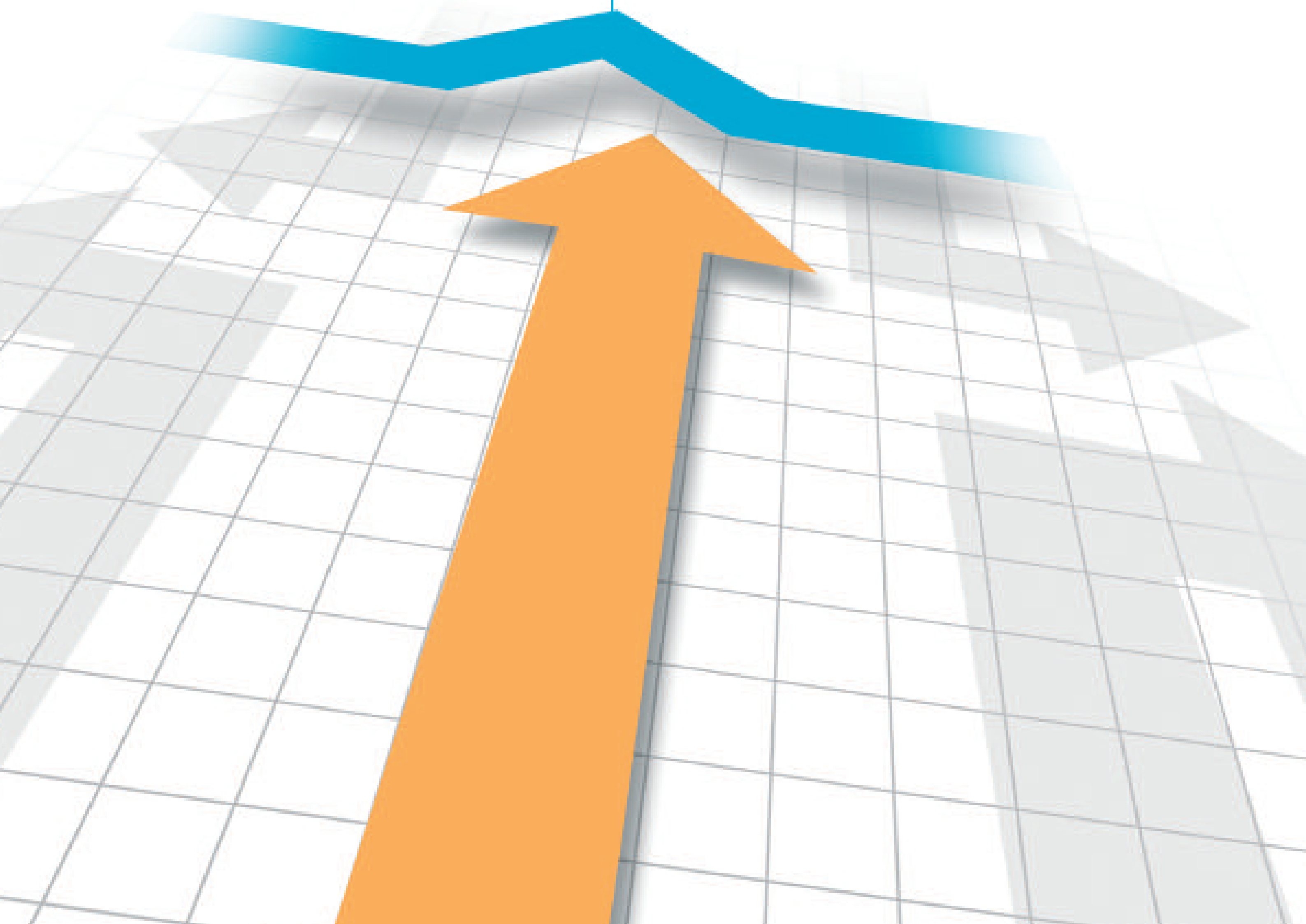
4 chapter

AC motors starting and protection systems

Presentation :

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



4. AC motors starting and protection systems

Summary

4. AC motors starting and protection systems

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

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

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

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

4.1 Asynchronous motor starting systems

Introduction

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

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

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

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

Main starting modes

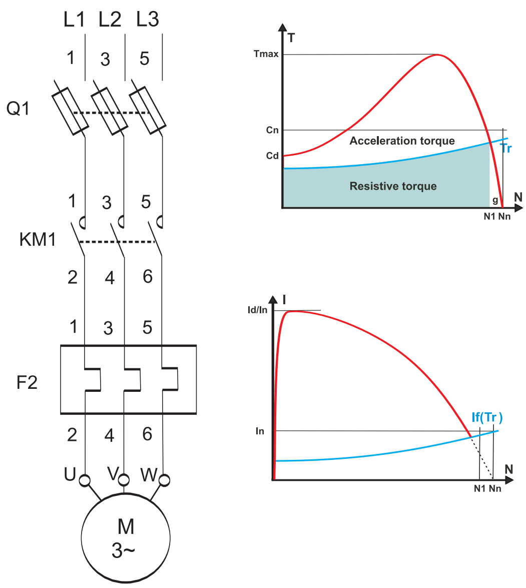
Direct on-line starting

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

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

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

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



↑ *Fig. 1* Direct on-line starting

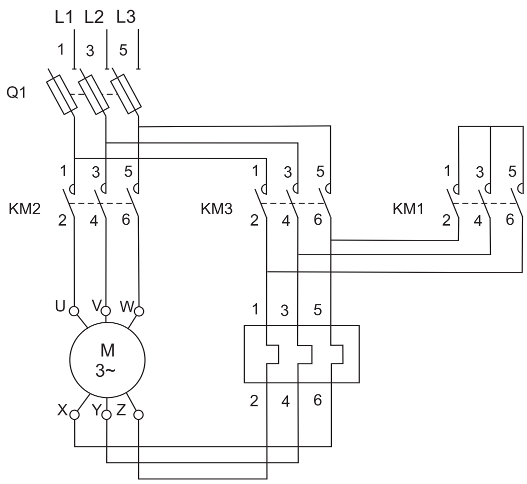


Fig. 2 Star-delta starting

Star-delta starting

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

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

The starting current peak (SC) is divided by 3:
- SC = 1.5 to 2.6 RC (RC rated Current).

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

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

ST = 0.2 to 0.5 RT (RT Rated Torque)

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

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

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

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

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

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

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

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

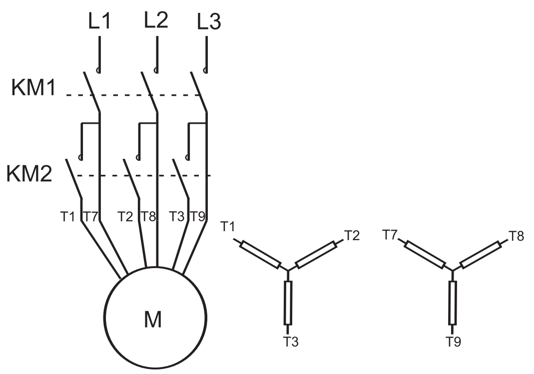


Fig. 3 *Part winding starting*

Part winding motor starting

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

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

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

Resistance stator starting

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

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

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

- SC = 4.5 RC
- ST = 0.75 RT

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

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

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

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

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

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

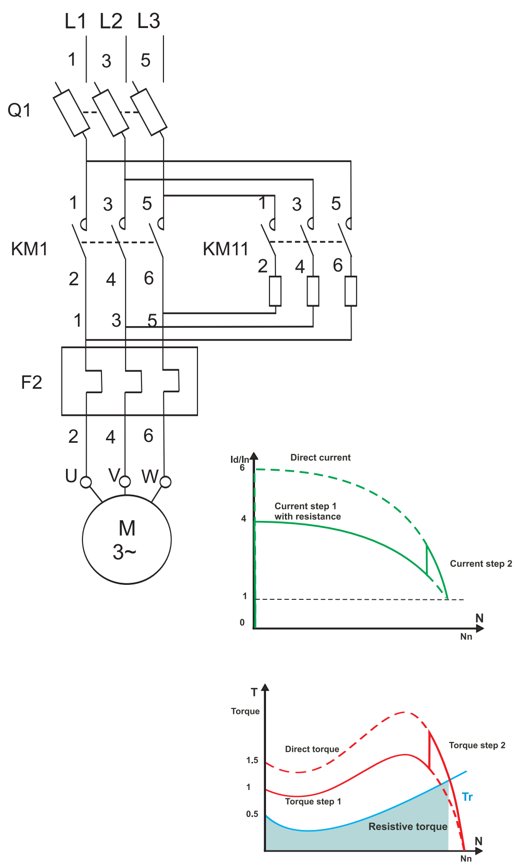


Fig. 4 *Resistance stator starting*

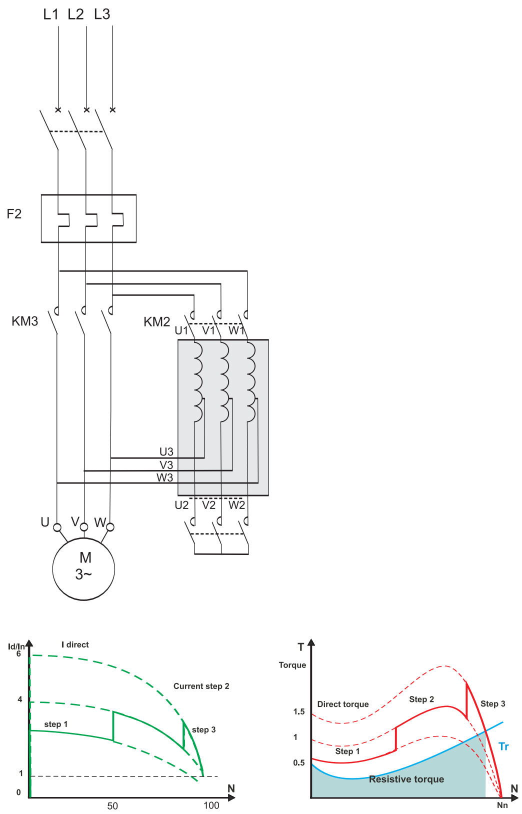


Fig. 5 Autotransformer starting

Autotransformer starting

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

The starting process is in three steps:

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

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

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

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

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

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

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

Slip ring motor starting

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

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

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

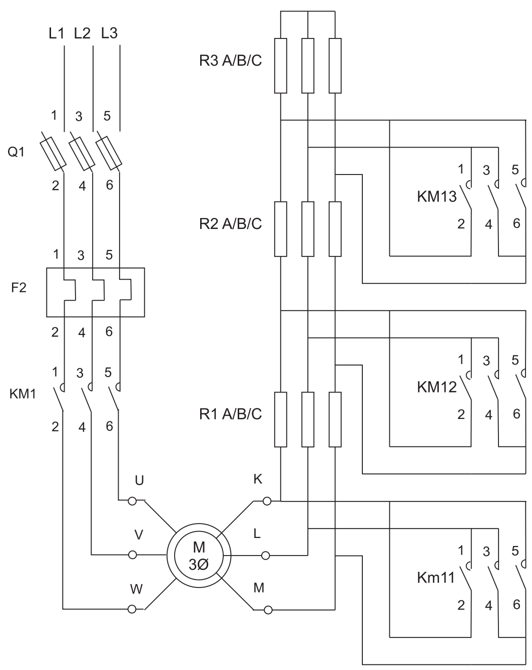


Fig. 6 Slip ring motor starting

4. AC motors starting and protection systems

4.1 Asynchronous motor starting systems

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

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

◻ Soft starter starting/slackening

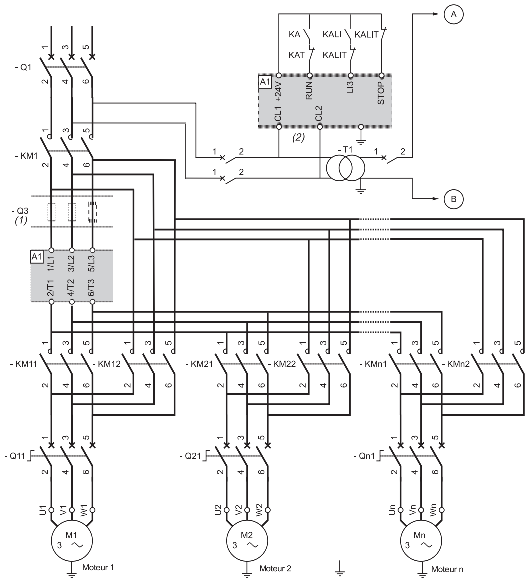
This is an effective starting system *(⇨ Fig. 7)* for starting and stopping a motor smoothly *(see the section on electronic speed controllers for more details)*.

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

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

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

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



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

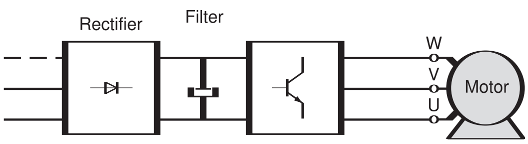
◻ Frequency converter starting

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

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

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

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



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

4. AC motors starting and protection systems

4.1 Asynchronous motor starting systems

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

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

This starting system requires the motor to be specifically sized.

↑ Fig. 9 *Summary table*

Single-phase motor starting

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

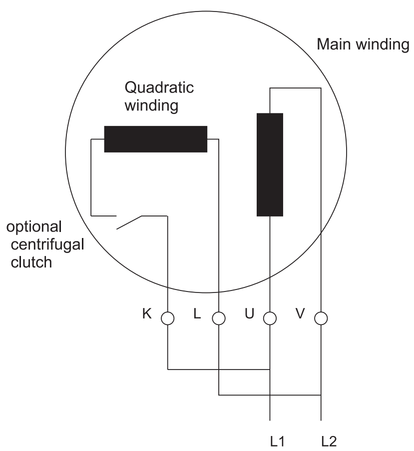
Auxiliary phase starting

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

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

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

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



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

Auxiliary phase and resistance starting

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

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

Auxiliary phase and inductance starting

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

Auxiliary phase and capacitor starting

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

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

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

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

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

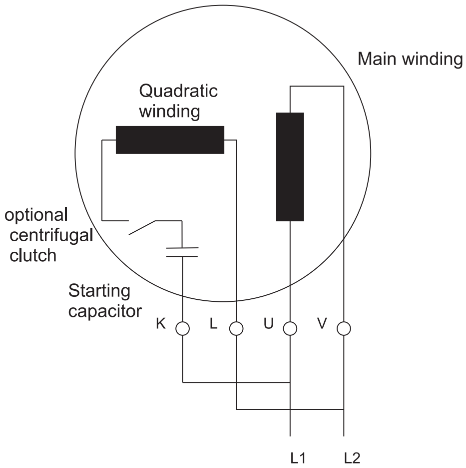
Only low-powered 4-pole motors of no more than 4kW are suitable for this system.

Manufacturers provide tables for selecting capacitors with the right values.

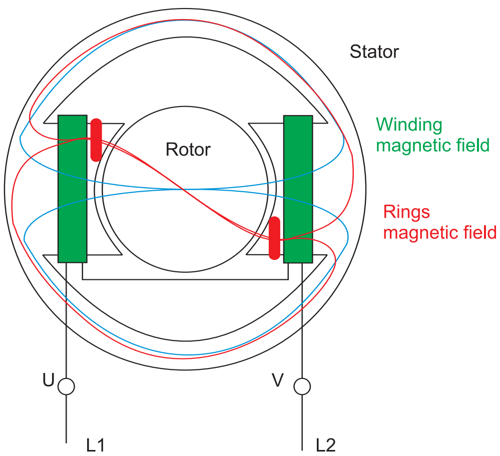
Shaded pole winding starting

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

Efficiency is low but adequate in this power range.



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



↑ *Fig. 12* *Shaded pole winding motor*

4.2 Electrical braking of 3-phase asynchronous motors

Introduction

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

Countercurrent braking: principle

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

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

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

Squirrel cage motor

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

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

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

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

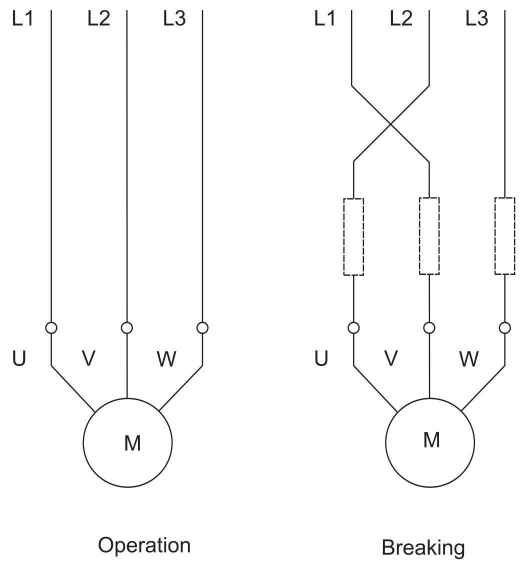


Fig. 13 *Principle of countercurrent braking*

Slip ring motor

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

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

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

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

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

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

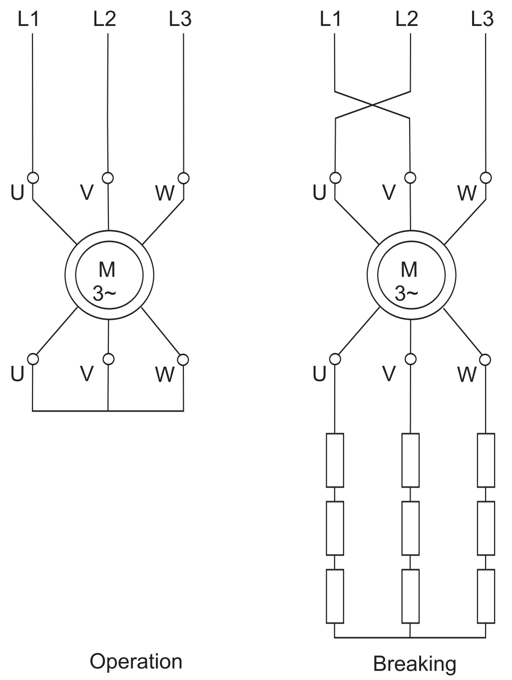
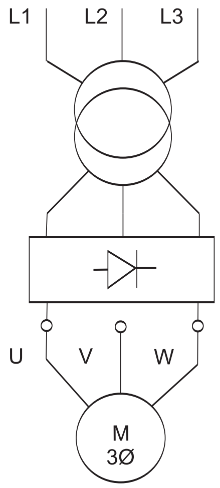


Fig. 14 *Principle of countercurrent braking in an asynchronous slip ring machine*



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

Braking by injection of DC current

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

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

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

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

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

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

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

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

Electronic braking

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

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

4.2 Electrical braking of 3-phase asynchronous motors

Braking by oversynchronous operation

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

- the speed is stable and practically independent of the driving torque,
- the energy is recovered and restored to the mains.

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

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

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

Other braking systems

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

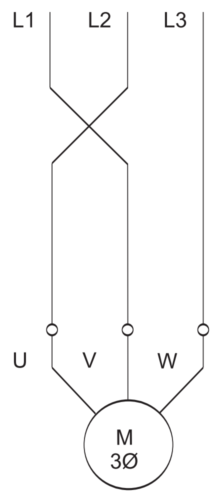
Another system is braking by eddy current slackening. This works on a principle similar to that used in industrial vehicles in addition to mechanical braking (electric speed reducers). The mechanical energy is dissipated in the speed reducer. Braking is controlled simply by an excitation winding. A drawback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

Reversing

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

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

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



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

Types of duty

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

4. AC motors starting and protection systems

4.2 Electrical braking of 3-phase asynchronous motors

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

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

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

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

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

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

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

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

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

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

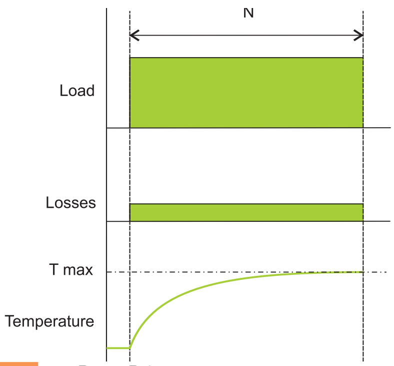


Fig. 17 Duty D1

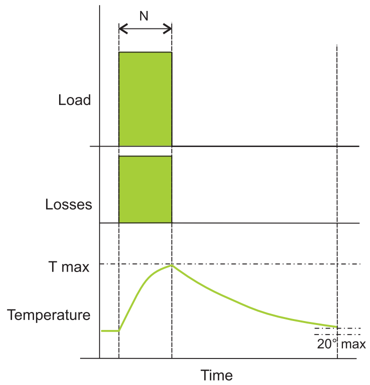


Fig. 18 Duty D2

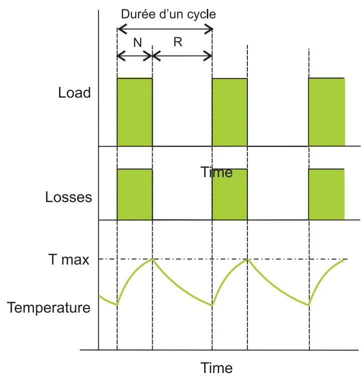


Fig. 19 Duty D3

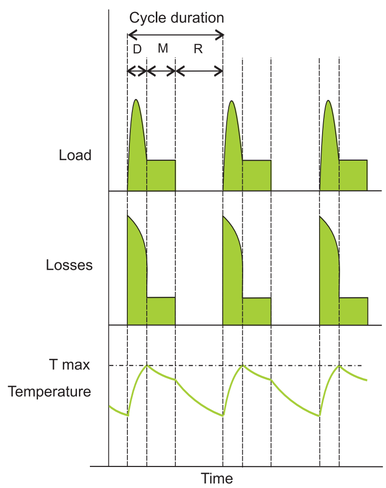


Fig. 20 Duty D4

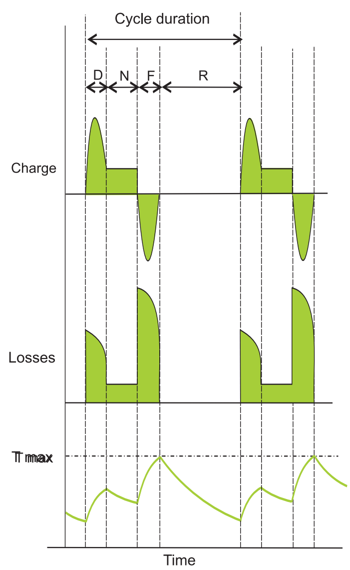
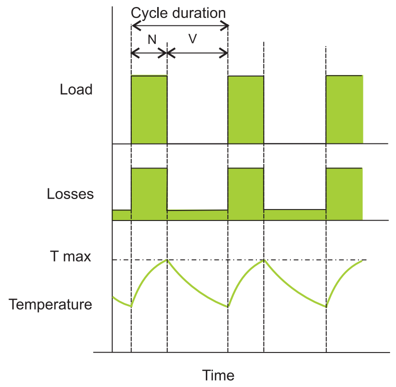


Fig. 21 Duty D5

4.2 Electrical braking of 3-phase asynchronous motors



↑ Fig. 22 *Duty D6*

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

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

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

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

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

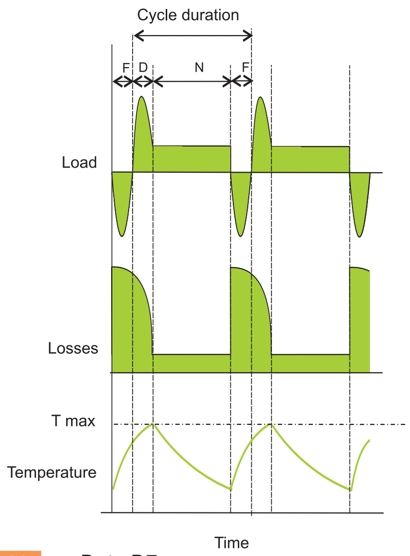
Series of identical duty cycles, each with a period of constant-load operation at a preset rotation speed, followed by one or more periods of constant-load operation at other speeds (e.g. by changing the number of poles). There is no pause.

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

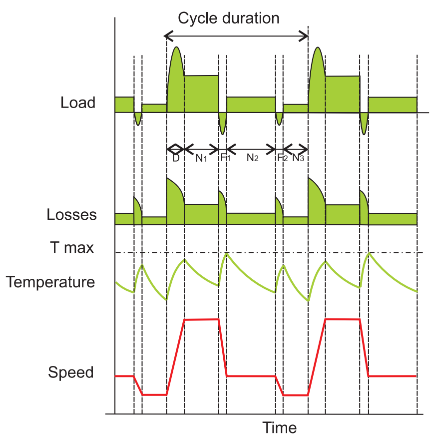
Duty where load and speed usually vary non-periodically within an allowed operating range. This duty often includes overloads which can be much higher than full load.

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

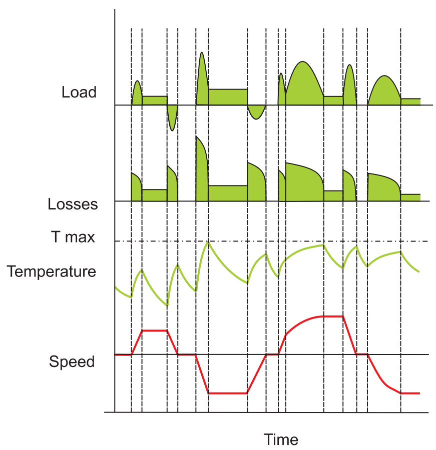
Duty with at most four separate load values (or equivalent load values), each one applied long enough for the machine to reach thermal equilibrium. The minimum load in a load cycle can be zero (no-load operation or pause).



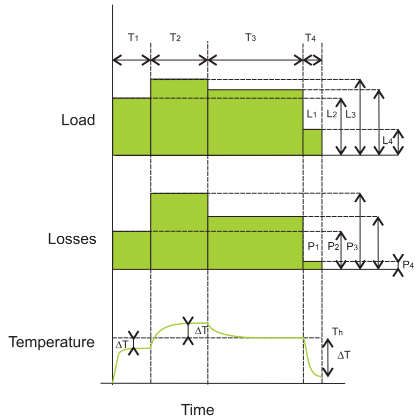
↑ Fig. 23 *Duty D7*



↑ Fig. 24 *Service D8*



↑ Fig. 25 *Duty D9*



↑ Fig. 26 *Duty D10*

4.3 Multifunction motor starter units

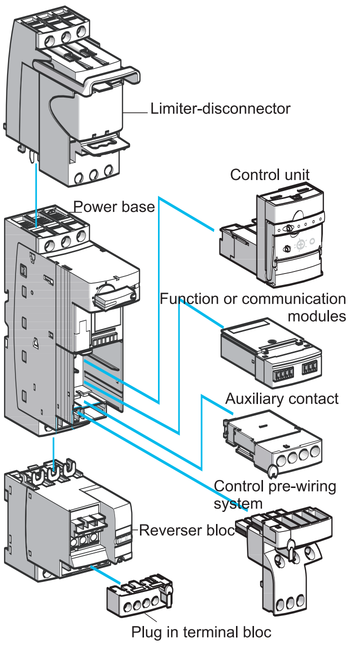


Fig. 27 Tesys U

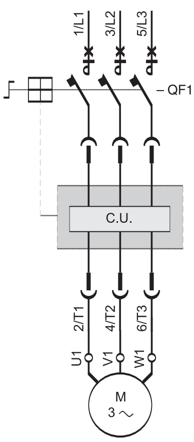


Fig. 28 Working diagram of Tesys U

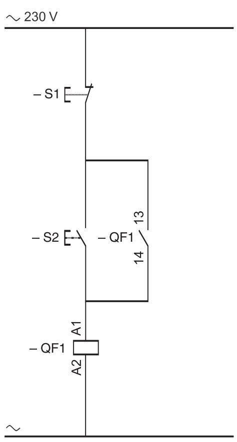


Fig. 29 3-wire control

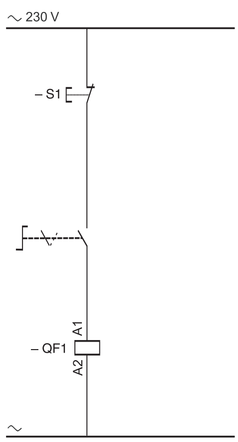


Fig. 30 2-wire control

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

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

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

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

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

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

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

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

Forward operation

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

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

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

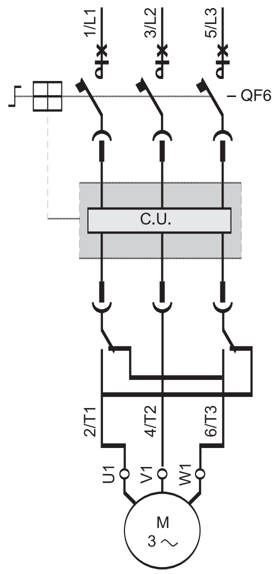


Fig. 31 Tesys U with reversing module (working principle)

Forward and reverse operation

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

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

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

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

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

4

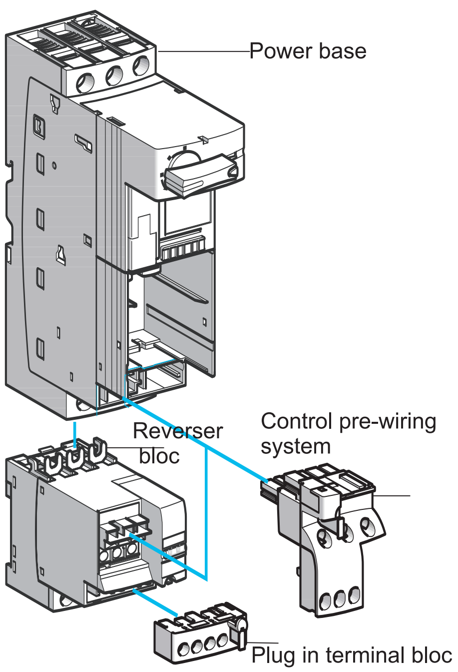


Fig. 32 Tesys U with reversing module

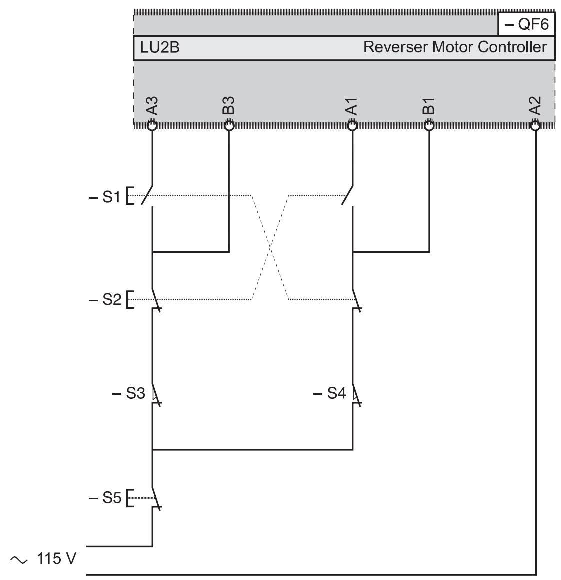


Fig. 33 Example of Tesys U used with reversing function

4.4 Motors protection

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

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

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

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

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

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

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

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

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

4.5 Motor losses and heating

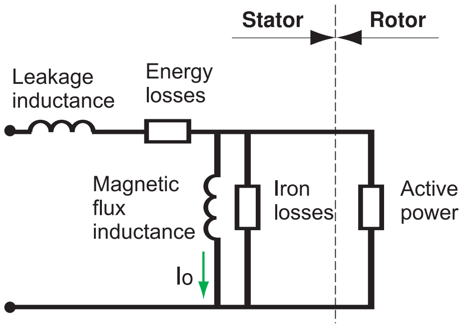


Fig. 34 *Equivalent diagram of an asynchronous motor*

Equivalent diagram of a motor

An asynchronous squirrel cage motor can be represented by the diagram *(⇨ Fig.34)*.
Part of the electrical power supplied to the stator is transmitted to the shaft as drive power or active power.

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

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

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

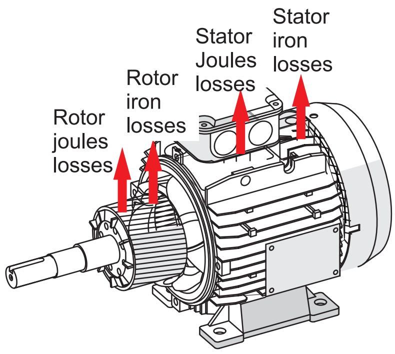


Fig. 35 *Losses in a AC motor*

Insulation categories

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

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

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

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

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

Fig. 36 *Insulation classes*

4.6 Causes of faults and their effects

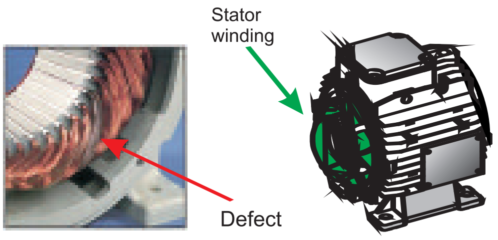
There are two separate types of fault with electric motors: faults in the motor itself and faults with external causes.

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

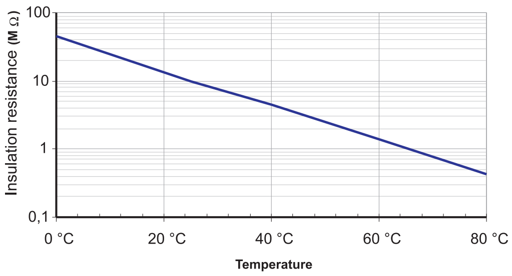
- **Faults with external causes**

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

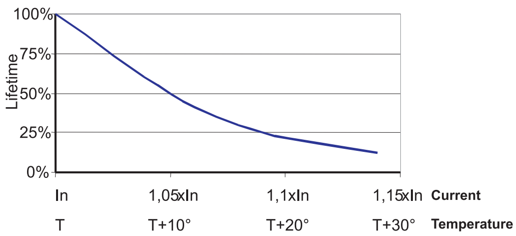
4.6 Causes of faults and their effects



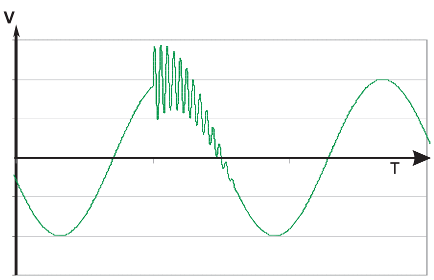
↑ Fig. 37 *Windings are the motor parts most vulnerable to electrical faults and operating incidents*



↑ Fig. 38 *Insulation resistance temperature*



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



↑ Fig. 40 *Example of a voltage surge*

□ Dysfunction can be caused by

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

Faults in the motor

Stator or rotor winding failure

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

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

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

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

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

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

Faults with external causes

Related to the motor power supply

□ Voltage surges

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

Temporary or permanent excess voltage (⇨ Fig. 40) can have different origins:

- atmospheric (lightning),
- electrostatic discharge,
- operation of receivers connected to the same power supply,
- etc.

4.6 Causes of faults and their effects

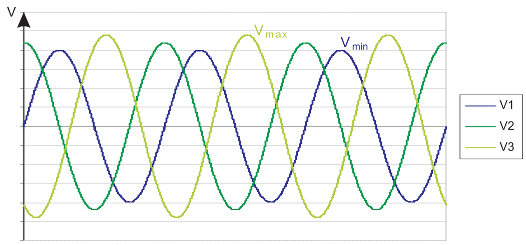
The main characteristics are described in the table (⇨ Fig. 41).

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

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

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

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



↑ Fig. 42 *3 phase unbalanced voltages*

Unbalanced phases

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

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

Unbalance can be approximated by the following equation:

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

where:
Vmax is the highest voltage,

Vmin is the lowest voltage,

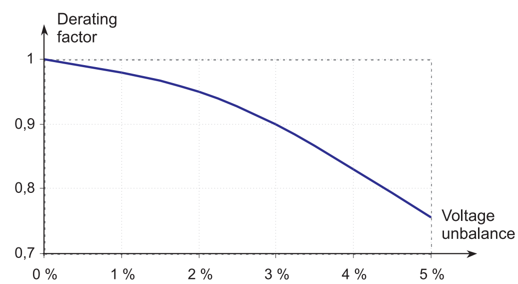
$$Vmoy = \frac{(V1 + V2 + V3)}{3}$$

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

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

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

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



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

4.6 Causes of faults and their effects

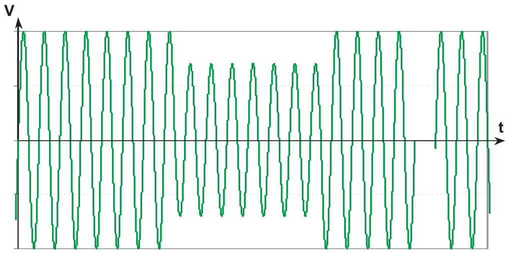


Fig. 45 Example of a voltage drop and a short voltage break

Voltage drops and breaks

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

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

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

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

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

- **Effects on asynchronous motors**

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

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

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

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

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

- **Effects on synchronous motors**

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

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

- **Effects on speed-controlled motors**

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

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

Harmonics

Harmonics can be harmful to AC motors.

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

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

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

where :

Y_0 : continuous component

h : harmonic rank

ω : pulse (2.π.f)

Y_h : amplitude of harmonic rank h

Y_1 : fundament component

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

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

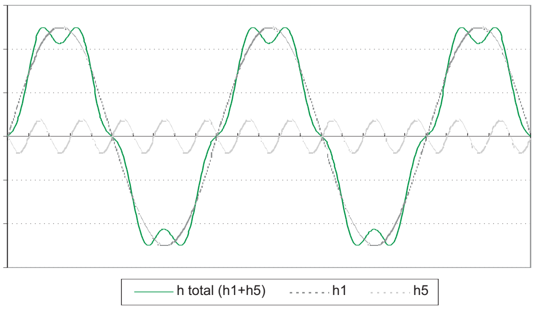


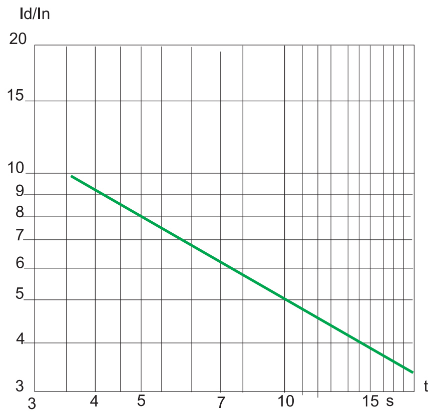
Fig. 46 Voltage with rank 5 harmonic

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

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

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

4.6 Causes of faults and their effects



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

Faults with external causes related to motor operation

Motor starting: too long and/or too frequent

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

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

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

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

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

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

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

Rotor locks

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

Overload (slow motor overload)

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

Summary

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

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

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

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

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

4.7 Protection functions

Protection against short circuits

Overview

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

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

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

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

• A thermal phenomenon

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

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

• An electrodynamic phenomenon

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

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

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

Two protection devices are commonly used for this:

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

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

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

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

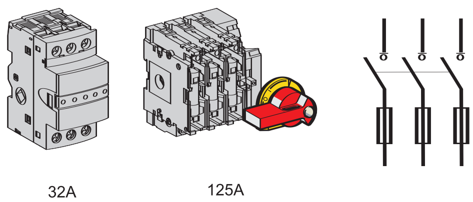


Fig. 50 *Fuse holder switch*

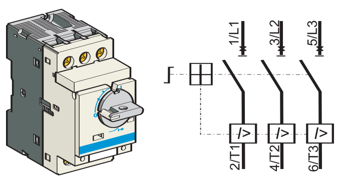


Fig. 51 *GV2-L magnetic circuit breaker (Telemecanique) and its graphic symbol*

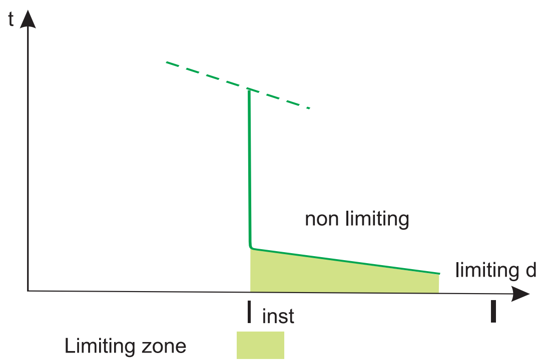


Fig. 52 *Curves of magnetic circuit breaker tripping*

Definitions and characteristics

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

Fuses

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

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

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

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

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

Magnetic circuit breakers

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

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

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

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

Protection against overload

Overview

Overload is the commonest fault in motors. It is revealed by an increase in the current absorbed by the motor and by thermal effects. The insulation category sets normal motor heating at an ambient temperature of 40°C. Any overshoot of this operating limit leads to a reduction in lifetime by premature ageing of the insulating material.

It should however be noted that overloads leading to overheating will not have any immediately detrimental effects if they are short and infrequent. They do not necessarily involve stopping the motor but it is important to restore normal conditions very quickly.

The importance of proper protection against overload is easy to understand:

- It preserves the lifetime of motors by preventing them from working in overheating conditions.
- It ensures operating continuity by:
- preventing motors from stopping abruptly,
- after tripping, enabling restart in the best conditions of safety for people and equipment.

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

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

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

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

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

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

Depending on the level of protection required, overload protection can be provided by relays:

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

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

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

□ Overload relays (thermal or electronic)

- Overview

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

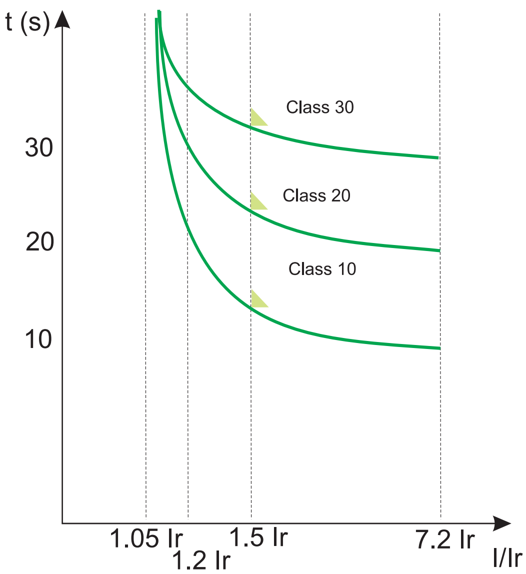
Depending on its use, motor starting can range from a few seconds (no-load starting, low resistant torque, etc.) to a few dozen seconds (high resistant torque, high inertia of the driven load, etc.).

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

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

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

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



↑ *Fig. 55* *Overload relay tripping curves*

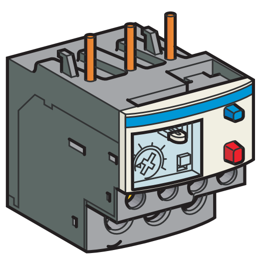
The relay size should be chosen on the basis of the motor's rated current and the estimated starting time.

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

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

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

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



↑ *Fig. 56* *Bimetal thermal overload relays*

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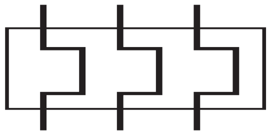


↑ Fig. 57 *Thermal relay diagram*

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

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

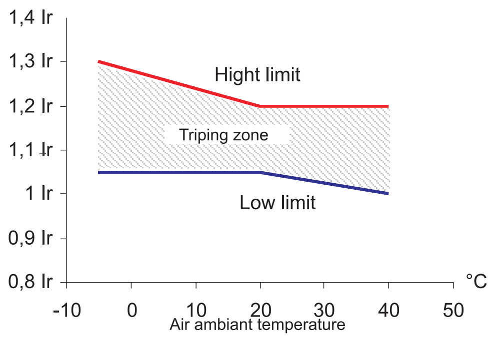
The relay can only be reset when the bimetal strips have adequately cooled down.

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

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

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

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



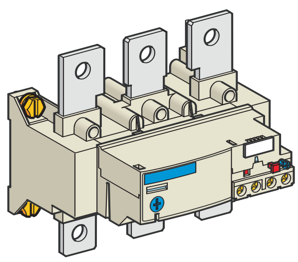
↑ Fig. 58 *Operating limit of a differential thermal overload relay (responding to loss of a phase)*

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

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

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

Apart from the usual functions of overload relays (protection against motor overload, unbalance and lack of phase) electronic overload relays can include options such as:
- PTC probe temperature control,
- protection against locking and overtorques,
- protection against phase inversion,
- protection against insulation faults,
- protection against no-load operation,
- etc.



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

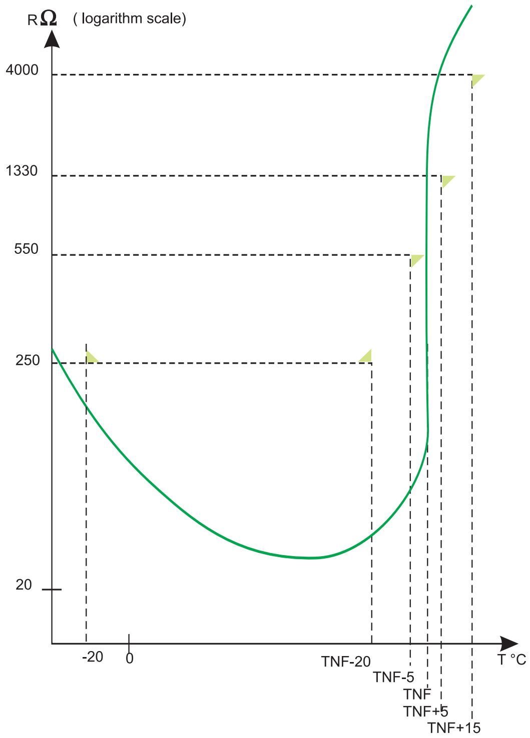


Fig. 61 PTC thermistor probe limits or "operating points"

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

Fig. 63 The overtorque relay (LR97D - Telemecanique

PTC thermistor probe relays

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

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

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

They consist of:

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

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

- **An electronic device**

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

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

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

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

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

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

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

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

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

Multifunction relays

- **Electromechanical or electronic relays**

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

- **Features**

These relays has been developed using the following technologies: voltage and current sensors, the latter's use ironless devices (Rogowsky sensors) which are fast and offer an outstanding linearity:

- an electronic combining numerical and analogic technologies, the result being a good capacity for treatment and data storage,
- use of field buses to exchange data to and from the PLC's and other devices,
- use of accurate motor modelisation algorithms,
- use of embedded programmes whose parameters can be defined.

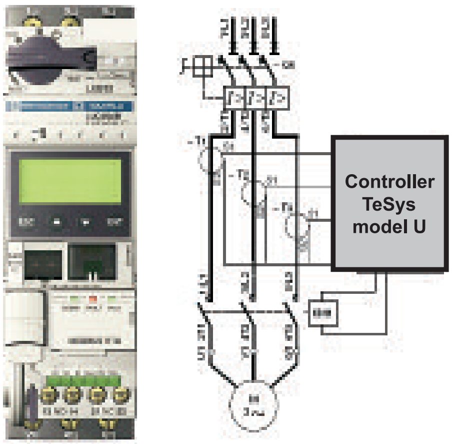
This new generation of product allow to reduce the costs from the design of the equipment, as PLC's programming are made simple, to the operation as maintenance cost and downtime are dramatically cut down.

The following is a brief description of the possible solutions and a basic selection guide.

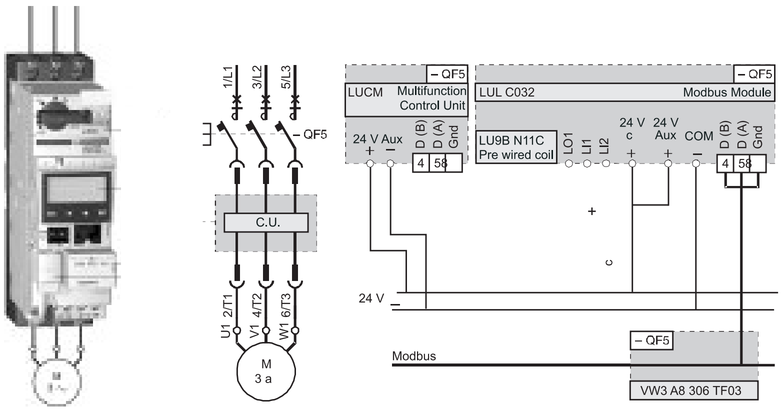
Readers should consult Schneider Electric technical documentation which give more in depth information.

- **The whole product line can be broken down in three families**

Solution 1: The multifunction relay is embed into the motor starter *(⇨Fig. 64)*.
The benefit of this all in one solution is a very compact product with a limited number of connections.
The upper limit is 32 Amps.



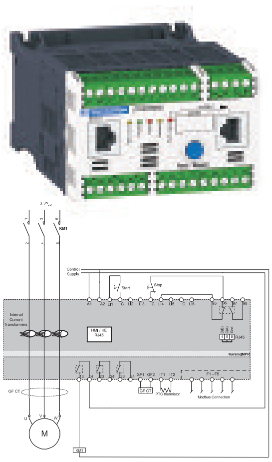
↑ *Fig. 65* *Multifunction relay is separated from the motor starter*



↑ *Fig. 64* *Multifunction relay embed into the motor starter*

Solution 2: the multifunction relay is separated from the motor starter and uses the same components as the all in one solution *(⇨Fig. 65)*.
The benefit is a possible connection to any motor starter.

Solution 3: the multifunction relay is segregated from the motor starter and offer multiple inputs / outputs.
It is the most versatile solution. *(⇨Fig. 66)*

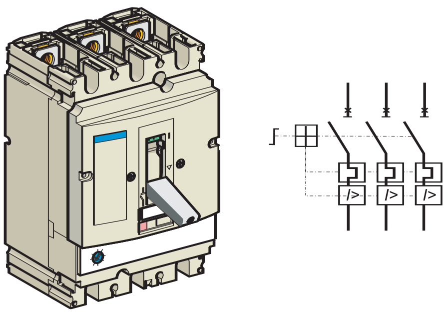


↑ *Fig. 66* *Multifunction relay with multiple I/O*

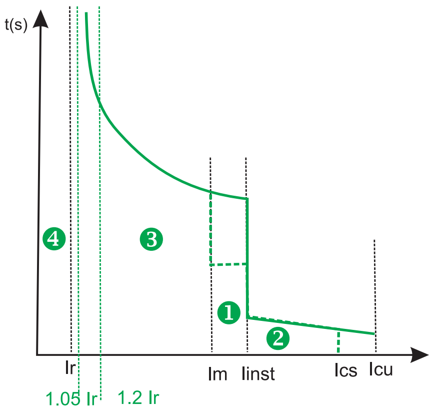
Protection relay selection guide
Main functions are given in the table bellow *(⇨Fig. 67)*. More in depth information can be found in the manufacturer data sheets.

Type of relays	Overload relay (thermorelay or electronic relay)	PTC probe relay	Overtorque relay	Muntifunction relay		
				Built in the starter	Outside the starter	Segregated motor monitor
Type of control						
Current						
Protection classes	10 et 20			5 to 20	5 to 20	5 to 30
Overcurrent	++		+++	+++	+++	+++
Ground fault						
Phase imbalance	++			++	++	+++
Mechanical locking during / after starting	+		++	++	++	+++
No load operation				module	module	+++
Votage and power supply						
Voltage imbalance						+++
Phase loss						+++
Phase inversion						+++
Undervoltage						+++
Overvoltage						+++
Power an power factor						+++
Temperature						
PTC probes				module	module	+++
PT100 probes				module	module	+++
Numerical functions						
Truth table				3 I/O	10 I/O	10 to 20 I/O
Timer						++
Starting mode						
Direct on line				+++	+++	+++
Reversing				+++	+++	+++
Star delta				+++	+++	+++
Part winding - two speed motors					+++	+++
Operation / maintenance						
Diagnostics				+	+	+++
Log				module	module	+++
Links / communication						
Local display	+			module	module	+++
Remote display (communication bus)				module	module	+++
Remote control (communication bus)				module	module	+++

↑ *Fig. 67* *Motor protection table*



↑ *Fig. 68* *Motor circuit breaker (GV7 - Telemecanique) and its graphic symbol*



↑ *Fig. 69* *Thermal magnetic circuit breaker operating zones*

Motor circuit breakers

Overview

This device is a thermal and a magnetic circuit breaker in the same package which protects a motor against short circuits and overload by rapidly opening the faulty circuit. It is a combination of a magnetic circuit breaker and overload relays It complies with the IEC 60947-2 and 60947-4-1 standards *(⇨ Fig.68)*.

In these circuit breakers, the magnetic devices (protection against short circuits) have a non-adjustable threshold, usually about 10 times the maximum current setting of thermal release units.

The thermal elements (protection against overload) are compensated for fluctuations of the ambient temperature. The thermal protection threshold can be adjusted on the front of the unit. Its value must correspond to the rated current of the motor to be protected.

In all these circuit breakers, coordination (type II) between the thermal elements and short-circuit protection is built into the device.

Moreover, in the open position, the insulation distance (between contacts) in most of these units is adequate to ensure isolation. They also have a padlocking device.

Tripping curves

A motor trip switch is characterised by its tripping curve, which represents the time it takes to trip based on the current (multiple of I_r).

This curve is divided into four zones *(⇨ Fig. 69)* :

- Ic normal operating zone ❶ . As long as $I < I_r$, there is no tripping,
- thermal overload zone ❷. Tripping is ensured by the “thermal” feature; the greater the overload, the less time it takes to trip. The standards refer to this as “inverse time”,
- strong high current zone ❸, monitored by the “instant magnetic” or “short-circuit” feature which works instantaneously (less than 5ms),
- and on some circuit breakers (electronic), an intermediate zone ❹ monitored by a “timed-delay magnetic” feature with a delay function (0 to 300ms). The standards refer to this as “definite time-lag”. This prevents accidental tripping at switch-on with magnetising peak currents.

Their limits are:

I_r: setting current for protection against overload; should correspond to the rated current value (I_n) of the motor to be protected,

I_m: tripping current of timed magnetic protection,

I_{inst}: tripping current of instant magnetic protection. This can range from 3 to 17 times Ir but is usually close to 10 I_r,

I_{cs}: service rated breaking capacity in short circuit,

I_{cu}: ultimate (maximum) breaking capacity in short circuit.

Conclusion

Motor protection is an essential function for ensuring the continuity of machine operation. The choice of protection device must be made with extreme care. The user would be wise to select devices that include electronic communication features to foresee and prevent any faults. These greatly improve the detection of abnormalities and the speed with which service is restored.