- the list of SCoD libraries;
- the list of authorised hardware modules;
- the access level;
- definition of process element names;
- specific HMI or SCADA properties.

To return to the valve example, the user has to define the valve exactly so that it cannot be confused with another in the system. The user is going to standardise the structure of the system component names: <position in 4 digits> <English abbreviation in 3 digits> <Type of element from 1 to 6>. A given valve will have a single name such as 2311VAL4.

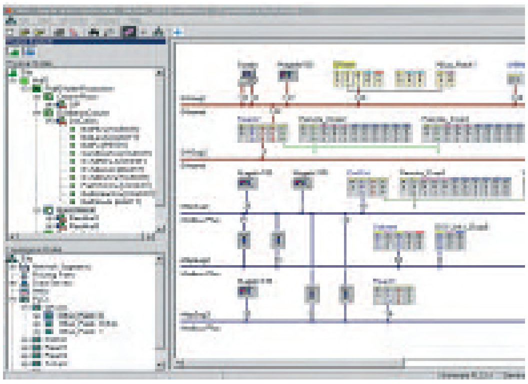
All elements can thus be defined by:
- the location of the SCoD corresponding to the valve;
- the section of the program in the PLC;
- the hardware modules linked to the PLC, etc.

In the PLC and HMI applications, standardisation is defined for all operators and experts in automation and the process. The project follows the rules without exception and maintenance staff can be trained with the tools. Project management is facilitated by knowing the number of valves.

□ Application generator

Unity Application Generator is a design and functional analysis program generating applications for PLCs and SCADAs *(⇨ Fig. 25)*.

10.5 UAG: Application generators



↑ *Fig. 26* *Screen shot of UAG topological model*

There are two independent tasks to generate the physical and topological models:

- The physical model describes the process in a tree structure of elements as shown *figure 25*.
- The typological model describes the hardware of the automation process, including the PLCs, inputs/outputs, networks, PCs, etc. as shown *figure 26*.

UAG and ISA88 standard

Standard ISA 88: "Advanced" process control organisation

"Advanced control" focuses on the basic algorithm used to enhance the behaviour of automatic control devices. It also takes into account organisational and economic disruptions and can go as far as casting doubt on the equipment, methods and results of the manufacturing process.

The ANSI/ISA-88 standard offers efficient concepts for the functional organisation of applications to achieve the degree of robustness required for ongoing adaptation of systems subjected to such constraints.

This standard focuses on a number of essential points:

- flexibility, development that is less complex and shorter and mastery of the process;
- object-oriented approach and reusable object classes;
- separation of the procedure and the process;
- separation of process control and equipment automation control.

Detailed information on this standard is available on http:// www.s88.nl.

Unity Application Generator uses the ISA 88 batch processing terminology in « Part 1: Models and Terminology ». With the structure of this standard, UAG users can break down process tasks to fit their own rules and then use UAG and the elements defined to rebuild the process.

10.6 Definition of the main abbreviations used

DCS Distributed Control System

HMI Human Machine Interface

PLC Programmable Logic Controller

SCADA Supervisory Control And Data Acquisition (see the paragraph on SCADA)

UAG Unity Application Generator

MES Manufacturing Execution System, a computing system primarily designed to collect complete or partial factory production data in real time. These data are then used for a number of analysis exercises:
- tracking, genealogy;
- quality control;
- production monitoring;
- sequencing;
- preventive and remedial maintenance.

ISA has standardised the MES structure.

An MES is often situated between the industrial automation system and the ERP systems like SAP.

ERP Enterprise Resources Planning, software to manage all the processes in a company by integrating all its functions such as human resources management, accounting and financial management, decision-aiding tools, sales, distribution, supplies and e-commerce.

CRM Customer Relationship Management, a new paradigm in the field of marketing.

The purpose of CRM is to create and maintain a mutually beneficial relationship between a company and its customers. In this commercial relationship system, the company focuses on winning customer loyalty by offering them service of a quality they cannot find elsewhere.

The image frequently used to illustrate this concept is the relationship between small shopkeepers and their customers. Customers are rewarded for their loyalty by the fact that the shopkeeper knows their habits and acts accordingly (like a baker who puts aside a loaf baked the way you like it and allows you credit).

11 chapter
Equipment manufacturing

Presentation:
- *Step by step manufacturing*
- *Quality rules*
- *Relevant standards*

Summary

11. Equipment manufacturing

Automated systems use equipment that implements products to facilitate the installation, wiring and connection of automation components. These products have to comply with local and international standards as well as safety standards for the protection of people and property.

Equipment is built in 3 stages:
- *design (diagram, program writing, choice of material, installation study);*
- *construction (assembly, wiring, tests, housing);*
- *installation (wiring, connections, commissioning).*

To complete these three stages satisfactorily, thought must previously be given to:
- *the understanding of potential problems which could have an impact on the safety and/or availability of the equipment;*
- *implementation of preventive actions and/or alterations to the initial automation diagram;*
- *the capacity of any subcontractors to comply with the requirements;*
- *the compliance of the equipment with the requirements.*

The purpose of this section is to describe the rules for implementing automation system components and the Schneider Electric products which can be used to build them.

A methodology and good engineering practice based on experience for each of the three stages make it possible to build reliable and cost-effective equipment.

11.1 Equipment design

Successful construction of automation system equipment basically depends on the understanding of exact specifications.

The design tools, diagram drawings, choice of components and their installation can differ according to the complexity of the system and the choices made by the service provider. Besides this, while a simple standalone machine may be adequately equipped by a mechanic and an electrician or automation system engineer, equipping more complex machines for production cells or process runs often requires the work of multidisciplinary teams. This implies project management and is beyond the scope of this publication.

Specifications

Specifications for the control section must include all the requisite elements for the project. They are closely tied to the specifications for the operating section (mechanics and actuators). The information they contain is used to:
- choose the solution to implement;
- build the equipment itself;
- run operating tests;
- define costs and schedules;
- refer to for acceptance.

To clarify customer requirements, it is preferable to structure the specifications as follows:
- general aspects: overview of the application, standards and recommendations, any material constraints;
- characteristics of the power supply, etc.;
- use: layout of control devices, operating modes, frequency of use, etc.;
- functional features: functions to perform, possible extensions, man-machine dialogue, peripheral devices, etc.;
- environment: temperature, hygrometry, vibrations, shocks, corrosive atmosphere, dust, etc.;
- special software: diagnosis help programs, supervision, communication protocols, etc.;
- adjustment: type, procedures, identification;
- on-site acceptance test procedures;
- accompanying documents;
- any other information which could affect the equipment-building process, such as packaging for transport.

11.2 Choice of supplier

To build equipment, the order initiator is advised to select a panel builder with ISO9000 certification.

Using a certified supplier will simplify discussions, cut down on checks, ensure an up-to-date equipment file and problem-free commissioning and facilitate maintenance. This helps to control costs.

ISO9000 standard

Equipment is increasingly sophisticated, technologies ever more critical and statutory requirements more and more severe.

All this can make it much harder to control events by reason of their complexity.

The order initiator must be certain that when the equipment is built, it will correspond exactly to the specifications and that all the requisite precautions have been taken.

In particular, the inevitable changes occurring during the manufacturing must be perfectly understood and applied by the panel builder, the staff involved in the process must be properly trained and non-compliant products must be identified and set aside.

This implies the development of an ongoing “Customer-Supplier” relationship.

The supplier must provide the customer with proof of competency and skill regarding the quality of the offer and control of the production process.

The customer must be assured of the supplier’s capacity to perform these undertakings which only stringent organisation can ensure.

The ISO9000 standard and certifications are designed to facilitate this customer-supplier relationship by quality management.

Quality management

“Quality management” means what an organisation does to ensure that the product, in this instance the equipment built to the customer’s specifications, complies with requirements when it leaves the supplier’s workshops.

The way an organisation manages its processes cannot fail to affect the final product. The ISO 9000 series focuses on knowing whether everything has been done to ensure a product meets customer requirements.

The international ISO9000 standard is a generic one covering ISO 9001, 9002 and 9003.

The difference between ISO 9001, ISO 9002 and ISO 9003 is confined to the field of application:

- ISO 9001 sets requirements for organisations with a business ranging from design and development to production, installation and related services;
- ISO 9002 is the standard for organisations that do not design or develop. It sets the standards for production, installation and related services;
- ISO 9003 is the standard for organisations that basically use inspections and tests to ensure that end services meet specified requirements.

The order initiator will choose the panel builder whose organisation best matches the services required. An ISO 9002 certification is usually the requisite minimum.

The choice of the order initiator will be made after examining the Quality Manual of the supplier(s) involved. This describes the organisation and management system adopted by the company.

11.3 Drafting diagrams and programs

Control and power diagrams

Control and power diagrams are usually drawn using graphics software linked to a database where graphic symbols and standard diagrams are stored.

The diagrams can be:
- created from scratch from database content;
- or adapted from an existing similar diagram.

PLC programs can also be developed with programming software and software workshops.

Complex equipment usually relies on one or more programmable multifunction PLC's.

Stop/start modes

The stop/start modes of an automation system are analysed by the AIADA and classified in a graphic guide called GDOSM which is used, regardless of the control technology, to define the operating modes or statuses of the system based on a specific vocabulary, possible links between the modes or statuses and upgrading conditions.

Operating procedures: functional analysis

The operating modes required for production are:
- normal production mode,
- preparation or closing modes;
- inspection modes, etc.;
- stopping procedures;
- input / output data files;
- identification of operations in order to structure the PLC's programs *(⇨ Fig. 4)*.

Failure procedures

These cover the operation of the machine in the event of a problem:
- emergency stop;
- degraded operation, etc.

Operating safety

Standard requirements

The operating safety of an automated system is its capacity to operate:
- without danger to people and property (safety);
- without hindering production when a failure occurs (availability).

Safety should be viewed as an aspect of risk analysis, legislation and relevant standards. It is examined through a risk evaluation procedure applied successively to the product, the process (operation and control) and utilisation. For further information on this topic, please refer to "Machine safety Parts 1 and 2" distributed by *Schneider Training Institute*.

European legislation is based on the machine directive (89/392/EEC) defining basic requirements in design and construction of industrial machines and installation for free circulation of these goods in the European Community.

Analysis tools

Analysis tools such as FMECA (Failure Modes, Effects and Criticality Analysis) can provide a systematic approach to all aspects of failure and provide suitable solutions.

FMECA is designed for evaluating the impact or criticality of failure modes in system components on the reliability, sustainability, availability and safety of the system.

The FMECA method lists the failure modes of components and sub-units and evaluates the effects on all the functions in a system.

It is widely recommended throughout the world and consistently used in all hazardous industries (nuclear power, space, chemical, etc.) for making preventive analyses of operating safety.

Before an FMECA analysis can be run, the system and its environment must be accurately understood. This information is usually obtained in the results of the functional analysis, risk analysis and any feedback.

Next, the effects of the failure modes must be evaluated. To find the effects on a specific entity, the components directly interfaced with it are examined first (local effect), and then gradually out to the system and its environment (global effect).

It is important to note that when a specific entity is examined for a specific failure mode, all other entities are assumed to be in their rated operating condition.

FMECA is based on the well-established fact of non-simultaneous failures.

The third step is to classify the failure mode effects by their level of criticality in relation to certain operating safety criteria predefined for the system according to the requisite objectives (reliability, safety, etc.).

The failure modes of a component or sub-unit are grouped by the criticality level of their effects and prioritised accordingly.

This typology helps to identify the most critical elements and propose the “strictly necessary” actions and procedures to remedy them. This process of results interpretation and recommendation implementation is the final step in FMECA.

To keep FMECA to the strictly necessary and control the number of entities to examine, it is advisable to run functional FMECA analyses. This helps to detect the most critical functions and thus confine the “physical” FMECA to the components that perform all or part of the functions.

FMECA methodology ensures:
- a different view of the system;
- means of thought, decision and improvement;
- information to use in operating safety examinations and remedial action.

11.4 Programming methodology

Programming organization

Industry uses more and more software programs for its production purposes. There is such a wide variety of these applications that understanding the place of each in its environment is a very complex matter. The need to interface programs requires a collaborative approach from the outset of new production unit design.

The design must be analysed throughout as it is intended to implement a series of activities which, starting from a request for process automation (which can range from a simple vocal question to full specifications) to devise, write and finalise software programs ready for their delivery to the customer.

Generally speaking, software design involves 3 major phases:
- functional analysis or design *(⇨ Fig.3)*;
- specifications;
- design.

Analysis and design methods

The purpose of analysis and design methods is to formalise the preliminary stages of system development to match the customer requirements. This starts with an informal statement (requirements as expressed by the customer completed by questioning of operating experts such as future program users) and an analysis of any existing system.

The analysis phase serves to draw up a list of the results expected with regard to functions, performance, robustness, maintenance, safety, extension capacity, etc.

The design phase serves to describe, usually in modelling language, the future operation of the system in unambiguous terms to facilitate its building.

Current trends in automation (driven by its close relationship with information technology) point in the direction of object-oriented programming. This leads to many advantages: reliable code, reusability, knowledge protection, faster qualification (acceptance), etc.

Programming tools

All these constraints lead to the creation of a modern, innovating software workshop designed to achieve the required results.

The term integrated development environment (IDE) is used to mean a set of software programs which can themselves produce industrial automation programs.

The activities an IDE covers are usually:
- general project design, building stages or phases;
- data and program subset naming conventions;
- data structuring;
- assistance for writing programs in different languages;
- compiling or generation;
- assistance for tests and correction monitoring;
- subset libraries that can be reused in other projects;
- documentation;
- management of successive versions or variants of individual programs;
- assistance for commissioning.

An IDE facilitates collaboration between programmers and subsequent program maintenance by promoting the use of common methods.

11.5 Choice of technology

The technologies available for building automation system equipment are mainly electromechanical, pneumatic or electronic (PLC's, micro-computers, standard or specific electronic cards). Networks and field buses have gained ground in equipment construction and have a great effect on the choice of materials.

For more information, please refer to *Field buses* distributed by *Schneider Training Institute* or Cahier Technique N° CT197: *Field bus: a user approach*.

There are three choice criteria:

- feasibility criteria to eliminate technologies which could not meet the specifications;
- optimisation criteria designed to minimise overall costs during the equipment's lifecycle (procurement, implementation, flexibility, fixed assets, production management, maintenance, etc.);
- financial criteria for building the equipment at optimal cost.

Eventually, preliminary FMECA can be used to help select the best suited technology.

Choice of components

A range of constraints should be considered:

- ambient temperature (which may derate the material), dust, vibrations, etc.;
- coordination of devices making up the power outputs;
- discrimination between protection devices up to the main circuit breaker;
- requisite machine cycle time;
- number of operating cycles;
- category of use (AC-1, AC-3, etc.);
- standards (petrochemical, electrical, marine, etc.).

11.6 Equipment design

Computer-Aided Design

Software tools can be of great assistance in the field of automation system design. Apart from building the diagram, the designer can use them throughout the project, from the record of the customer's request for a quotation to commissioning and maintenance assistance.

This way of proceeding not only boosts productivity in system design, it also improves the quality of the diagrams and programs and facilitates their upgrading.

The main features of CAD software are:

Intelligent symbol database

Each symbol has a behaviour mode (master, slave), an electrical function (isolation, switching, etc.) and connection terminals. It is linked to a family of hardware (disconnectors, contactors, etc.) and an identification method. It supports the variable references offered by the software or entered by the user.

The database also ensures information consistency and guides the user during input.

A hardware database with all the technical and sales information to facilitate the choice of components and input of product lists, quotations and purchases.

Standardised templates (single-line definition, automation system structure, power and control diagrams, overall dimensions, product lists, etc.).

A diagram database (motor starter, power and control sub-units, hoisting movements, etc.).

It helps to respond quickly to a call for tender (single-line diagrams) and simplifies diagram drawing.

Electrical installation information management

- equipotential links;
- detection of existing numbers;
- short-circuit control;
- terminal block control;
- hardware identification;
- automatic creation and control of identity uniqueness;
- cross references;
- control of auxiliary contactor capacity and terminal numbers;
- overall dimension calculation assistance.

Overall dimension calculation

Three methods are used to define the overall dimensions of equipment.

Direct layout method

This method applies to small equipment on standard pannels offered by device manufacturers.

For instance, devices can be laid out directly on an installation sheet reproducing the frame of the Telequik® pre-slotted plate on a scale of 1. This helps to calculate the overall dimensions of the equipment quickly and easily.

Surface area calculation

This is a fast and accurate way to calculate overall dimensions.

The procedure is to make the calculation of the total surface area of the devices in the equipment (these are given in the catalogues), multiply the total by the following space factor:
- 2.2 for a maximum total of 34.2dm²
- 2.5 for a total greater than 34.2dm²

Some customers have specifications that may require a greater factor to leave space for any modification.

The result gives the total working surface area of the equipment.

The choice rules provided by manufacturers such as Telemecanique make it easier to find the references for plates, uprights, mounting rails and boxes based on the working surface. These rules also give the heat losses that can be dissipated by the enclosure walls.

Computer-aided

This is more aimed at services specialising in automation system equipment studies.

The installation tool in the CAD software offers overall dimension transfers based on the diagram and a Hardware Database.

Manufacturing file

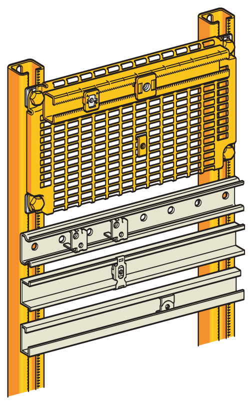
The complete file should be compiled before manufacturing starts. It defines:
- the list of all documents in the contents;
- boxes: installation, drillings, parts, etc.;
- cabinets: installation, framework plan, drillings, etc.;
- control stations: drillings, parts, etc.;
- electrical diagrams;
- programs;
- hardware list;
- overall dimension.

11.7 Building an equipment

Many electrical equipment manufacturers develop auxiliary components to implement their products. This is the case of the Telequik® system offered by Telemecanique *(⇨ Fig. 1)*.

This system contains all the products required for building equipment and ensures that the components of an automation system are quick and easy to implement.

Given their features, we have classified the products in it into four different functions to Enclose, Structure, Distribute and Connect.



↑ *Fig. 1* *Telequick® pre-slotted plate by Telemecanique*

"Enclose" function

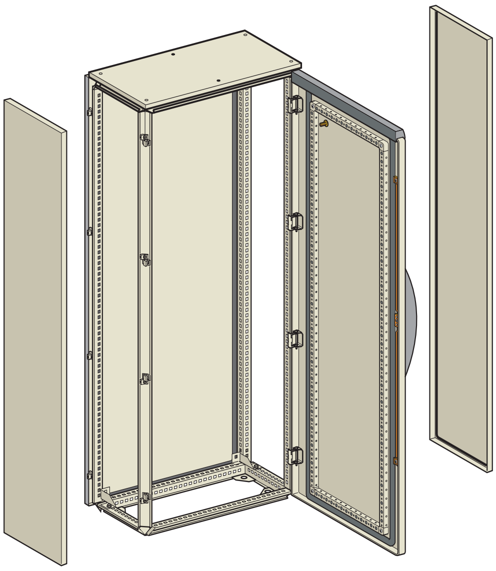
To protect the hardware from shocks, severe weather and ensure it can resist the most stringent conditions of use in industry, the equipment must be housed in boxes or cabinets. These should have all the features required for cutting down assembly and maintenance time.

Depending on the degree of protection needed, enclosures comply with defined standards and IP (International Protection) codes.

The IP code is described in the 60529 document published by the International Electrotechnical Commission.

It uses an alphanumerical method to define the level of protection the enclosures provide against the approach of dangerous parts, penetration of solid foreign bodies and the detrimental effects of water.

11.7 Building an equipment



↑ *Fig. 2* *Telemecanique AA3 cabinet*

The first figure from 0 to 6 indicates simultaneously the protection of persons from dangerous parts and protection from penetration of foreign bodies.

The second figure, also 0 to 6, indicates protection from water splashes.

The additional letters indicate further protection such as internal baffles. Cahier Technique CT 166 *“Enclosures and levels of protection”* gives a detailed description of the codes and the stringency of the corresponding tests.

The builder is responsible for end product compliance with standards, but the enclosure manufacturer documentation must specify where the hardware must be fitted to ensure the stated levels of protection are maintained.

The installer who connects (wiring) and attaches the cabinets and in some cases adapts the auxiliary components (push buttons, measuring devices, etc.) must also ensure the specified level of protection is maintained.

Schneider Electric offers an entire range of boxes, cabinets and parts compliant with IP standards (⇨ *Fig. 2*).

“Structure” function

To bind the components together mechanically, there is a range of perfectly adapted products to assemble and attach automation system components firmly. Put together, these products make up the structure of the equipment and their assembly systems provide great flexibility of use, a wide choice of assembly options and significant cost savings in implementation.

“Distribute” function

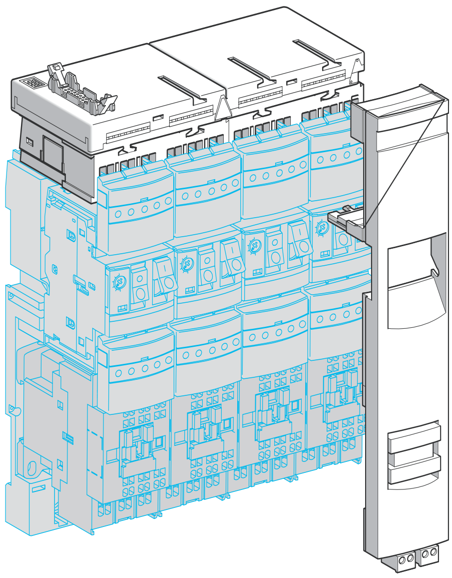
Electrical power distribution

When building equipment, product implementation must comprise safety, simplicity and fast assembly and wiring. Maintenance and any modification to the equipment must be easy to perform, with the least possible impact on operating continuity.

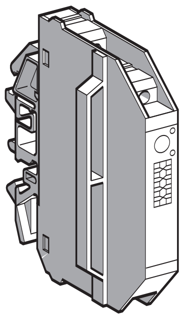
To meet these criteria, there are distributors basically designed to shift the main current to a number of secondary circuits (see the Schneider Electric general catalogue for more information).

Some models are designed as product supports so it is possible to intervene on live equipment (e.g. connection or disconnection of a motor starter unit).

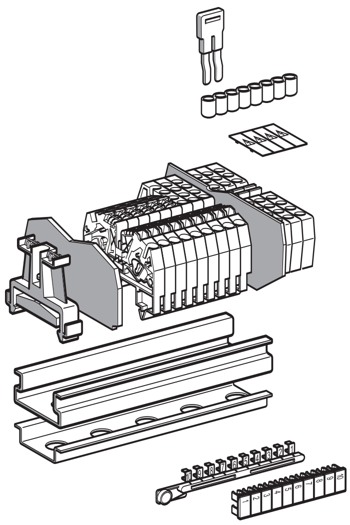
This is notably the case with the Telemecanique TegoPower technology (⇨ *Fig. 3*).



↑ *Fig. 3* *Motor starter units built with Telemecanique TegoPower technology*



↑ *Fig. 4* *Interface ABS2*



↑ *Fig. 5* *Telemecanique terminal block*

◻ Distribution of low signals

Manufacturers' catalogues offer interfaces and connection systems for different control signals:
- discrete signal interfaces *(⇨ Fig. 4)*;
- analogue signal interfaces;
- temperature probe interfaces;
- wiring interfaces;
- peripheral automation system components;
- field bus interfaces.

◻ "Connect" function

This function covers the products required for wiring and connecting equipment.

- **Terminal blocks** *(⇨ Fig. 5)*

These comply with TEU standards and the major certification requirements. They are made of coloured nylon enabling them to be used at temperatures ranging from -30 to + 10°C.

Their fire-resistance complies with the standard NF C 20-455. They are identified by characters on clip-on strips and are designed for connecting conductors with a maximum section of 240 mm^2.

They cover all needs:
- a wide range of currents, from a few amperes (control, signal electronic circuits, etc.), to several hundred amperes (power connections);
- fixed or detachable single- or multiple-pole blocks;
- screwed, bolted, clipped, welded or spring connections;
- blocks for special functions such as fuse or electronic component holders, draw-out terminals, overload conductor connection, etc.;
- mounting on rails, pre-slotted plates or printed circuits.

- **Cable ends**

Cable ends have a number of advantages:
- easier wiring, as the copper sleeve is crimped automatically when the connection is fitted in the terminal;
- perfect resistance to vibration;
- wire strands cannot creep;
- timed saved in connection work;
- the same marker tag holders and markers for all cable sections. Each holder can take up to 7 marking rings (letters or digits).

Telemecanique cable ends also have:
- a different collet colour for each section;
- 3 sleeve lengths depending on the model.

There are insulated cable ends:
to standard NF C 63-023
- without tag holders for sections from 0.25 to 6 mm^2;
- with built-in tag holders for sections from 0.25 to 6 mm^2;
- with removable tag holders for sections from 4 to 50 mm^2;

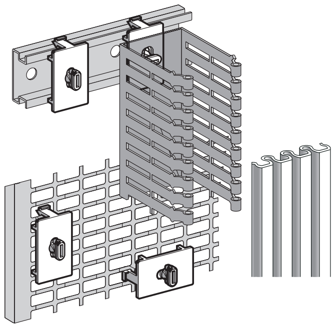
to standard DIN 46228
- collet colour per section different from the French standard;
- without tag holders for sections from 0.25 to 50 mm^2.

- **Cable clips and ducts**

Cable clips and ducts are designed to channel wires into horizontal and vertical layers on the same plane as the devices.

All the wiring is on the front facing, so repair work and alterations are made easier.

They are made of PVC and have no metal parts that can come into contact with the conductors they hold.



↑ *Fig. 6* *Telemecanique duct*

- **Ducts** *(⇨ Fig. 6)*

These have open slots in the sides and perforations at the back. They are fitted vertically or horizontally on feet with quarter-turn fixing devices. These can be clipped to combination or omega rails of 35 mm and to pre-slotted plates. Ducts are available in several sizes and can hold up to 700 wires of 1.5 mm^2. They are closed with covers that slot into them. The same tag holders can be used for ducts and cable clips.

11.8 Mounting

Automation system and distribution components are designed to be mounted on chassis or frame structures. This sub-section describes a few definitions, useful tips or rules and draws attention to the precautions to take in mounting work.

Chassis

This consists of two pre-drilled vertical uprights, with or without notches.

The device, depending on its mounting system, is either clipped or screwed to:
- horizontal rails;
- pre-slotted plates;
- solid plates;
- a combination of plates and rails.

Depending on the dimensions of the rails or plates and, above all, the mass of the device, it is advised to use:
- combination or omega rails of 35 mm;
- omega rails of 75 mm;
- "C" uprights to support the devices instead of horizontal rails;
- pre-slotted plates stiffened at the back with a horizontal rail.

Chassis are usually mounted in monoblock cabinets or boxes.

Frame

This is a unit consisting of one or more chassis side by side or back to back, held to the floor by a cross piece/foot or hung on the wall by the top of an upright. It can also be installed in and linked to a cabinet the upper part of which is equipped with horizontal busbars to power each chassis.

Devices on doors or front plates

Certain control or viewing devices are mounted on the doors or front plates of enclosures. To maintain their ergonomics, they must be arranged according to rules which depend on their type (control or viewing) and their elevation from floor level.

The layout must take into account the number of parts to be placed:
- few parts: distributed along the horizontal axis of the area;
- many parts: distributed over the entire area.

Some doors and front plates have reinforcements or parts inside which restrict installation. The depth of parts on doors must be checked against the parts mounted on the chassis. The weight of these parts must also be considered.

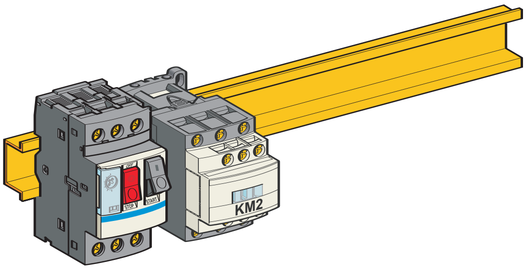


Fig. 7a Mounting on omega rail

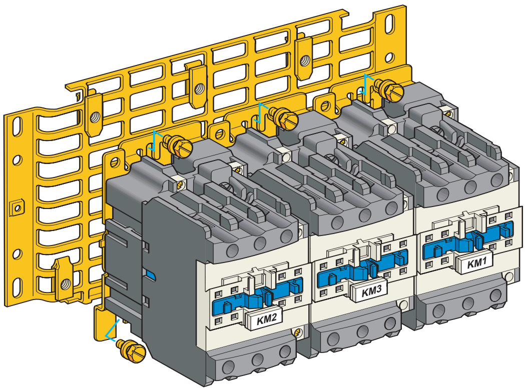


Fig. 7b Devices screwed to pre-slotted plate

Device mounting

The following general rule should apply when mounting and attaching devices to chassis and frames: attachment should always be possible from a front access. Since equipment is nearly always in a box or cabinet, such access makes it much easier to carry out any alterations or additions to it.

The *figures 7a and 7b* shows some examples of device mounting.

11.9 Device fitting tools

To ensure the requisite levels of protection and facilitate integration work, Schneider Electric offers software and products to simplify integration of push buttons and man-machine interfaces (Tego dial range).

The software helps to keep account of the ergonomics and mounting and attachment kits help to cut down study and fitting times considerably.

Wiring

The wiring procedure "by explanatory circuit diagram" works by systematic use of the device terminal markings represented on the circuit diagram. It applies to the power and control circuit wiring of all equipment with contactors, regardless of complexity.

This wiring procedure saves time for the user.

The circuit diagram is noted for:
- execution speed: time saved in design;
- clarity: simple illustration of electrical circuits;
- easy understanding: intuitive wiring;
- operational efficiency: easy comprehension, searches, modifications and servicing.

It can be accompanied by a hardware layout and installation plan to help locate components and by an external connections diagram.

Wiring with the help of the circuit diagram

Whatever the power or control circuit, the wiring engineer picks out the device terminal markers on the circuit diagram and connects the relevant sections between the corresponding markers in the equipment.

Linking examples:
- terminal 2 of disconnector Q1 to terminal 1 of fuse F1;
- terminal 22 of contact KM3 to terminal 57 of contact KA1.

11.10 Platform tests

The purpose of platform tests is to correct any errors made when building the equipment and make adjustments prior to commissioning. The following points must be checked:

- the hardware is the same as specified in the plans and is correctly mounted;
- the wiring is the same as in the diagrams;
- operation complies with the specifications.

Some of these checks must be made with live equipment, so the following points are mandatory:

- platform tests must always be run by trained personnel qualified to work with live electrical equipment;
- all the requisite precautions must be taken to ensure the safety of persons in compliance with current legislation..

Hardware compliance inspection

This is an inspection of the physical aspect of the equipment and comprises the following points:

- presence of contractual documents (diagram, product list, installation, etc.);
- the hardware mounted on the chassis is the same as stipulated in the documents;
- the hardware is laid out and mounted as stipulated in the documents;
- the hardware has not suffered any mechanical damage;
- component markings appear on the devices and door-mounted components are marked by tags;
- the voltage of all devices is the rated voltage;
- lamp bulbs are in place and use the rated voltage;
- device ratings are the same as stipulated in the diagrams;
- fuse ratings and types are compliant (usually, appropriate fuses are installed by the platform engineer);
- the terminal blocks are properly marked, mounted and of the right section for easy connection of external wiring. It is important to check that the frame terminals are adequately insulated from adjacent terminals (correct position of latching strips);
- requisite distances between terminals, devices, frames and safety limits are observed;
- the component characteristics are the right ones for their use;
- construction rules or particular contract specifications have been followed.

Proof that the inspection has really been undertaken is to be given in a special document or mentioned on the installation diagram and signed by the operator.

Connection clamping checks and preliminary adjustments

Before proceeding to electrical tests on the equipment, all the control and power connections must be checked to see if they are properly clamped. This operation is important because a poorly clamped connection can cause problems: abnormal heating, voltage drops or short circuits.

The operator can then adjust the value of the trip current of the thermal overload relays by displaying the current indicated on the diagram beside the motor power on the adjustment dial of each of them.

Insulation test

The quality of insulation is measured in meg-ohms (= 10^6 Ω) with a megger.

Insulation is measured:
- between two conductors insulated from each other;
- or between a conductor insulated from the earth and frames and from earthed frames.

Sensitive devices and circuits are disconnected before checking the insulation of each circuit's wiring between terminals and between terminals and the earth. Likewise, the insulation of break device conductors is checked on both sides.

The *figure 8* gives the voltage values for measuring insulation and the isolation resistance to be reached.

Rated voltage of circuit	Insulation test direct voltage	Isolation resistance 1n MΩ
< 48 V	250 V	Equal to or higher than 0.25
Voltage from 48 to 500 V	500 V	Equal to or higher than 0.5
Voltage higher than 500 V	1 000 V	Equal to or higher than1

↑ *Fig. 8* *Insulation voltage test*

Dielectric tests

These are designed to test the dielectric rigidity of a device unit at an alternating voltage defined according to the circuit's rated insulation voltage.

Dielectric rigidity is expressed by resistance to a test voltage applied between active conductors and the chassis frame. The test is considered satisfactory when there is no breakdown or flashover.

The device used is a flashover bridge delivering an alternating voltage that can be adjusted to a frequency between 45 and 55Hz. It can provide high voltage with a very weak current.

When it is applied, the test voltage must not exceed 50% of the value indicated in *figure 9*.

Rated insulation voltage	Dielectric test voltage (RMS voltage)
< = 60 V	1 000 V
Voltage from 61 to 300 V	2 000 V
Voltage from 301 to 660 V	2 500 V

↑ *Fig. 9* *Dielectric voltage test*

It is then gradually increased until it reaches the specified value a few seconds later. This voltage is maintained for one minute.

When the equipment includes electronic devices, dielectric tests cannot be run afterwards but must be run during the mounting and wiring process to prevent any destruction.

11.10 Platform tests

Power circuit check

This check is designed to ensure the power wiring complies with the diagram and is run with the equipment turned off.

In most cases, it is run with a test lamp.

Control circuit check

Wire-by-wire check

This check is designed to ensure the control circuit wiring complies with the diagram and is usually run with the equipment turned on. It is also used to check that the devices work properly.

To run the tests safely, the power and control circuits must be completely separated from each other for the entire duration. Furthermore, it is advisable to insulate electronic units such as speed controllers and PLC's to prevent any voltage injection that could cause partial or total destruction.

Wiring checks are made "line by line". The action of each contact must be checked, including that of external contacts by short-circuiting the corresponding terminals.

Electrical continuity must be checked.

For small equipment, wire-by-wire checks can be run with the power off, using a test lamp or megger.

General test

The general test involves simulating all the operating phases of a machine or process in the order they are supposed to run and checking the servosystems and safety.

An adequate power supply must be provided and the interconnections and connections made with the test benches which replace the external control auxiliaries by switches, push buttons, etc.

The purpose of the general test is to ensure that the equipment operates as described in the specifications.

It is also designed to check the effect of an operating error in machine or process control, of an impaired external control element (limit switch, detector, etc.).

The programs are loaded in the PLC's and tested as fully as possible by simulating discrete inputs by contacts and analogue inputs by signals. This simulation is used to correct any programming error and substantially reduce the time required for commissioning.

For equipment with electronic speed controllers, simulation should include a dynamic test using the installation's motors or, failing this, a test motor, preferably with comparable ratings.

It is advisable to draft a test report mentioning the adjustments (values) and alterations (programs and hardware) made, as well as any elements that could not be tested or were only partly tested.

This document will help to make commissioning work easier.

The diagrams, listing and product lists should be altered to give an exact description of the equipment that is to be commissioned.

Cabinets and boxes are unwired before shipping. If necessary, heavy parts are wedged to prevent frames and cabinets from warping during transport.

The bases of cabinets should be thoroughly cleaned to prevent any foreign bodies (washers, wires, etc.) from getting into the devices.

11.11 Equipment commissioning

All devices leaving the factory are checked by experts before shipping and adjusted or calibrated with extreme precision.

It is advisable not to make new adjustments, except to overload relays and timed auxiliary contacts, which can be adjusted on site to suit operating conditions.

As for platform tests, on-site commissioning of equipment includes work done with it switched on. The same rules therefore apply: supervision by qualified authorised personnel, compliance with safety rules.

Installation

Upon receipt of equipment

Check that:

- the enclosures have not received any shocks;
- the mobile part of the rotating contactors has not been warped or shifted;
- no foreign bodies have entered the air gap in the magnetic circuit, between the contacts or terminals;
- the mobile part of the contactors and disconnectors and the overload relay trip devices work freely;
- the closing devices (boxes, cabinets) work properly;
- seals are tight (for proofed hardware);
- the control and signalling auxiliaries and the measuring devices on the doors are in good condition;
- the shipment includes up-to-date diagrams, commissioning instructions, operator manuals and any platform test reports.

Before connecting external conductors:

- check the voltage and frequency of the power supply to the power and control circuits;
- check that the type and gauge of fuses and protection relays are properly adapted to the receivers to protect.

Attaching and connection equipment

- work out the section of the connection cables according to the current absorbed by the machines under control. To prevent voltage drops, increase the section of the wires and cables powering the control and power circuits when the line is long or when very low voltage is used;
- on units with watertight boxes, the conductor duct must be inserted into the rubber seal of the box. This must be tightened to immobilise the cable completely;
- external connections must be made in strict compliance with the diagram;
- current installation rules must be followed. For this purpose, there is a marked terminal on the boxes, cabinets and control auxiliaries for connecting frames to the external ground conductor;
- for devices used in highly corrosive or tropical atmospheres, it is advised to cover the terminals with a layer of protective varnish after connection.

Adjusting thermal overload relays

The graduations in amperes on the dial correspond to the current absorbed by the motor. Adjustments are made by displaying the value etched on the dial opposite the index, which corresponds to the absorbed current (look at the full load current corresponding to the mains voltage on the motor rating plate).

For a star-delta starter, when the relay is directly connected in series with the motor windings, the adjustment value should be I / √3, I being the current absorbed by the motor.

11.11 Equipment commissioning

Thermal overload relays are compensated, so there is no need to make adjustments for ambient temperature within the limits indicated on the technical data sheets.

These adjustments are usually made on the platform and are indicated in the test report.

When the power line and all the external power and control circuits are connected, general tests of the equipment can be made. These are run in two steps:

No-load test

This test is run to check that all the connections (control and signalling auxiliaries, sensors, safety switches, etc) have been made correctly and in compliance with the diagram. To run it, the power to all the receivers must be cut off:

- by removing the fuse cartridges protecting the power circuit from their base;
- or by powering the control section only and leaving the power section off.

When the control circuit is powered, an action on the starter control auxiliary should stop the contactor(s) it governs and, on more complex equipment, start the automatic cycle. At this point, it is advised to operate external devices manually (particularly safety devices) or simulate their operation, then deliberately and methodically trigger every control and operation anomaly to check the efficiency of the control, servosystem, safety and signalling circuits.

On-load test

Now, turn on the power circuit to run a general on-load test to check the exactness of the connections and receiver operation. This test can be completed by a series of further ones to check the automatic equipment governs the installation's mechanical functions properly.

Successful commissioning is the result of the operator's experience along with the contents of the equipment file (automation system lists, commissioning instructions, device manuals, etc.).

Troubleshooting

The wide variety of automation equipment makes it impossible to define a troubleshooting procedure that applies to all diagrams.

Experience and knowledge of the equipment and its functions are indispensable to an efficient troubleshooting.

Knowledge of the FMECAs carried out at the design stage can be very useful when seeking the reason for failures.

11.12 Equipment maintenance

At the design stage, FMECAs are used to define maintenance operations and their intervals:
- motor brush replacement when applicable;
- filter cleaning;
- wear part replacement;
- consumable item provisions, etc.

Electronic and electromagnetic devices require practically no maintenance. However, a few important points should be noted.

◻ Electromagnet in the contactor

If the magnetic circuit is noisy, check:
- the mains power voltage. An electromagnet vibrates when it is powered by an alternating voltage lower than the one it is designed for;
- there is no foreign body between the mobile and immobile parts of the magnetic circuit;
- the state of ground surfaces. These should never be painted, scraped or filed. If they are very soiled, clean them with spirit or appropriate solvent.

◻ Contactor coil

If a coil has to be replaced (such as when the control circuit voltage changes), the new coil must be defined according to the actual control circuit voltage. It then ensures:
- closing of the contactor when the voltage reaches 85% of its rated value;
- opening of the contactor when the voltage drops below 65% of its rated value;
- permanent tolerance of voltage corresponding to 110% of the rated value.

A coil can be damaged due to:
- incomplete closure of the magnetic circuit caused by a mechanical incident or a control circuit voltage of less than 85% of the rated value. In alternating current, this lowers the reluctance of the magnetic circuit and, in direct current, destroys the efficiency of the consumption control system where the contact has not opened. It also prevents there being adequate pressure on the poles, which overheat and can weld if the current crossing them is the one absorbed by a motor during starting;
- a poorly adapted control circuit;
- a power voltage greater than 110% of the rated value.

In all cases, the coil will deteriorate if the energy dissipated by Joule effect is higher than normal. To prevent such incidents, use coils adapted to the voltage measured at the equipment's power supply terminals.

◻ Contactor poles

Knowledge of controlled power and the category of use (such as disconnecting a running squirrel-cage motor) helps to ascertain the electrical durability of the contacts in an individual contactor or to choose a contactor on the basis of the intended operations.

11.12 Equipment maintenance

- **Block contactor**

Block contactor poles need no maintenance.

For example, in category AC-3, a contactor powering a compressor motor that starts 6 times in an hour and operates 24 hours a day will have a lifetime of: 2,500,000 = 17,360 days, i.e. about 50 years without maintenance.

Contacts that have made many breaks may appear to be worn.

Only regular checks of the compression rate or monitoring, with some calibres, of the general wear indicator can ensure the wear rate is properly ascertained.

When in use, never adjust the compression rate. When this ranges from 20 to 50% of the initial rate, the contacts must be changed.

After this operation:
- the contacts must be aligned according to the initial compression rate;
- it is advised to scrape the sides of the blow-out chambers;
- it is indispensable to check the screw tightening torque.

- **Auxiliary contactor contacts**

No maintenance and no adjustment except the duration of timing on timed auxiliary contacts.

- **Thermo relays**

No maintenance. The only possible intervention is adjustment of the trip current value which depends on the current absorbed by the receiver.

- **Enclosures**

Grease hinges and the closing device from time to time.

On sealed boxes and cabinets, check the efficiency of sealing devices (seals, cable glands, cable boxes).

Clean filters with a vacuum cleaner, never use compressed air.

- **Radiators of electronic devices**

Devices that use electronic power components are fitted with radiators, usually with forced ventilation.

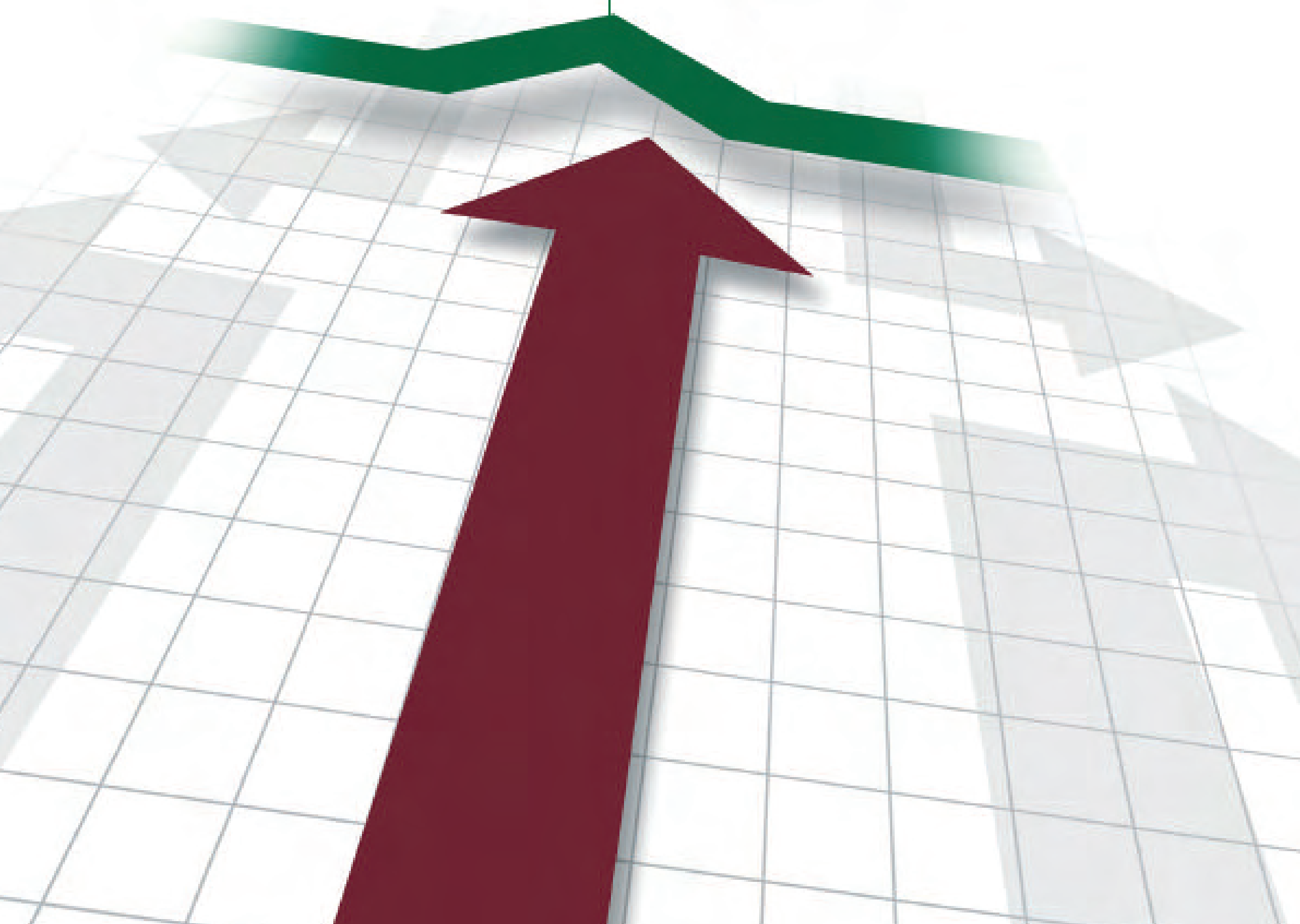
Depending on the environment and any dust in the atmosphere, clean the fins periodically to prevent them from clogging.

NEVER

- file or grease contacts;
- alter a part or replace it with an improper spare;
- rearm an overload relay without having found and eliminated the cause of tripping;
- replace a fuse and repower the equipment without having remedied a fault;
- leave a cabinet or box open unnecessarily, especially in a dusty atmosphere;
- use inappropriate solvents.

12 chapter
Eco-design

Environment concern shall take into account several requirements as:
selection of raw materiel at the design stage,
energy consumption during operation,
recycling capability at the end of lifetime.



Summary

12.1 Foreword

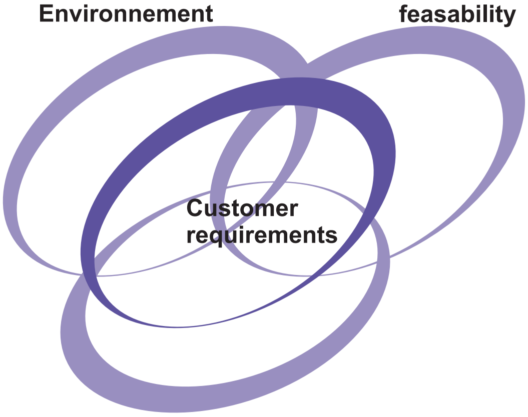


Fig. 1 *Environmental parameters*

The term "eco-design" means products (goods and services) designed with the environmental factor in mind.

It implies that this factor is included with the rest of the conventional design ones (customer requirements, cost control, technical feasibility, etc.) (⇨ *Fig. 1*).

This policy involves different players in the economy – suppliers, producers, distributors, consumers, and private buyers – who wish to offer or choose products that offer the same service but are more environment-friendly.

Because is it upstream of the decision-making process, eco-design is a preventive policy. It is based on a global attitude, a multicriteria approach to the environment (water, air, soils, noise, waste, energy, raw materials, etc.) encompassing all the stages in the lifecycle of a product: raw material extraction, production, distribution, use and disposal at the end of the lifetime.

This double nature of eco-design (multicriteria and multiple stages) is what may be called its signature.

Investigation methods can be described as in-depth or simplified depending on the degree to which they keep account of environmental impact throughout the product lifecycle.

Excerpt from the definition of eco-design by Ademe (the French environment and energy agency).

In this guide, we propose a general methodology for eco-design which can be used for any new development of products or services and for new versions of existing ones.

Introduction

It is Schneider Electric's policy to act as an environmentally responsible company. As regards to products and services, this means that eco-design has to be part of any new development and any new version of existing ones if we want to mitigate the environmental impact of our products throughout their lifetime.

To achieve this goal, this guide must:
- state the environmental policy of Schneider Electric, the main object of which is to promote respect for all natural resources and act positively and constantly for a better environment for all;
- outline the main European regulations that will soon apply to us, in order to plan ahead;
- provide designers with a methodology to help them design eco-friendly products/services;
- describe the EIME software available from Schneider Electric for designers to use in eco-friendly design projects

Schneider Electric's environmental policy

For Schneider Electric, behaving as an environmentally and, more widely, a socially responsible company contributes to performance by promoting relevance in long-term decision-making and winning the support of all partners in the group: employees, customers, suppliers and shareholders.

Schneider Electric therefore aims to be a "socially responsible company" wherever it is established throughout the world. This includes compliance with a dynamic and ambitious environmental policy based on the following principles:

Schneider Electric

- **Environmental protection as part of management policy**
  - by taking the requisite steps to make respect for the environment an integral part of Schneider Electric's common culture and a natural approach to all our work and throughout our industry;
  - by promoting environmental protection within Schneider Electric, through awareness raising, training and communication in line with our environmental policy;
  - by providing our customers, suppliers and partners with relevant information.
- **Sustainable environment-friendly industrial development**
  - by adopting an ongoing positive approach to mitigate the environmental impact of our products/services throughout their lifecycle;
  - by developing more environment-friendly new products/services and manufacturing procedures with special attention to forward planning;
  - by using new techniques that help to conserve natural resources and control our products' power consumption;
  - by designing our products with a view to making them recyclable;
  - by complying with current directives and anticipating new ones.
- **ISO 14001 certification for all our sites**
  - by adopting an environmental management system based on the international ISO 14001 standard;
  - by building and running our sites in a way worthy of Schneider Electric's local image, in compliance with rulings in force and going further whenever relevant,
  - By eliminating or reducing waste and improving its recovery;
  - by ongoing improvement of current manufacturing processes to optimise their environmental impact.

12.2 Concepts and main directives

Main concepts

□ Since 1987, **the concept of sustainable development** has been an incontrovertible reference with regard to protection of the environment. It can be resumed as follows:
- development which meets the needs of society today, without preventing future generations from meeting their own needs.

□ **The European Union's 6th Environment Action Programme** (drawn up for the next ten years), designed to implement sustainable development, is based on the precautionary principle, the principle of tackling pollution at the source and priority to preventive measures and the polluter pays principle (Treaty of Amsterdam).

□ The main objective of the **IPP (Integrated Product Policy),** a priority of the Action Programme, is:
- in relation to the concept of sustainable development, to stimulate environment-friendly product and service supply (eco-design, information on lifecycles) and demand (awareness, communication, provision of raw material and services more environmental friendly).

Main directives

The main directives based on these concepts, currently in the European discussion stage, are:

- **EUP (Energy Using Product):** Based on the IPP concept, this aims to standardise the design of electric and electronic equipment to ensure its free circulation and **mitigate its environmental impact throughout its lifecycle,** ensure more efficient use of resources and protect the environment in a way compatible with sustainable development.
- **WEEE (Waste of Electrical and Electronic Equipment)**
  - To reduce waste from electric and electronic equipment and, for this reason, commit the producer to recovering and recycling (70 to 80% in weight) equipment at the end of its lifetime.
- **RoHS (Restriction of Hazardous Substances)**
  - To restrict the use of certain substances considered hazardous for the environment and especially for health. These are heavy metals: lead ***(Pb)***, mercury ***(Hg)***, cadmium ***(Cd)***, hexavalent chromium ***(Cr6)*** and polybrominated biphenyl ***(PBB)*** and polybrominated biphenyl ether ***(PBDE)*** flame retardants.

Use of a number of other substances not covered by this directive should also be avoided. The EC jury is still out on the subject of PVC, the use and recycling of which are controlled by some local regulation.

12.3 Standards

In addition to the European directives, there are a number of other standards to regulate inclusion of environmental aspects in product design. These include:

ISO, NF and EN standards

- ISO 140xx: a set of environmental management standards;
- ISO TC 61: plastics – environmental aspects;
- ISO 64 guide: inclusion of environmental aspects in product standards;
- NF FD X30 310: inclusion of environmental aspects in product design;
- EN 13428 to 13432: packaging – environmental aspects.

This non-exhaustive list gives some idea of the rules on the inclusion of environmental aspects in product design. Designers have to consider them as well as the usual standards and directives such as:

- LVD: Low Voltage Directive;
- IEC 60 947- 2: low voltage device standard – circuit breakers;
- IEC 60 947- 4 - 1: switchgear and control gear standard.

Note: there are also a number of national regulations (batteries, packaging, etc.) in addition to these standards and directives.

As an environmentally responsible company, Schneider Electric develops new, more environment-friendly products/services and manufacturing procedures compliant with the above directives, standards and rules and also plans ahead for them by implementing eco-design.

12.4 Eco-design

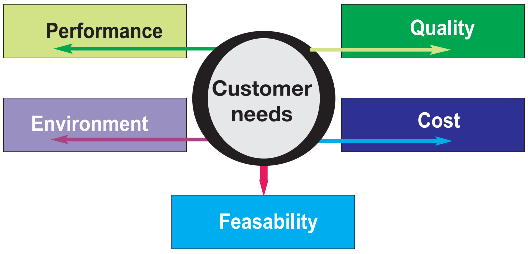


Fig. 2 *Balance between design criterias*

Eco-design, an important feature of sustainable development, as we saw in the foreword, is a proactive customer-oriented approach which can be defined as follows:

- products/services designed to best satisfy customer requirements and mitigate their environmental impact throughout their lifecycle.

It involves ongoing dynamic progress which can, by common upstream thinking (techniques, marketing, training, etc.) change a restriction into an opportunity. This is clearly the strategy manufacturers should strive to follow.

This strategy, which should apply as much to design of new products as upgrading of existing ones, implies that the designer must include a further criterion when seeking solutions: minimum environmental impact throughout the entire lifecycle (⇨ *Fig. 2*).

As stipulated in the EUP directive, the choice of an "optimal" solution meeting customer requirements must be consistent with maintaining a reasonable balance between the design criteria:

- performance, cost, quality, environment, industrialisation, etc., as well as complying with safety and health criteria.

12.5 Lifecycle

The point of eco-design, as we have seen, is to design products/services with a lesser impact on the environment throughout their entire lifecycle.

How can we define this lifecycle?

The lifecycle of a product goes from the "cradle to the grave", i.e. from the extraction of the raw material to ultimate disposal, via all the stages of manufacture/assembly, distribution, use and recovery at the end of the lifetime.

It is obvious that every stage in a product's lifecycle has an impact on the environment and it is this impact we must strive to mitigate. This is the aim of eco-design, which has to take into account all the stages together in order to prevent any improvement in the ecological behaviour of one stage having a detrimental effect on that of the others.

This requires full detailed analysis of the lifecycle (LCA) so the right choice can be made. This is what EIME software is for.

The end-of-lifetime recovery stage can involve major constraints and so must be considered from the outset of product design.

To comply with regulations, recovery should cover 70% to 80% of the product (in weight) and can be in the form of:

- repair/restoration of the product;
- reuse of parts/sub-units;
- recycling of materials;
- energy recovery.

The lifecycle of a product can be summed up as in the diagram *figure 3*.

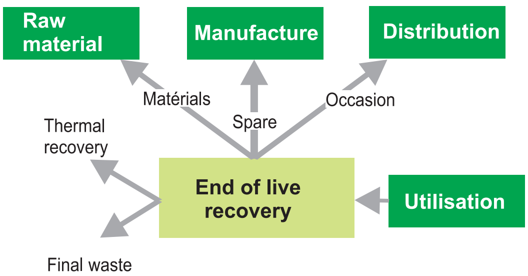


Fig. 3 *Product life cycle*

12.6 Main rules of eco-design

With regard to compliance with the principal of sustainable development and the rulings on it, we may define a number of general rules to guide designers in all eco-design studies:

- conservation and efficient use of natural resources;
- reduction of emissions (greenhouse effect, noise, etc.);
- reduction of waste (manufacture, end of lifetime);
- prohibition or minimal use of hazardous substances;
- reduction of power consumption.

However, as we already pointed out, these general recommendations for making more environment-friendly products are not intended to replace regular design rules; rather they should be applied in addition to them to optimise the response to customer requirements with the following criteria in mind:

- performance;
- cost;
- quality;
- environment;
- industrialisation, etc.

But prior to any study, it is essential to look into how to optimise the function required. This means asking the following questions:

- What is the best way to respond to the customer's needs: product/service?
- Can the product offer include an environment-friendly service offer?
- Can a product offer lead to a service offer?
- Can new concepts be introduced?
- Can some sub-units be common to several products or product ranges?
- Should new functions be included?
- Can active materials be used?

Once the function optimisation stage is completed, the next step is to look closely at the stages in the product's lifecycle (choice of materials, production, distribution, end of lifetime) to which the basic rules may apply.

■ Choice of materials

The designer can have an effect on a product's environmental impact through the choice of materials. So, in line with the general rules of eco-design described above, this choice should be made using criteria targeting smaller consumption of the raw material and lower environmental impact of the materials used.

• Reduction of the mass and volume of materials used

- optimisation of the volume and mass of parts and products,
- reduction in number of parts.

• Choice of non-toxic or only slightly toxic materials in extraction, production, utilisation and disposal (end of lifetime).

• Choice of materials based on renewable resources to save natural non-renewable resources.

• Choice of power-saving materials in raw material extraction, material processing and use.

• Use of recycled materials, the environmental impact is then due to recycling and not production.

• Use of recycled materials with a view to product recovery at the end of its lifetime.

It goes without saying that compliance with these environmental criteria does not dispense the materials chosen from having to meet the usual requirements for the product with regard to mechanical, electrical, cost and manufacturing (casting, cutting, etc.) factors.

12.6 Main rules of eco-design

Production

The production stage is an important part of the lifecycle and should never be neglected in eco-design. Design choices can have significant effect on industrial processes and therefore on their environmental impact.

This is why a certain number of optimisation criteria should be considered from the outset.

- **Reduction in environmental discharges (water, soils, air)**
  - choice of production methods that cut down environmental dumps.

Example: wherever possible, avoid surface treatments

- **Reduction in power consumption at all stages of production**
  - choice of power-saving manufacturing, mounting and assembly methods.
- **Reduction in the amount of waste (machining, cutting, casting, etc.)**

Example:
  - parts designed to reduce offcuts;
  - reuse of casting sprues;
  - reduction of scrap.
- **Reduction in the number of production stages**
  - example: fewer different parts.
- **Less transport between stages**
  - less transport from plant to plant (parts, sub-units),
  - less power consumed for transport,
  - use of new production methods,
  - new methods with a lower environmental impact than conventional methods - BAT (Best Available Technique).

Distribution

Product distribution is another stage in the lifecycle which can have a substantial impact on the environment. This is why it is necessary to optimise packaging and the distribution system itself from the outset of product design.

To this end, in compliance with standards (EN 13428 to 13432) and the decree published 25/07/98, the following criteria should apply.

- **Reduction in the mass and volume of packaging**
  - reduction in volume and mass of products;
  - optimisation of the packaging function.
- **Fewer packages: packages common to several products**
- **Choice of greener packaging minimum heavy metal content (lead cadmium, mercury, etc.)**
- **Packages designed to be reused or recovered**
  - recovery of 50 to 65% in weight;
  - avoid use of different materials (cardboard, foam, etc.).
- **Optimisation/reduction in transport: fewer masses and volumes to transport**
- **Choice of means of transport using less fuel**

As always, compliance with these criteria should not be detrimental to the basic functions of packaging such as protection and safety.

12.6 Main rules of eco-design

Utilisation

Product utilisation is a stage in the lifecycle which can have a significant effect on the environment, especially with regard to electricity consumption. Here again, there are a number of criteria which can play a decisive part:

- **Lower power consumption when the product is used**
  - consumption in electrical contacts (contact resistance, welds, etc.) and bimetal strips;
  - consumption by control units (electromagnets, etc.);
  - power dissipated in electronic components, etc.
- **Reduction in leaks and discharges into the environment**
  - noise reduction;
  - less leakage (e.g. SF_6).
- **Greater product durability**
- **Easier maintenance and repairs**
  - greater product reliability;
  - customer link (pre-alarm, etc.);
  - modular products.

Another important point in this stage is the use of clean renewable fuels but the designer's impact on this does not seem decisive.

End of lifetime

As we have already said, recovery at the end of a product's lifetime should be an important part of it (70 to 80% in weight) and should be taken in charge by its producer. If this environmental criterion is to be complied with at reasonable cost, the product must be designed so as to facilitate this operation.

This in turn implies a certain number of criteria.

- **Products easy to dismantle**
  - avoid the use of assembly systems that cannot be dismantled;
  - modular products.
- **Reuse of sub-units/components: preference for modular products**
- **Product repair/restoration (2nd hand)**
- **Recycled materials**
  - marked plastic parts (see technical directive FT 20 050);
  - fewer different materials.
- **Choice of non-toxic materials: incineration**
- **Easy dismantling of toxic products and/or products requiring special processing**
- **Easy access to and quick dismantling of batteries, mercury relays, electronic cards, LCD monitors, etc.**
- **Simple product safety devices (tension springs, etc.)**
- **End of lifetime guide enclosed with product**

This short list of design criteria for each stage in a product's lifecycle and the examples to illustrate them do not claim to cover all cases of eco-design. They are principally intended as a guide to help the designer's thought process.

Moreover, dividing the product's lifecycle into major stages (choice of material, production, distribution, utilisation and end of lifetime) should not get in the way of the final object, which is to mitigate the overall impact of the product from beginning to end of its lifecycle. It is therefore crucial, as we have already said, that improvement in the ecological behaviour of one stage should not have a detrimental effect on that of the others.

To achieve this requires full detailed analysis of the lifecycle (LCA) made. This is what EIME software (see further in this document) is used for.

12.7 Conclusion

The policy of Schneider Electric includes eco-design to:
- promote respect for all natural resources;
- constantly and positively improve conditions for a clean environment to satisfy its customers and users of its products, its employees and the communities where the company is established.

This constant positive progress policy can enhance the company's performance and should be seen as an opportunity. Therefore, **eco-design**, the purpose of which is to design products/services with a lower impact on the environment throughout their lifetime and which best satisfy customer requirements, **will be our general policy for the development of every new product/service, and for new versions of existing ones.**

12.8 Applications

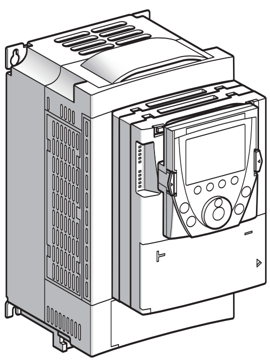
EIME software

EIME (Environmental Information and Management Explorer) is an application to help in the design of environment-friendly products. It is owned and controlled by Alcatel, Alstom, Legrand, Schneider Electric and Thomson Multimedia.

It is used to evaluate the environmental impact of a product from beginning to end of its lifecycle and guides designers in their choice of materials and designs. It can be accessed from anywhere in the world; its database (materials, procedures, etc.) is the same for all Schneider Electric designers all throughout the world.

The main features of this software are:
- help in the choice of materials and procedures;
- information on compliance with regulations;
- evaluation of environmental impact (LCA);
- help in identifying weak points;
- comparison of two design options.

The environmental profile of a product built with EIME is an essential basis for environmental product communication with customers.



↑ *Fig. 4* *This product has won the "Eco-product for sustainable development" prize*

Altivar 71: an example of eco-design Product Environment Profile (PEP)

Altivar 71 *(⇨ Fig. 4)* is a range designed to control and vary the rotation speed of electric asynchronous motors.

It consists of products rated from 0.37 to 18kW with single-phase or 3-phase input voltages of 200 and 500V.

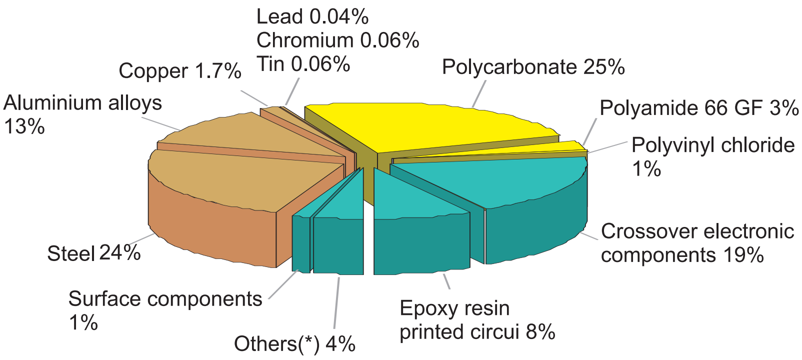
The product used for this study is the complete Altivar 71 rated 0.75kW, 500V (ref. ATV71 H075N4). It is representative of the rest of the range. The other products in the range are built with the same technology and by the same manufacturing process.

The environmental analysis was made in compliance with standard ISO 14040 "Environmental management: lifecycle analysis, principle and framework". It covers all the stages in the product lifecycle.

12.8 Applications

◻ Constituent materials

In mass, the products in the range extend from 2680 g to 9000 g The Altivar 71 – rated 0.75kW, 500V, weighs 2680g without packaging. The constituent materials are made up as *figure 5* :



↑ *Fig. 5* *AT71 material constituents*
(*) "Others" comprises all elements at less than 1% such as shrinkable tubing, EPDM elastomers, etc.

All our departments, suppliers and subcontractors have been briefed to ensure that materials used in the Altivar 71 – 0.37 to 18kW range contain none of the substances prohibited by current legislation (list available on request) when it goes on the market.

The range is designed to need no batteries or accumulators. The site where this product family was designed is certified ISO 14001 for its eco-design process.

◻ Manufacture

The range is manufactured at a Schneider Electric production site which has set up an environmental management system certified ISO 14001.

Ongoing process enhancement reduces the annual average power consumption on site by 5%.

Waste is thoroughly sorted for a recovery rate of 99%.

◻ Distribution

The packaging is designed to cut down its weight and volume, in compliance with the European packaging directive 94/62/EC. Its overall weight is 1080 g, and it is made mainly of cardboard with a recyclable polyethylene bag. No packing foam or staples are used.

The distribution channels are optimised by local distribution centres in the vicinity of the market areas.

◻ Utilisation

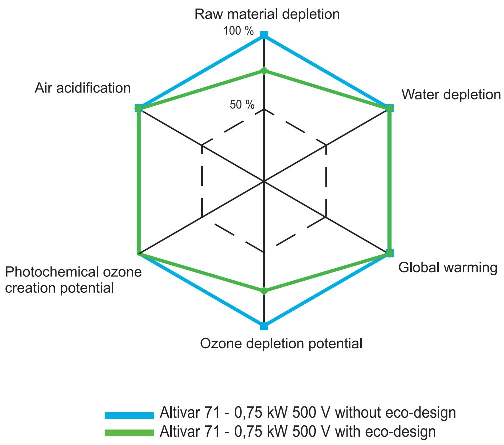
The products in the Altivar 71-0.37 to 18kW range cause no pollution requiring special conditions of use (noise, emissions). Their electricity consumption depends on how they are commissioned and operated.

Their power losses spread from 44 W to 620 W. For example the Altivar 71-0.75kW, 500V losses are 44W, i.e. under 6% of the total power circulating in it.

◻ End of lifetime

At the end of their lifetime, the products in the Altivar 71-0.37 to18 kW range shall be dismantled to recover their constituent materials. Their recycling potential is more than 80%. This includes ferrous metals, copper and aluminium alloys and marked plastics.

The products in the range also contain electronic cards which should be withdrawn and sent through special processing channels. The end-of-lifetime data is detailed in the relevant data sheets.



↑ *Fig. 6* *LCA comparison of impacts of Altivar 71-0.75W, 500V with and without eco-design*

□ Environmental impacts

The Lifecycle Analysis (LCA) was made with EIME (Environmental Impact and Management Explorer) version 1.6 and its database version 5.4 (⇨ *Fig.6*).

The product's theoretical duration of use is 10 years and the electrical power model used was the European model.

The device analysed was an Altivar 71-0.75kW, 500V.

Environmental impacts were analysed in the stages of manufacturing (M) including processing of raw materials, distribution (D) and utilisation (U).

The environmental impact analysis was made by comparing the impacts of a non-eco-designed and an eco-designed product. The eco-designed product was 27% less in mass and 19% less in volume than the one from the earlier range.

The plastics used are 100% recoverable owing to the choice of materials and the new product architecture.

These modifications result in an overall reduction in the product's impact on the environment.

■ Product Environment Profile - PEP

□ System approach

Speed controllers help to save power by optimising the operating cycles of asynchronous electric motors.

In a transient state, the products in the Altivar 71 - 0.37 to 18kW range can cut more than halve the power consumption of an installation.

The figures cited for environmental impact on the previous page are solely valid for the stated context and cannot be used as is for an environmental assessment of an installation

□ Glossary

Raw Material Depletion (RMD)

This indicator quantifies raw material consumption during a product's lifetime. It is expressed as a fraction of the raw materials depleted every year in relation to their annual overall reserves.

- **Water Depletion (WD)**

This indicator calculates the amount of drinking water or industrial water consumed. It is expressed in cubicmeters.

- **Global Warming Potential (GWP)**

Global warming is the result of the increase in the greenhouse effect caused by greenhouse gas absorption of solar radiation reflected by the earth's surface. The effect is measured in grams of CO_2.

- **Ozone Depletion (OD)**

This indicator describes the part played by emissions of specifigases in the depletion of the ozone layer.

It is expressed in grams of CFC-11.

- **Photochemical Ozone Creation (POC)**

This indicator quantifies the part played by ozone-producing gases in the creation of smog and is expressed in grams of ethylene (CH_2:CH_2).

- **Air Acidification (AA)**

Acid substances in the atmosphere are carried by rainfall. Highly acid rain can destroy forests.

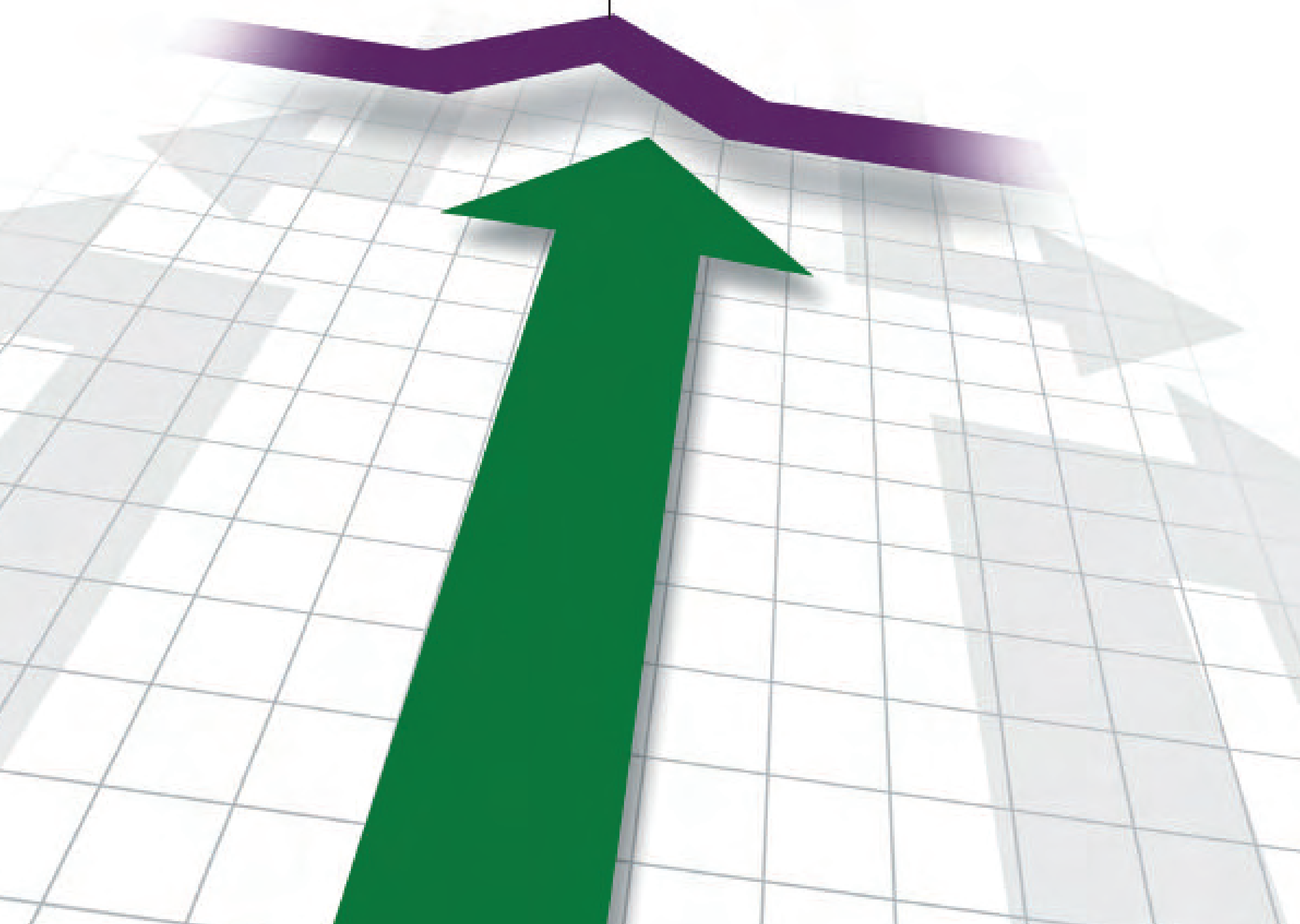
The degree of acidification is calculated using the acidification potential of the substance and is expressed in moles of H+.

M

chapter
Memorandum

Presentation:

- *Fundamental laws which reign in the electrical and mechanical universe.*
- *Tables of the main quantities and constants.*
- *Measurement units and symbols, and conversion tables with common units.*
- *Neutral regimes.*



Summary

M.1 Quantities and units of measurement

Quantity	Literal symbol	Unit of measurement	Symbol
acceleration (free fall)	g	metre per second squared	m/s²
active power	P	watt	W
angle (plane angle)	α, β, γ	radian	rad
		degree (angular)	...°
		minute (angular)	...'
		second (angular)	..."
angular acceleration	α	radian per second squared	rad/s²
angular velocity	ω	radian per second	rad/s
apparent power	S	voltampere	VA
area (surface)	A or S	metre squared	m²
capacitance	C	farad	F
depth	d	metre	m
diameter	d	metre	m
duration	T	second	s
efficiency	η	%	✭
electric current	I	ampere	A
electricity (quantity) (electrical load)	Q	coulomb or ampere hour	C or A.h
electromotive force	E	volt	V
energy	W	joule	J
force	F	newton	N
frequency	f	hertz	Hz
heat (quantity)	Q	joule	J
height	h	metre	m
impedance	Z	ohm	Ω
length	l	metre	m
linear acceleration	a	metre per second squared	m/s²
linear velocity	v	metre per second	m/s
mass	m	kilogramme	kg
magnetic field strength	H	ampere per metre	A/m
magnetic flux	ϕ	weber	Wb
magnetic flux density	B	tesla	T
moment of force	M	newton metre	N.m
moment of inertia	J or I	kilogramme-metre squared	kg.m²
mutual inductance	M	henry	H
potential difference	U	volt	V
pressure	p	pascal	Pa
radius	r	metre	m
reactance	X	ohm	Ω
reactive power	Q	voltampere (var)	VAR
reluctance	R	ampere per Weber	A/W
resistance	R	ohm	Ω
resistivity	ρ	ohm-metre/metre squared	Ω.m/m²
rotational speed	n	turns per second	tr/s
self inductance	L	henry	H
slip	s or g	%	✭
temperature Celsius	θ	degree Celsius	°C
temperature rise	Δ θ	kelvin or degree Celsius	K or °C
thermodynamic temperature	T	kelvin	K
thickness	d	metre	m
time	t	second (time)	s
		minute (time)	mn
		hour	h
		day	d
time constant	–	second	s
torque	T	newton metre	N.m
volume	V	cubic metre	m³
voltage	U	volt	V
weight	G	newton	N
width/breadth	b	metre	m
work	W	joule	J

✭ *No symbol*

Sub-multiples of units

Prefix	Symbol preceding the unit	Multiplication factor
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

Examples : Five nanofarads = 5 nF = 5.10^{-9} F
Two milliamperes = 2 mA = 2.10^{-3} A
Eight micrometres = 8 µm = 8.10^{-6} m

Multiples of units

Prefix	Symbol preceding the unit	Multiplication factor
deca	da	10^{1}
hecto	h	10^{2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

Examples : Two megajoules = 2 MJ = 2.10^{6} J
One gigawatt = 1 GW= 10^{9} W
Three kilohertz = 3 kHz= 3.10^{3} Hz

M.2 Average full-load currents of asynchronous squirrel cage motors

Three phases motors 4 poles 50/60 Hz

kW	HP	200/208 A	220 A	230 (1) A	380 A	400 A	415 A	433/440 A	460 (1) A	500/525 A	575 (1) A	660 A	690 A	750 A	1000 A
0.37	*0.5*	2	1.8	2	1.03	0.98	-	0.99	1	1	0.8	0.6	-	-	0.4
0.55	0.75	3	2.75	2.8	1.6	1.5	-	1.36	1.4	1.21	1.1	0.9	-	-	0.6
0.75	1	3.8	3.5	3.6	2	1.9	2	1.68	1.8	1.5	1.4	1.1	-	-	0.75
1.1	*1.5*	5	4.4	5.2	2.6	2.5	2.5	2.37	2.6	2	2.1	1.5	-	-	1
1.5	*2*	6.8	6.1	6.8	3.5	3.4	3.5	3.06	3.4	2.6	2.7	2	-	-	1.3
2.2	3	9.6	8.7	9.6	5	4.8	5	4.42	4.8	3.8	3.9	2.8	-	-	1.9
3	-	12.6	11.5	-	6.6	6.3	6.5	5.77	-	5	-	3.8	3.5	-	2.5
	5	-	-	15.2	-	-	-	-	7.6	-	6.1	-	-	-	3
4	-	16.2	14.5	-	8.5	8.1	8.4	7.9	-	6.5	-	4.9	4.9	-	3.3
5.5	*7,5*	22	20	22	11.5	11	11	10.4	11	9	9	6.6	6.7	-	4.5
7.5	*10*	28.8	27	28	15.5	14.8	14	13.7	14	12	11	6.9	9	-	6
9		36	32	-	18.5	18.1	17	16.9	-	13.9	-	10.6	10.5	-	7
11	*15*	42	39	42	22	21	21	20.1	21	18.4	17	14	12.1	11	9
15	*20*	57	52	54	30	28.5	28	26.5	27	23	22	17.3	16.5	15	12
18.5	*25*	70	64	68	37	35	35	32.8	34	28.5	27	21.9	20.2	18.5	14.5
22	*30*	84	75	80	44	42	40	39	40	33	32	25.4	24.2	22	17
30	*40*	114	103	104	60	57	55	51.5	52	45	41	54.6	33	30	23
37	50	138	126	130	72	69	66	64	65	55	52	42	40	36	28
45	*60*	162	150	154	85	81	80	76	77	65	62	49	46,8	42	33
55	75	200	182	192	105	100	100	90	96	80	77	61	58	52	40
75	*100*	270	240	248	138	131	135	125	124	105	99	82	75.7	69	53
90	*125*	330	295	312	170	162	165	146	156	129	125	98	94	85	65
110	*150*	400	356	360	205	195	200	178	180	156	144	118	113	103	78
132	-	480	425	-	245	233	240	215	-	187	-	140	135	123	90
	200	520	472	480	273	222	260	236	240	207	192	152	-	136	100
160	-	560	520	-	300	285	280	256	-	220	-	170	165	150	115
	250	-	-	600	-	-	-	-	300	-	240	200	-	-	138
200	-	680	626	-	370	352	340	321	-	281	-	215	203	185	150
220	*300*	770	700	720	408	388	385	353	360	310	288	235	224	204	160
250	*350*	850	800	840	460	437	425	401	420	360	336	274	253	230	200
280	-	-	-	-	528	-	-	-	-	-	-	-	-	-	220
315	-	1070	990	-	584	555	535	505	-	445	-	337	321	292	239
	450	-	-	1080	-	-	-	-	540	-	432	-	-	-	250
355		-	1150	-	635	605	580	549	-	500	-	370	350	318	262
	500	-	-	1200	-	-	-	-	600	-	480	-	-	-	273
400	-	-	1250	-	710	675	650	611	-	540	-	410	390	356	288
450	*600*	-	-	1440	-	-	-	-	720	-	576	-	-	-	320
500	-	-	1570	-	900	855	820	780	-	680	-	515	494	450	350
560			1760	-	1000	950	920	870	-	760	-	575	549	500	380
630	-	-	1980	-	1100	1045	1020	965	-	850	-	645	605	550	425
710	-	-	-	-	1260	1200	1140	1075	-	960	-	725	694	630	480
800	*1090*	-	-	-	1450	-	1320	1250	-	1100	-	830	790	-	550
900	*1220*	-	-	-	1610	-	1470	1390	-	1220	-	925	880	-	610

(1) Values in conformity with the NEC (National Electrical Codes).
These values are indicative, they vary according to the type of motor, its polarity and the manufacturer.

M.3 Electrical formulae

Active power

direct current	$P = UI$
single-phase	$P = UI\cos\varphi$
3-phase	$P = UI\sqrt{3}\cos\varphi$

where P : active power in watts
U : voltage in volts (3-phase voltage between phases)
I : current in amperes
$\cos\varphi$: power factor of the circuit

Reactive power

single-phase	$Q = UI\sin\varphi = UI\sqrt{1-\cos^2\varphi}$
3-phase	$Q = UI\sqrt{3}\sin\varphi = UI\sqrt{3}\sqrt{1-\cos^2\varphi}$

where Q : reactive power in VAR
U : voltage in volts (3-phase voltage between phases)
I : current in amperes
$\cos\varphi$: power factor of the circuit

Apparent power

single-phase	$S = UI$
3-phase	$S = UI\sqrt{3}$

where S : apparent power in voltamperes
U : voltage in volts (3-phase voltage between phases)
I : current in amperes

Power factor

$$\cos\varphi = \frac{\text{active power}}{\text{apparent power}}$$

Efficiency

$$\eta = \frac{\text{power capacity}}{\text{actual input power}}$$

Motor current

single-phase	$I = \frac{P}{U\eta\cos\varphi}$
3-phase	$I = \frac{P}{U\sqrt{3}\eta\cos\varphi}$
direct current	$I = \frac{P}{U\eta}$

where P : active power in watts
I : motor current in amperes
U : voltage in volts (3-phase voltage between phases)
η : motor efficiency
$\cos\varphi$: power factor of the circuit

Resistance of a conductor

$$R = \rho\frac{l}{S}$$

where R : resistance of conductor in ohms
ρ : resistivity of conductor in ohm-metres
l : length of conductor in metres
S : cross-sectional area of conductor in metres squared

Resistivity

$$\rho\theta = \rho(1 + \alpha\Delta\theta)$$

where $\rho\theta$: resistivity at temperature θ in ohm-metres
ρ : resistivity at temperature θ_0 in ohm-metres
$\Delta\theta$: $\theta - \theta_0$ in degrees Celsius
α : temperature coefficient in degrees Celsius to the power minus one

Joule's Law

$W = RI^2t$ single-phase

where W : energy dissipated in joules
R : resistance of circuit in ohms
I : current in Amperes
t : time in seconds

Inductive reactance of an inductance only

$$X_L = L\omega$$

where X_L : inductive reactance in ohms
L : inductance in henrys
ω : angular frequency = $2\pi f$
f : frequency in hertz

Inductive reactance of a capacitance only

$$X_C = \frac{1}{C\omega}$$

where Xc : capacitive reactance in ohms
C : capacitance in farads
ω : angular frequency = $2\pi f$
f : frequency in hertz

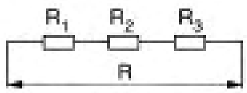
Ohm's Law

Circuit with resistance only	$U = RI$
Circuit with reactance only	$U = XI$
Circuit with resistance and reactance	$U = ZI$

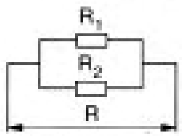
where U : voltage at the terminals of the circuit, in volts
I : current in amperes
R : resistance of the circuit in ohms
X : X_L or X_C reactance of the circuit in ohms
Z : impedance of the circuit in ohms

To determine Z, see next page.

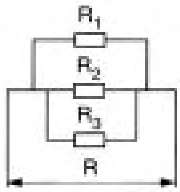
Different types of resistive circuits



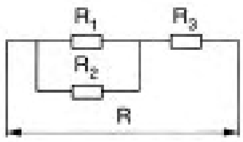
$$R = R_1 + R_2 + R_3$$



$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1 . R_2}{R_1 + R_2}$$

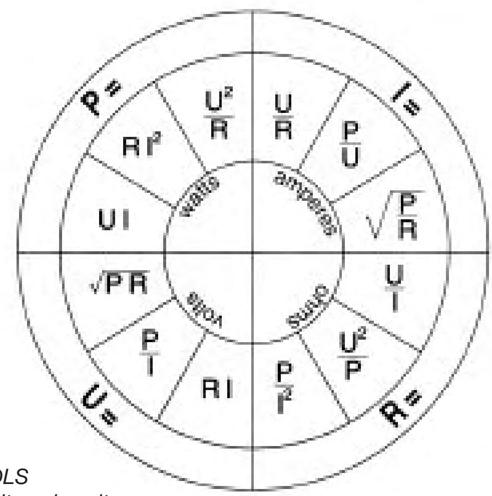


$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{R_1 . R_2 . R_3}{R_1 . R_2 + R_2 . R_3 + R_1 . R_3}$$



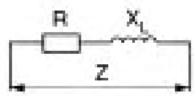
$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} + R_3 = \frac{R_1 . R_2}{R_1 + R_2} + R_3$$

Ohm's Law

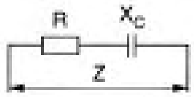


SYMBOLS
U = Voltage in volts
I = Current in amperes
R = Resistance in ohms
P = Power in watts

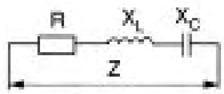
Circuits comprising resistance and reactance



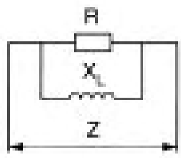
$$Z = \sqrt{R^2 + X_L^{\ 2}}$$



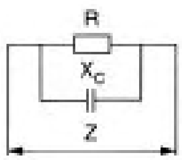
$$Z = \sqrt{R^2 + X_C^{\ 2}}$$



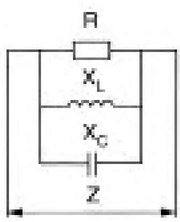
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$



$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}} = \frac{R . X_L}{\sqrt{R^2 + X_L^{\ 2}}}$$



$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C}\right)^2}} = \frac{R . X_C}{\sqrt{R^2 + X_C^{\ 2}}}$$



$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}} = \frac{R . X_L . X_C}{\sqrt{X_L^{\ 2} . X_C^{\ 2} + R^2 (X_L - X_C)^2}}$$

M

M.4 Calculation of starting resistances

For squirrel cage motors

Primary resistance

3-phase

$$R = 0.055 \frac{U}{In}$$

where R : ohmic value of resistance per phase in ohms,
U : supply voltage in volts,
In : rated motor current in amperes.

I average = 4.05 In

To order a resistance indicate : the resistance connection time (resistance in circuit) and the number of starts per hour.
Normally, we envisage 12 starts per hour of 10 seconds each, two of which are consecutive from the cold start.

Resistance for 3 step star-delta starting

$$R = \frac{0.28\ U}{In}$$

where R : ohmic value of the resistance per phase in ohms,
U : supply voltage in volts,
In : rated motor current in amperes.

I average = 1.5 In

To order a resistance indicate : the resistance connection time and the number of starts per hour.
Normally, we envisage two consecutive starts of 3 seconds each, 20 seconds apart.

Auto-transformer

During starting.

U motor = k U supply
T motor = k^2 T
I supply ≠ k^2 I
I motor = k I

where k : voltage ratio of auto-transformer U output / U supply,
T : direct-on-line starting torque,
I : direct-on-line starting current.

To order an auto-transformer indicate :
– that it is an air gap type auto-transformer (if possible),
– the peak current of the motor with direct-on-line starting (given by the motor manufacturer),
– the value of the output voltage with respect to the supply voltage, expressed as a percentage,
– the switch on time of the auto-transformer and the number of starts per hour.

Generally speaking, we provide for connections at 0.55 Un and 0.65 Un and allow for 5 starts per hour of 8 seconds. Without the exact motor characteristic we adopt :

$$\frac{Id}{In} = 6$$

For slip-ring motors

Unit resistance (1)

3-phase

$$Ru = \frac{333\ P}{Ir^2}$$

where P : rated power in kilowatts,
Ir : rated rotor current in amperes,
Ru : in ohms,
or,

$$Ru = \frac{245\ P}{Ir^2}$$

where P : rated power in horsepower,
Ir : rated rotor current in amperes.

Value of the resistance in the first step

$$R(1) = \frac{Ru + r}{1^{st}\ peak} - r$$

where R(1) : value of the resistance per phase,
Ru : unit resistance,
r : internal resistance of the motor,
1^{st} peak : desired current peak on starting.

Intermediate values of the resistance

$$R(n) = \frac{R(n-1) + r}{Peak} - r$$

where R(n) : value of the resistance per phase for this step,
R(n-1) : resistance of the preceding step,
r : internal resistance of the motor,
Peak : desired current peak for this step.

Peak on last step

$$Peak = \frac{R(n-1) + r}{r}$$

where Peak : current peak obtained,
R(n-1) : resistance of the preceding step,
r : internal resistance of the motor.

Other characteristics

$$I\ average = Ir + \frac{Ip - Ir}{3}$$

where I average : equivalent thermal current,
Ir : rated rotor current,
Ip : current peak.

To order a resistance indicate : the switched on time of the resistance, the number of starts per hour and, if required, the possibility of counter-current braking.

(1) The unit resistance is the theoretical value of the resistance per phase to be inserted in the rotor circuit to obtain the rated torque, with the rotor stalled. it is necessary for determining the starting resistance.

M.5 Mechanical formulae

Angular velocity

$$\omega = \frac{2\pi n}{60}$$

where ω : angular velocity in radians per second,
n : rotational frequency in revolutions per minute (rpm).

No-load frequency rotation

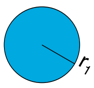
Synchronous speed (no-load) of an induction motor

$$\omega = \frac{2\pi f}{p} \quad \text{or} \quad n = \frac{60f}{p}$$

where ω : angular velocity in radians per second,
n : rotational frequency in revolutions per minute (rpm),
f : supply frequency in hertz,
p : number of pole-pairs.

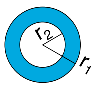
Radius of gyration

solid cylinder



$$r^2 = \frac{r_1^2}{2}$$

hollow cylinder



$$r^2 = \frac{r_1^2 + r_2^2}{2}$$

where r : radius of gyration,
r_1 : outer radius,
r_2 : inner radius.

Moment of inertia of a body of mass m

$$J = mr^2$$

where J : moment of inertia in kilogramme metres squared,
m : mass in kilograms,
r : gyration radius in metres.

It is sometimes expressed by the formulae :

$$J = \frac{MD^2}{4} \quad \text{or} \quad \frac{GD^2}{4} \quad \text{or} \quad \frac{PD^2}{4}$$

Moment of inertia related to velocity ω

$$J\omega = J'\omega' \frac{\omega^2}{\omega'^2}$$

where $J\omega$: moment of inertia in kilogramme metres square related to the angular velocity ω,
$J'\omega'$: moment of inertia in kilogramme metres squared related to the angular velocity ω'.

Rated torque

$$T_n = \frac{P_n}{\omega_n}$$

where T_n : rated torque in newtons-metres,
P_n : rated power in watts,
ω_n : rated angular velocity in radians per second.

Accelerating torque

$$T_a = T_m - T_r$$

where T_a : accelerating torque in newtons-metres,
T_m : motor torque in newtons-metres,
T_r : resistant torque in newtons-metres.

Starting time

Starting time from 0 to ω_n with constant accelerating torque T_a

$$t = \frac{J\omega_n}{T_a} \quad \text{or} \quad t = \frac{J\omega_n^2}{P_n} \frac{1}{(T_a/T_n)}$$

where t : starting time in seconds,
J : total moment of inertia of the masses in movement (motor + load) in kilogramme metres squared,
ω_n : rated angular speed in radians per second,
T_a : accelerating torque in newtons-metres,
P_n : rated power of motor in watts,
T_a/T_n : ratio of accelerating torque to rated motor torque.

In cases where accelerating torque varies with speed, practical formulae specific to the various applications are generally used for conversion to the equivalent constant accelerating torque, so as to provide rapid approximate calculations.
For example, the accelerating torque in the case of stator rotor starting can be compared, for an approximate calculation, to an equivalent constant torque :

$$T_a = T_m \text{ min.} + \frac{T_m \text{ max.} - T_m \text{ min.}}{3} - T_r$$

where

T_m min. : motor torque immediately before short-circuiting a resistance section,
T_m max. : motor torque immediately after short-circuiting this section,
T_r : resistance torque, assumed constant.

M.6 Fundamental formulae

International system SI : MKSA

Quantity	Unit	
length	l = metre	m
mass	m = kilogramme	kg
time	t = second	s
electrical current	i = ampere	A

Kinematic (linear movement)

Length l

Velocity

$v = \frac{dl}{dt} = \frac{l}{t}$ in m/s

Acceleration

$a = \frac{dv}{dt}$ in m/s²

Dynamic (linear movement)

Force

$F = m\,a$ in N (newton)

Motive force

$F = m\,a$

Work

$W = F \times l$ in J (joule)

Power

$P = \frac{W}{t} = \frac{Fl}{t} = Fv$ in W (watt)

$1 \text{ watt} = \frac{1 \text{ joule}}{1 \text{ second}}$

Energy

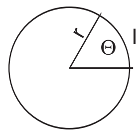
$W = 1/2\ mv^2$

The kinetic energy is characterised by the velocity of the body

Kinematic (circular movement)

Arc

Θ in radian, where $\Theta = \frac{l}{r}$



Angular velocity

$\omega = \frac{d\Theta}{dt} = \frac{\Theta}{t}$ in rad/s

$\omega = \frac{2\pi n}{60}$ n in tr/mn

Velocity

$v = \frac{l}{t} = r\omega$ ω in rad/s

Angular acceleration

$\alpha = \frac{d^2\Theta}{dt^2} = \frac{d\omega}{dt}$ in rad/s²

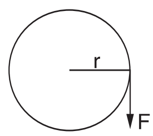
Tangential acceleration

$a_T = r\,\alpha$ α in rad/s², a in m/s²

Dynamic (circular movement)

Torque

$T = F \times r$ in N.m or J/rad



Motive torque

$T = J\frac{d\omega}{dt}$

J = moment of inertia in kgm²

Work

$W = T\Theta$ in J (joule)

Power

$P = \frac{T\Theta}{t} = T\omega$ in W (watt)

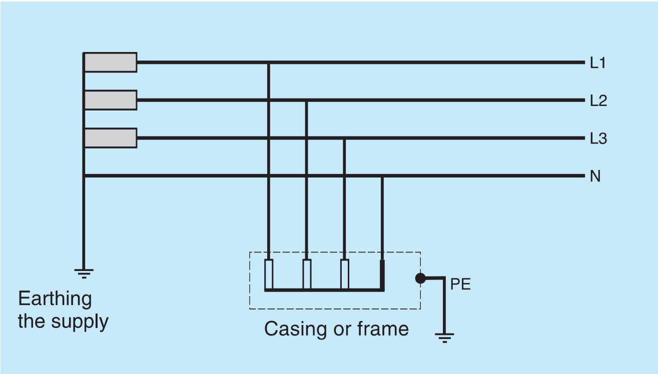
$P = T\frac{2\pi n}{60}$ N in tr/mn

Energy

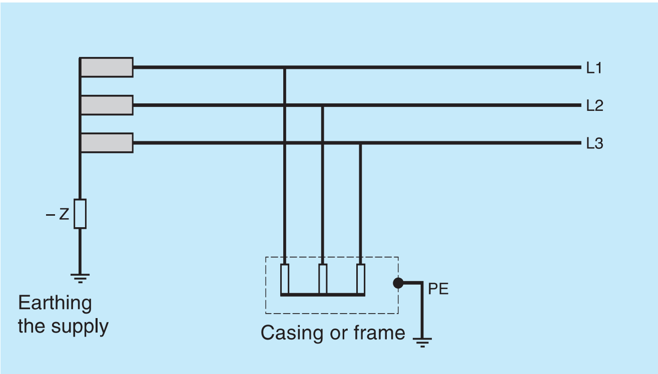
$W = 1/2\ mr^2\omega^2 = 1/2\ J\omega^2$

The kinetic energy is characterised by the velocity of the body

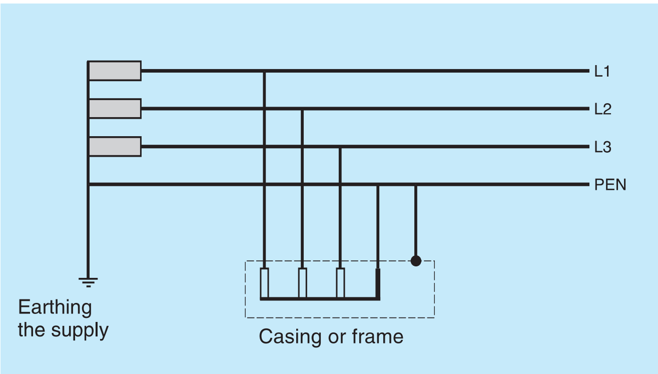
M.7 Neutral connections



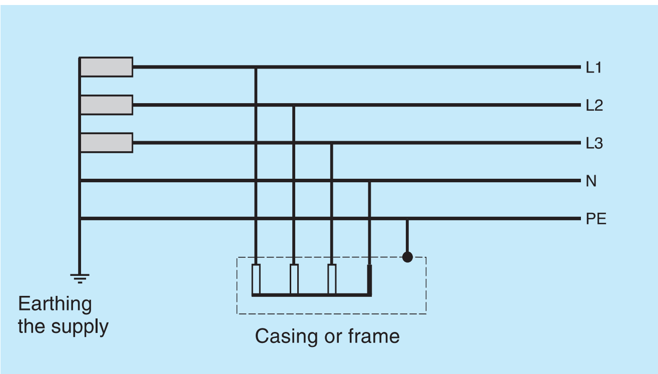
Scheme EE



Scheme IE



Scheme C.EN



Scheme S.EN

Neutral connections mainly concern the following :

Neutral

These are neutral points on HV/MV and MV/LV transformers as well as neutral conductors which, in balanced circuits, do not carry any current.

Casing or frame

These are conducting parts accessible to electrical equipment, and therefore susceptible to becoming live under fault conditions.

Earth

The earth can be considered as a conducting body with a voltage conventionally fixed at zero.

Low voltage connections

There are three low voltage neutral connection methods defined by the drawings and referenced by two letters. These are the EN (C or S), EE or IE methods. The first letter corresponds to the position of the neutral with respect to earth, the second to the situation of the casing. The letters signify the following :

E = Earth	N = Neutral	I = Impedance
C = Combined	S = Separate	

The C.EN (Combined Earth and Neutral) scheme

Corresponds to a neutral linked to the earth and the casing to the neutral. It is important to note that the neutral and protective earth conductors are combined.

The S.EN (Separate Earth and Neutral) scheme

Corresponds to a neutral linked to the earth and the casing to the neutral, but here the neutral and protective earth conductors are separate.

The EE scheme

The neutral is linked directly to the earth and the casing by two separate earth plates.

The IE scheme

The neutral is isolated or linked to the earth via an intermediate impedance. The casing is linked directly to the earth.

These different connection methods allow adaptation to the locality and the application, by respecting breaking time, based upon the duration of resistance of an individual to the effects of electric current as a function of its voltage (normally 50 V for 5 seconds and 100 V for 0.2 seconds).

Consumer low voltage distribution circuits are similar to the EE scheme except when a separating transformer is placed in the circuit, giving freedom of choice.

The EE scheme is simple to install, but is limited to short distance and simple installations. It trips at the first fault and offers complete safety.
The IE scheme has the peculiarity of not tripping until the second fault. It can, therefore, be shown that when continual service is necessary, this then causes particularly severe maintenance problems in order to detect and react to the first fault before the second appears.
However, the assurance of power supply continuity is not yet a deterrent for designers who prefer the S.EN scheme, with extra precautions and specific protection components.
The EN scheme offers low cost installation compared to the previous example. This is an indispensable connection method with high leakage current.

M.8 Driving machines

A machine coupled to a motor essentially presents an inertia J (kg.m²), to which the often sizeable inertia of the motor must also be added. Knowing this total inertia enables the study of transitory conditions (starting and stopping), but does not interfere with steady states.

Rotational motion

If the machine is driven by an intermediate reducer at speed N1, its reduced moment of inertia to the motor rotating at the speed N2 is expressed by the formula :

$$J\ (\text{reduced machine motor}) = J\ (\text{machine}) \left(\frac{n1}{n2}\right)^2$$

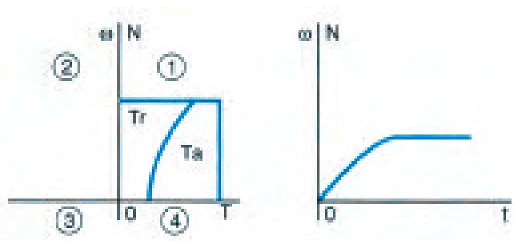
Translatory motion

If the machine, of mass m (kg), moves at the linear velocity V(m/s), for the rotational speed ω (rad/s) of the driving motor, the moment of inertia at the level of the driving axis is expressed by the formula:

$$J\ (\text{machine}) = m\frac{v^2}{\omega^2} = m\frac{v^2.3600}{4\ \pi^2 .\ N^2} \quad \text{with } \omega = \frac{2\pi N}{60}$$

Starting

To start in a given time t (time from stop to an angular speed ω), knowing the moment of inertia J enables calculation of the necessary acceleration torque Ta.



$$Ta\ (\text{N.m}) = J\ (\text{kg.m})^2\ \frac{d\omega\ (\text{rad/s})}{dt\ (\text{s})}$$

$$= J\ (\text{kg.m})^2\ \frac{2\ \pi\ N\ (\text{tr/min})}{60t(\text{s})}$$

The average torque resistance Tr, due to the mechanics, and the acceleration torque Ta determine the average motor torque necessary during the starting period Ts.

Ts = Tr + Ta

Inversely, if the accelerating torque Ta is fixed, the starting time, for a constant Ta, is determined by :

$$t = \frac{J\omega}{Ta}$$

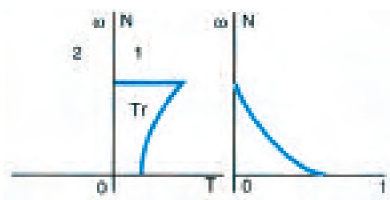
In practice :

– for direct current
Td = kTn where Tn = rated motor torque,
k = overload coefficient of the motor. It is linked to the overload time and the initial temperature. Generally, values are between 1.2 and 1.9 (see motor manufacturer's catalogue). In this area, the current induced and the torque can be approximately proportional.

– for alternating current
Refer to the overtorque, overcurrent and operating characteristics stated in the manufacturer's catalogue.

Stopping

If the machine is left to itself when the power supply is cut, the slow-down torque is equal to the resistive torque.

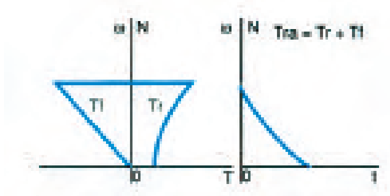


$$Tra = Tr = J\ \frac{d\omega}{dt}$$

The stop will occur at the end of time t, linked to the moment of inertia by the relation :

$$t = \frac{J}{Tr}\ \omega \text{ if Tr is roughly constant.}$$

Rheostatic braking

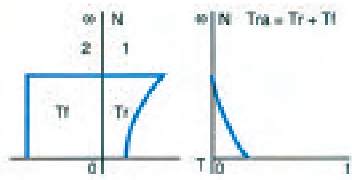


If the stopping time is unacceptable, the slow-down torque has to be increased by use of an electric braking torque Tb such that :

$$Tra = Tr + Tb = J\frac{d\omega}{dt}$$

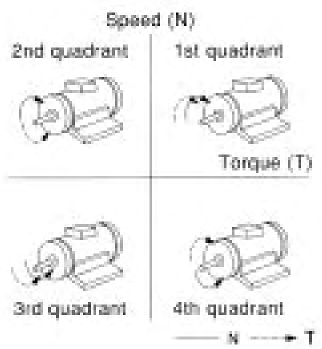
The braking can be the rheostatic type. Always remember that its efficacy is proportional to the speed (Tb = kω)

Regenerative braking



Braking can be of the regenerative type by using reversible variable speed drives.
By limiting the current, the braking torque is constant up to the stop.
The machine not only determines the size of the motor and the equipment which must be used in steady state, but also in transitory states : frequent or rapid starts, repeated load surges.

Direction of rotation



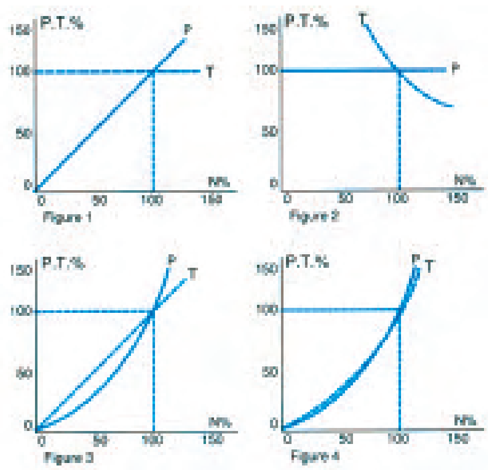
The diagram above shows the 4 operating possibilities (4 quadrants) in the torque speed plan.
A summary is shown in the table below.

Rotation	Machine operation	Torque T	Speed N	Product T x N	Quadrant
1st direction	motor	+	+	+	1
	generator	–	+	–	2
2nd direction	motor	–	–	+	3
	generator	+	–	–	4

By convention, for all our products, a positive reference voltage causes the motor to rotate in a clockwise direction (1st quadrant), if the appropriate polarities are applied to the armature and the field magnet.

Torque and power

To suitably determine the motor/variable speed drive system, it is very important to know the torque/speed characteristic of the different machines being driven.



In practice, all machines can be classed into 4 basic categories :
– constant torque (figure 1),
– constant power (figure 2),
– linear increase of torque with speed T = kN, the power P varying as the square of the speed (figure 3),
– torque increasing as the square of the speed $T = kN^2$, the power varying as the cube of the speed (figure 4).
A limited number of machines can have operating characteristics resulting from the composition of these different categories.

M.9 Conversion tables for standard units

Length

Unit	m	in	ft	yd
1 metre (m)	1	39.37	3.281	1.094
1 inch (in or ")	0.0254	1	0.0833	0.02778
1 foot (ft or ')	0.3048	12	1	0.3333
1 yard (yd)	0.9144	36	3	1

Area

Unit	m^2	sq in	sq ft	sq yd
1 square metre (m^2)	1	1550	10.764	1.196
1 square inch (sq in) (in^2)	6.45×10^{-4}	1	6.944×10^{-3}	7.716×10^{-4}
1 square foot (sq ft) (ft^2)	0.0929	144	1	0.111
1 square yard (sq yd) (yd^2)	0.8361	1296	9	1

Volume

Unit	m^3	dm^3	cu in.	cu ft	cu yd
1 cubic metre (m^3)	1	1000	61024	35.3147	1.3079
1 cubic decimetre (dm^3) (litre)	0.001	1	61.024	0.0353	0.0013
1 cubic inch (cu in.) (in^3)	1.639×10^{-5}	0.0164	1	5.787×10^{-4}	2.143×10^{-5}
1 cubic foot (cu ft) (ft^3)	0.0283	28.32	1728	1	0.0370
1 cubic yard (cu yd) (yd^3)	0.7645	764.5	46656	27	1

Weight

Unit	kg	oz	lb
1 kilogramme (kg)	1	35.27	2.205
1 ounce (oz)	0.028	1	0.0625
1 pound (lb)	0.454	16	1

Pressure

Unit	Pa	MPa	bar	psi
1 pascal (Pa) or newton per square metre (N/m^2)	1	10^{-6}	10^{-5}	1.45×10^{-4}
1 mega Pascal (MPa) or 1 Newton per mm^2 (N/mm^2)	10^{6}	1	10	145.04
1 bar (bar)	10^{5}	0.1	1	14.504
1 pound per square inch 1 lbf/in^2 (psi)	6895	6.895×10^{-3}	0.06895	1

Angular velocity

Unit	rad/s	tr/mn
1 radian per second (rad/s)	1	9.549
1 turn per minute (tr/min)	0.105	1

Linear velocity

Unit	m/s	km/h	m/mn
1 metre per second (m/s)	1	3.6	60
1 kilometre per hour (km/h)	0.2778	1	16.66
1 metre per minute (m/mn)	0.01667	0.06	1

Power

Unit	W	ch	HP	ft-lbf/s
1 watt (W)	1	1.36×10^{-3}	1.341×10^{-3}	0.7376
1 cheval (metric HP) (ch)	736	1	0.9863	542.5
1 horse power (HP)	745.7	1.014	1	550
1 ft-lbf/s	1.356	1.843×10^{-3}	1.818×10^{-3}	1

Force

Unit	N	kgf	lbf	pdl
1 newton (N)	1	0.102	0.225	7.233
1 kilogramme-force (kgf)	9.81	1	2.205	70.93
1 pound weight (lbf)	4.448	0.453	1	32.17
1 poundal (pdl)	0.138	0.0141	0.0311	1

Energy - Work - Heat

Unit	J	cal	kWh	B.t.u.
1 joule (J)	1	0.24	2.78×10^{-7}	9.48×10^{-4}
1 calorie (cal)	4.1855	1	1.163×10^{-6}	3.967×10^{-3}
1 kilowatt-hour (kWh)	3.6×10^{6}	8.60×10^{5}	1	3412
1 British thermal unit (B.t.u)	1055	252	$2.93\ 10^{-4}$	1

Moment of inertia

Unit	$kg.m^2$	$lb.ft^2$	$lb.in^2$	$oz.in^2$
1 kilogramme metre squared	1	23.73	3417	54675
1 pound foot squared ($lb.ft^2$)	0.042	1	144	2304
1 pound inch squared ($lb.in^2$)	2.926×10^{-4}	6.944×10^{-3}	1	16
1 ounce inch squared ($oz.in^2$)	1.829×10^{-5}	4.34×10^{-4}	0.0625	1

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