5 chapter

Motor starter units

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5.1 Forward

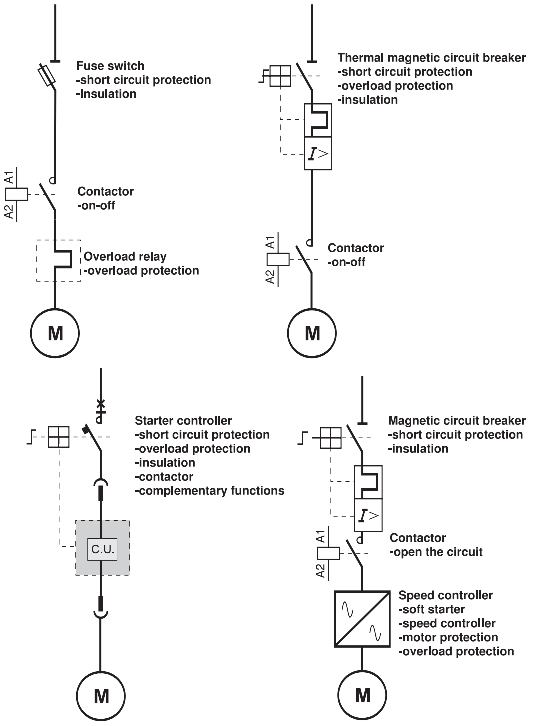


Fig. 1 *The different functions and their combinations to build a motor starter*

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

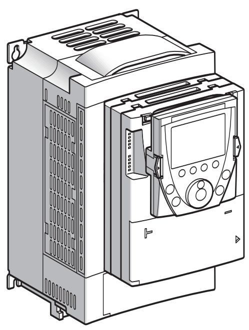
Direct starting on the asynchronous motor power supply is the most common solution, the most cost-effective and usually the most suitable for a large variety of machines. However, it does include constraints which can be impeding for certain applications, or even incompatible with what the machine is 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

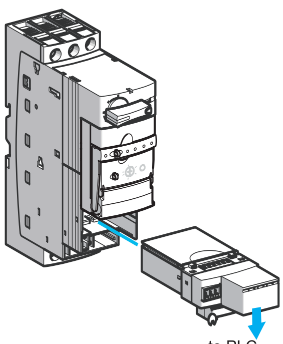
In industrial production processes and systems, remote control is used to check and interrogate devices and control the machines on a production system.

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

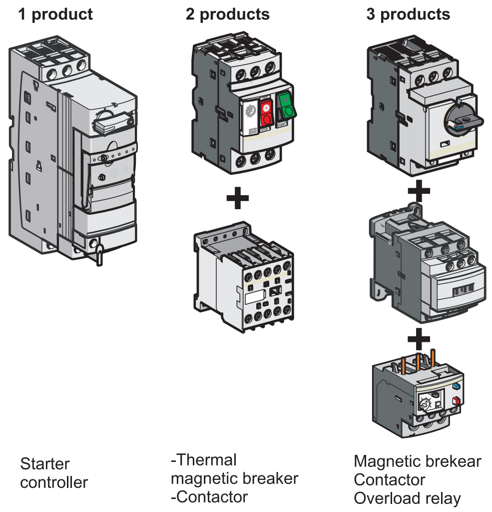


Fig. 5 *The three device combinations for making a motor starter unit*

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.

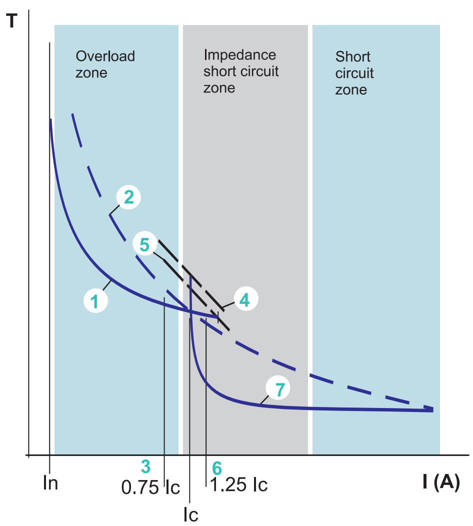
This work (compatibility, choice and installation) may not be straightforward for users as they must establish all the features of the devices and know how to compare them. This is why manufacturers first study and then offer the device combinations in their catalogues. Likewise, they try to find the most efficient combinations between protections. This is the notion of coordination.

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.



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*

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.

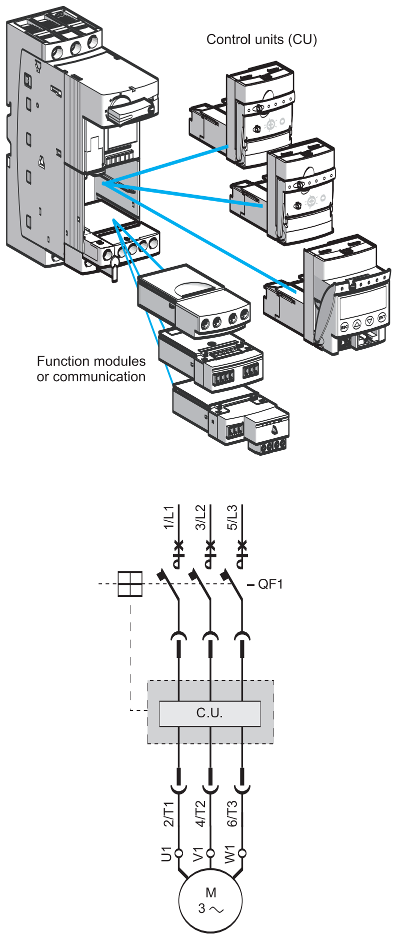


Fig. 7 *Example of a CPS modularity (Tesys U starter controller by Telemecanique)*

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.

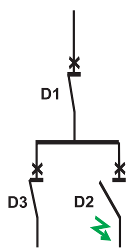
■ Selectivity

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.

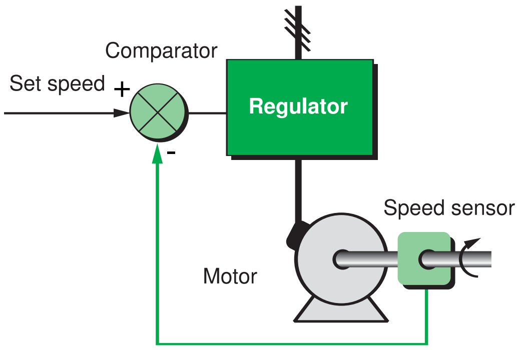
Regulation makes speed practically independent of perturbation (load variation, temperature etc.).

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:

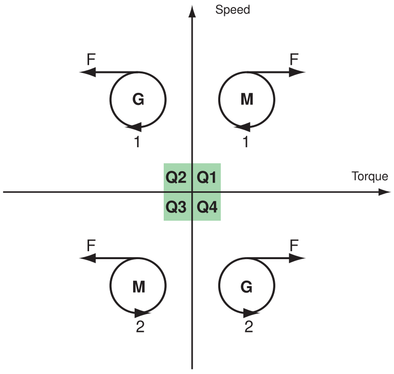
- short circuits between phase-to-phase and phase-to-ground;
- voltage surges and drops;
- phase unbalances;
- single-phase operation.

■ 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*

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.

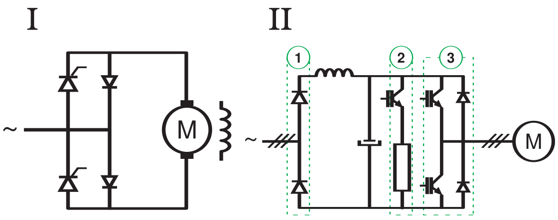
If it is not reversible, the machine only runs in quadrants 1 and 3.

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. 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*

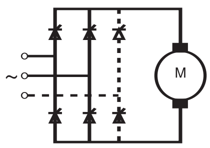


Fig. 13 DC bridge for a DC motor

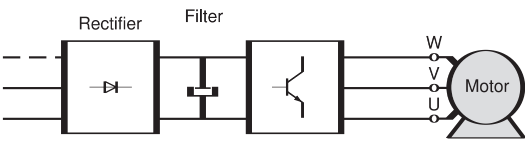


Fig. 14 Working diagram of a AC drive

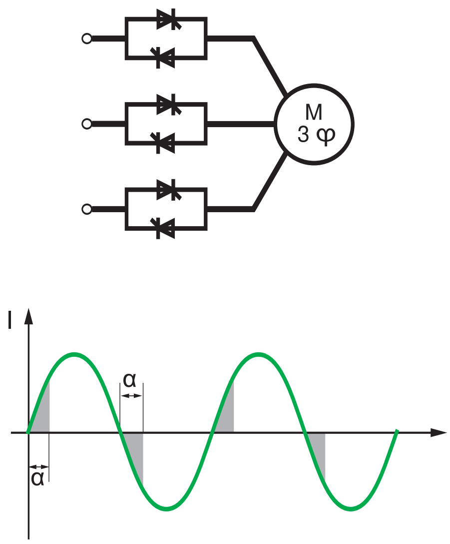


Fig. 15 Asynchronous motor starter and supply current waveform

- **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)*.

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5.6 Structure and components of starters and electronic speed controllers

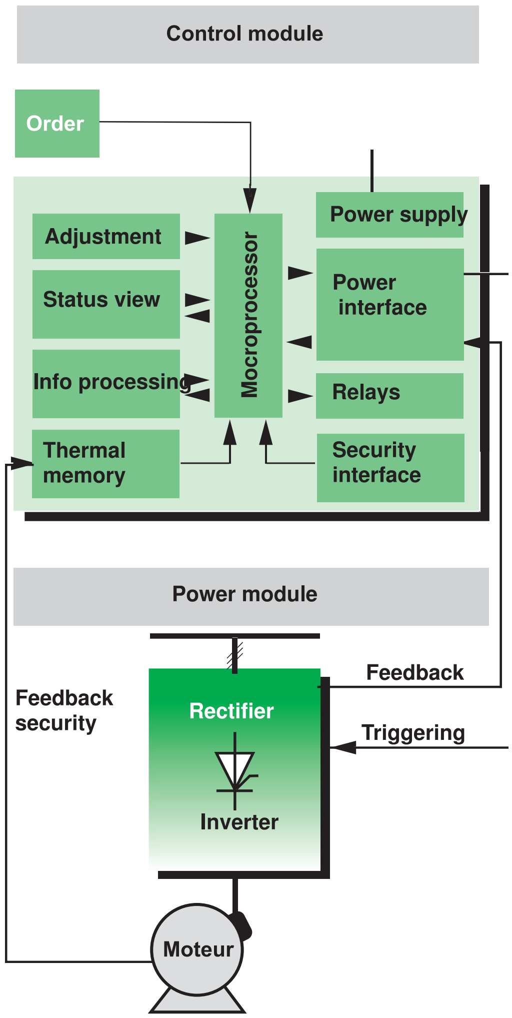


Fig. 16 Overall structure of an electronic speed controller

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.

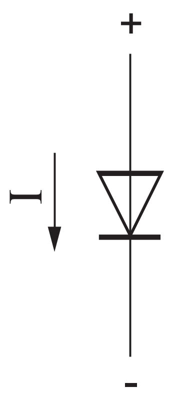
- **Power Components**

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.

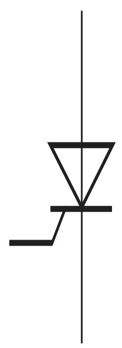
The power components are the keystones of speed controllers and the progress made in recent years has led to the development of electronic speed controllers.

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.

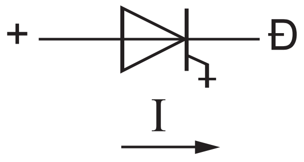
The thyristor has the main following characteristics:

- **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).



↑ 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.

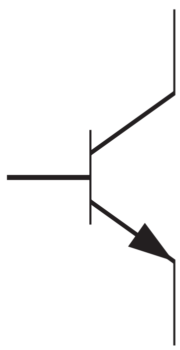
The GTO is used on very powerful converters as it is able to handle high voltages and currents (up to 5000V and 5000A). However, progress in the IGBT has caused their market share to drop.

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.



↑ Fig. 17d

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.

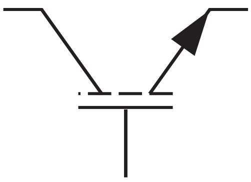
Bipolar transistors cover voltages up to 1200V and support currents up to 800A.

This component is now supplanted by IGBT converters.

In the operations which interest us, the bipolar transistor has the main following characteristics:

- **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.

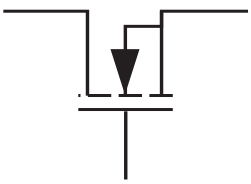
The IGBT transistor has the main following characteristics:

- **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.

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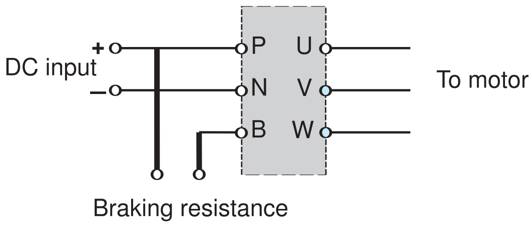


↑ *Fig. 18* *Intelligent Power Module (IPM)*

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

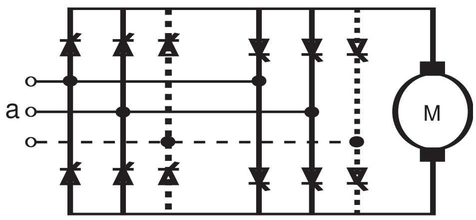
To invert the direction of rotation, the armature voltage must be inverted. This can be done with contactors (a solution now dropped) or statically by inverting the output polarity of the speed controllers or the polarity of the excitation current.

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.

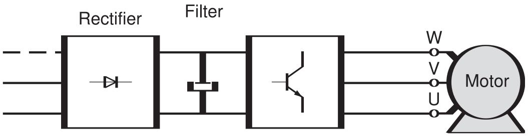
The power, for a given armature current, is therefore constant in all speed ranges, but the maximum speed is limited by two parameters:
- the mechanical limit linked to the armature and in particular the maximum centrifugal force a collector can support,
- the switching possibilities of the machine are 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).

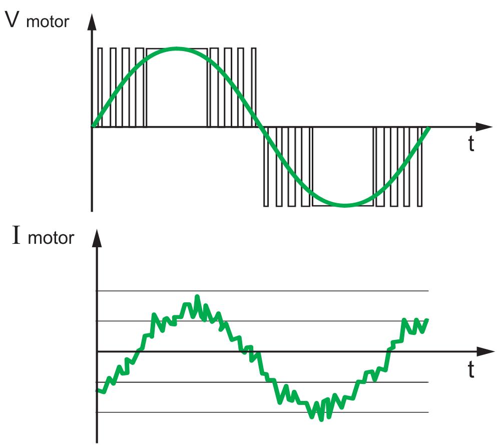
The inverter

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)*.

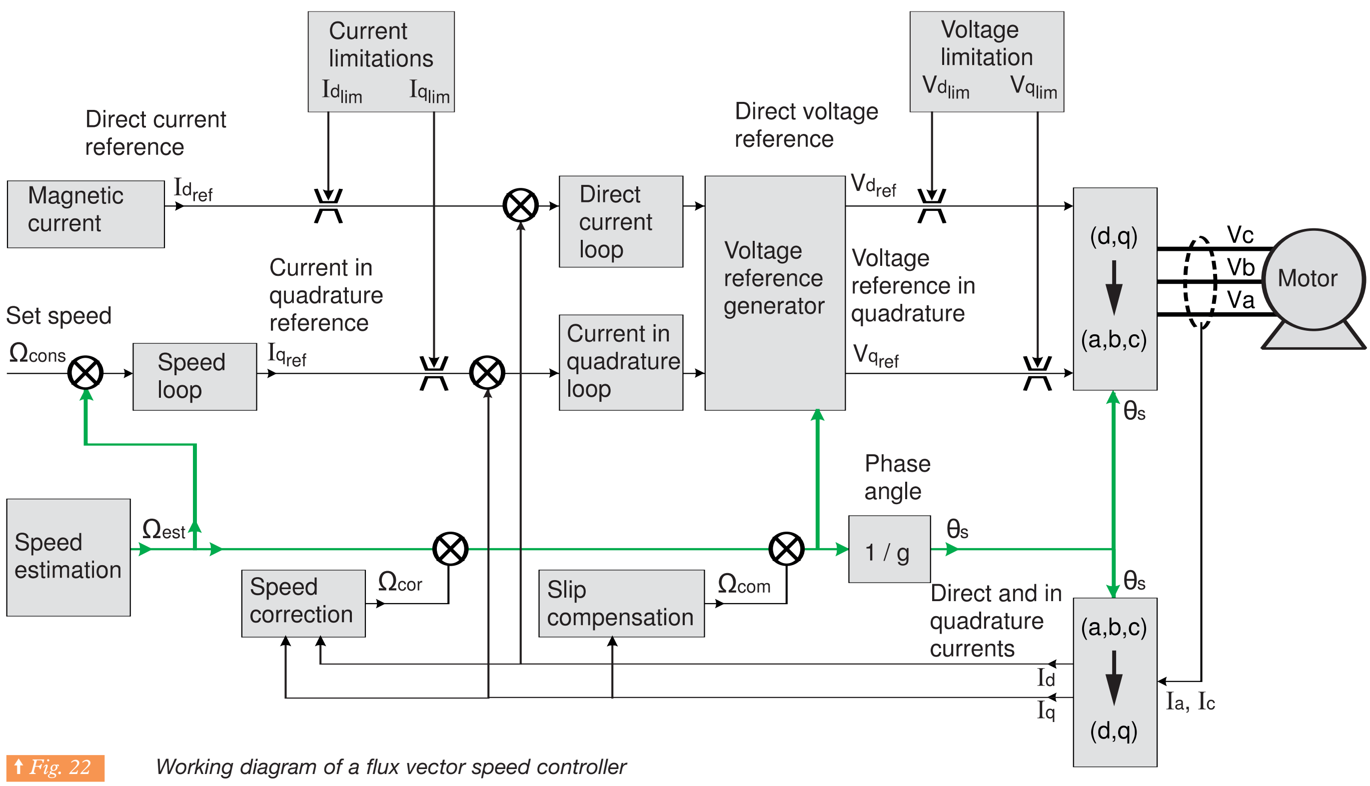


Fig. 22 *Working diagram of a flux vector speed controller*

Schneider Electric

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.

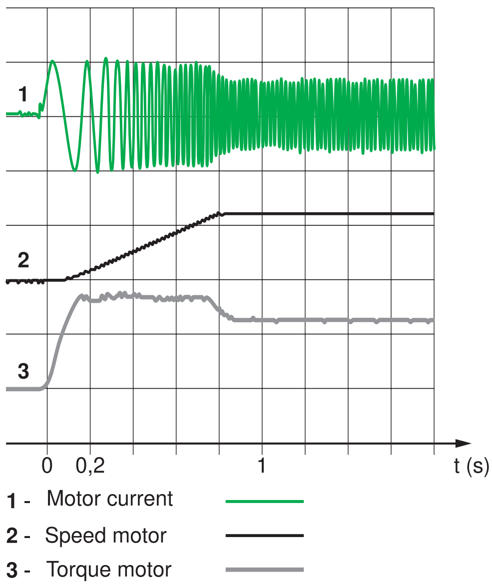
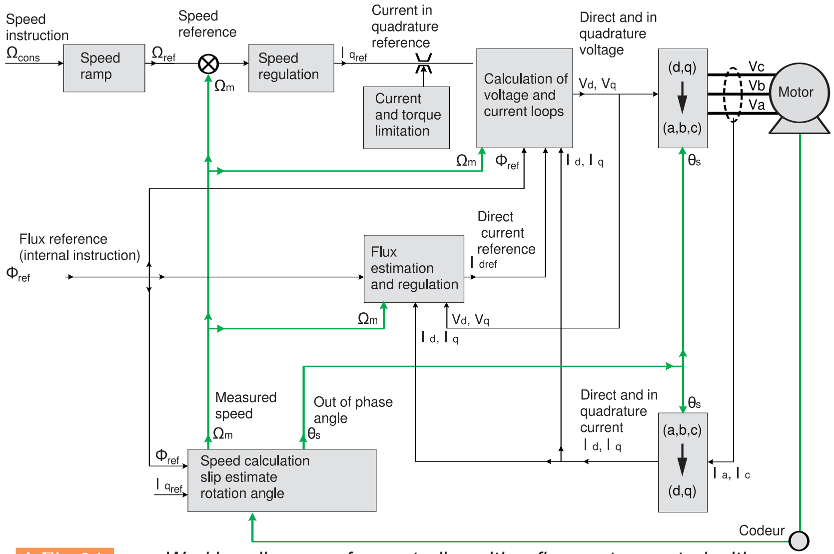


Fig. 23 *Characteristics of a motor fed by a sensorless flux vector controller (e.g. ATV58F – Telemecanique)*

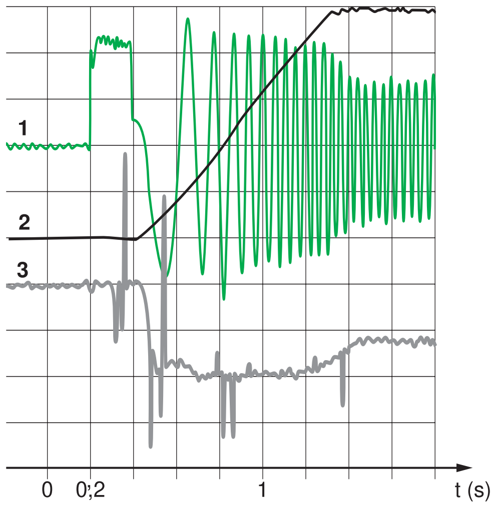
◻ Controller with closed loop flux vector control and sensor

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*



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)*

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.

	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.

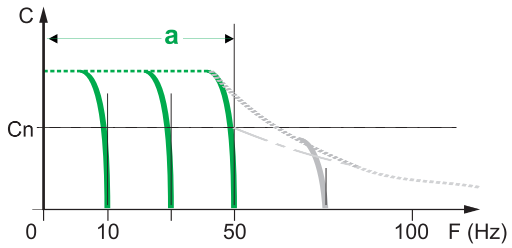


Fig. 27a Torque of an asynchronous motor powered by a frequency converter (a) – constant torque operation zone

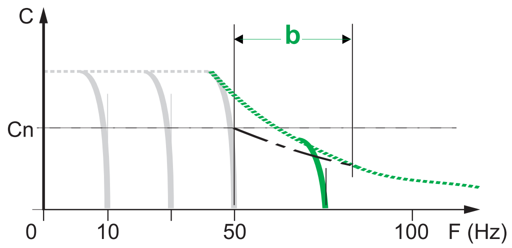


Fig. 27b Torque of an asynchronous motor powered by a frequency converter (b) – constant power operation zone

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

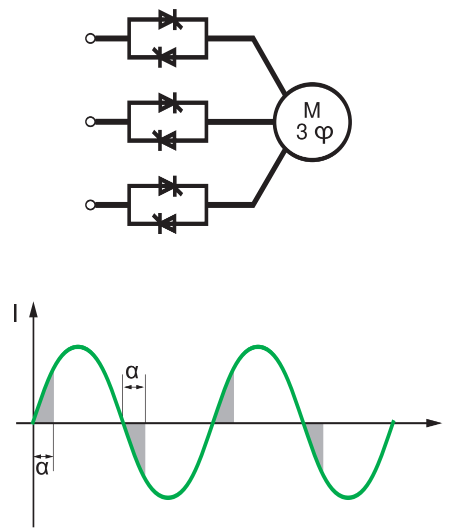
When a machine is powered at the rated voltage and frequency, the speed can still be increased by powering it at a higher frequency.
But as the output voltage of the converter cannot exceed that of the mains, the available torque decreases inversely in proportion to the speed *(⇨ Fig.27 part b)*.

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

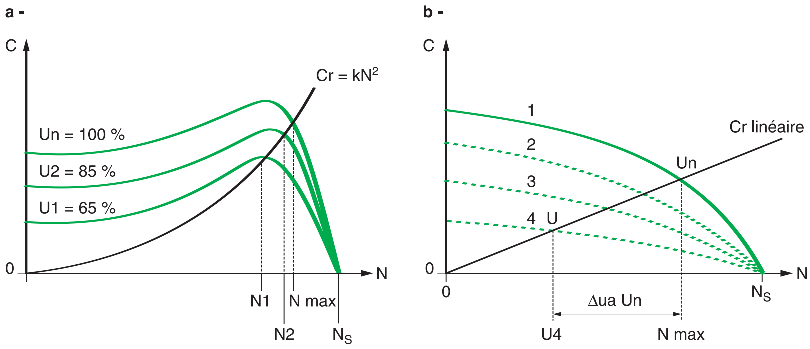


↑ *Fig. 28* *Asynchronous soft starter and current shape*

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.

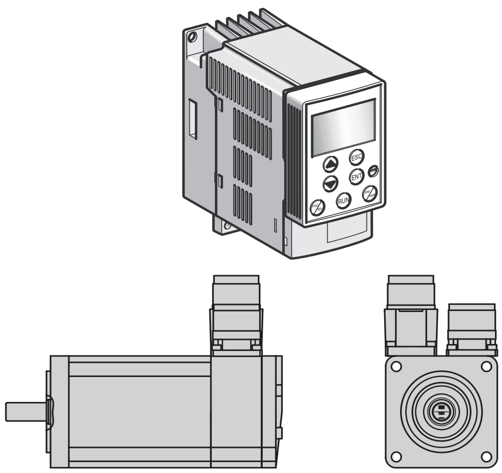
Counter-current braking results and all the energy is dissipated in the machine rotor. The operation is therefore naturally intermittent.

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

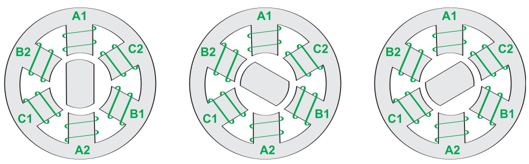
Synchronous motor-speed controllers *(⇨ Fig. 30)* are a combination of a frequency inverter and a permanent magnet synchronous motor equipped with a sensor. These motors are often called “brushless motors”.

Motor-speed controller units are designed for specific markets such as robots or machine tools where smaller motors, acceleration and bandwidth are prerequisites.

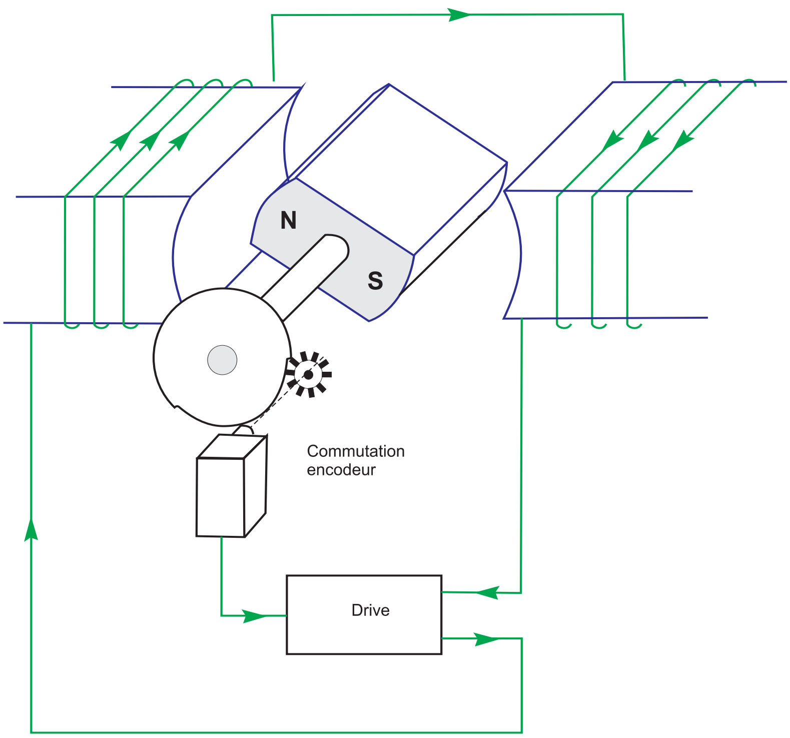
■ Motor

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.

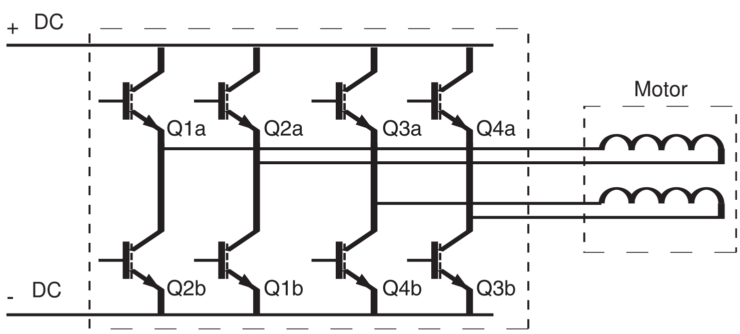
Motor

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*

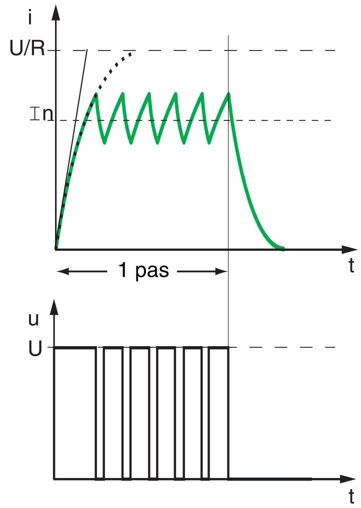


Fig. 34 *Appearance of current with a PWM command*

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°.

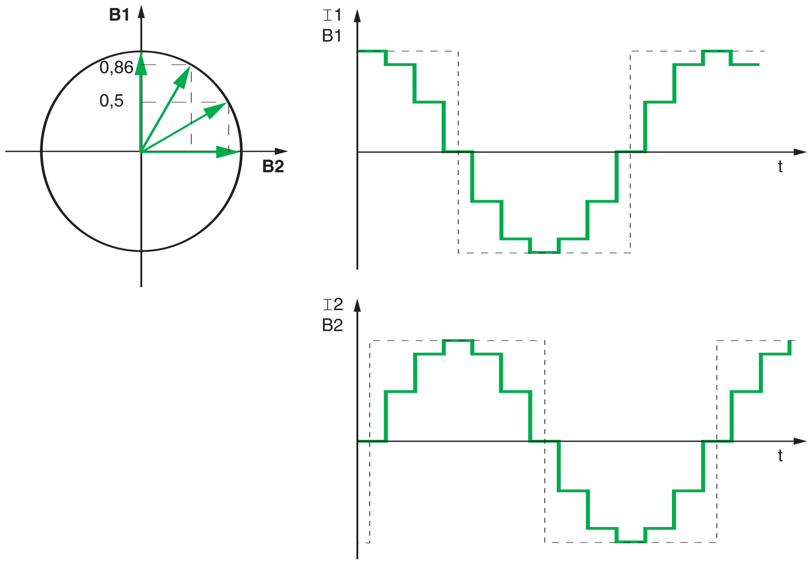


Fig. 35 *Diagram, current curves and graduation principle for micro-step control of a stepper motor-speed controller*

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: $S = V \times I_{eff}$

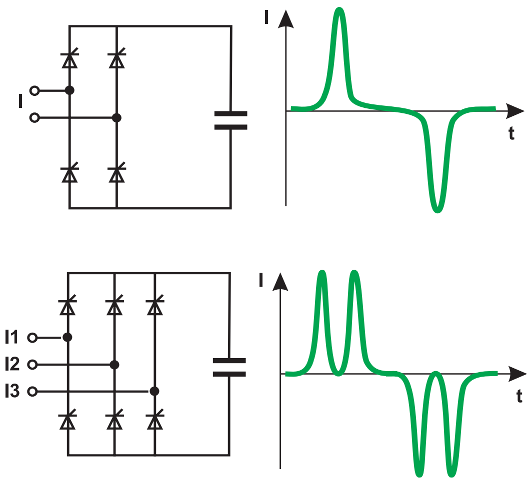


Fig. 36 Current in a DC bridge feeding a capacitor

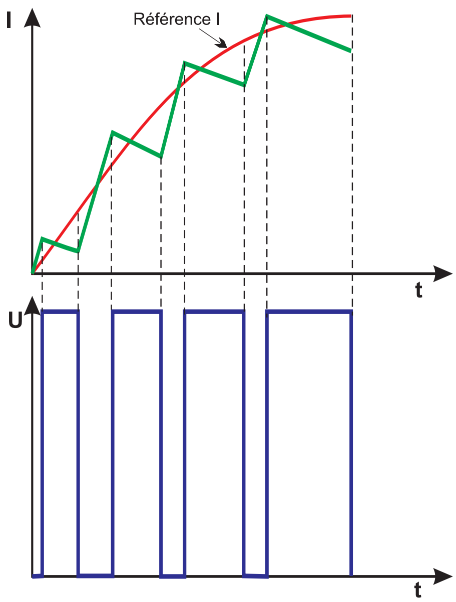


Fig. 37 PWM operation

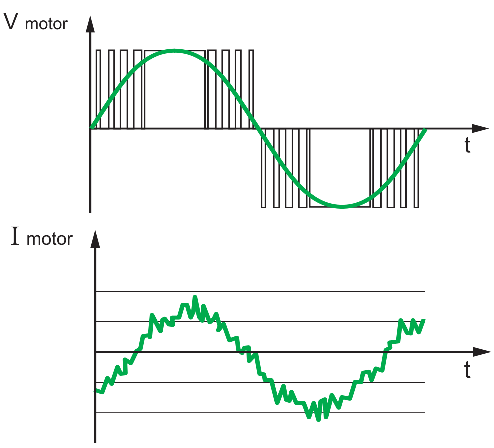


Fig. 38 Shape of the motor current

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

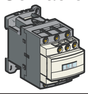
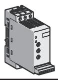
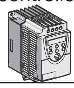
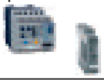
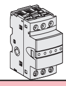
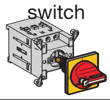
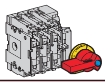
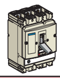
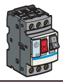
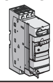
The choice of a starter or speed controller being contingent on the type of load driven, the performance demanded and the protections required, the definition and choice must be based on an analysis of functional requirements for the equipment then the performance required for the motor itself.

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											