1SDC007106G0201

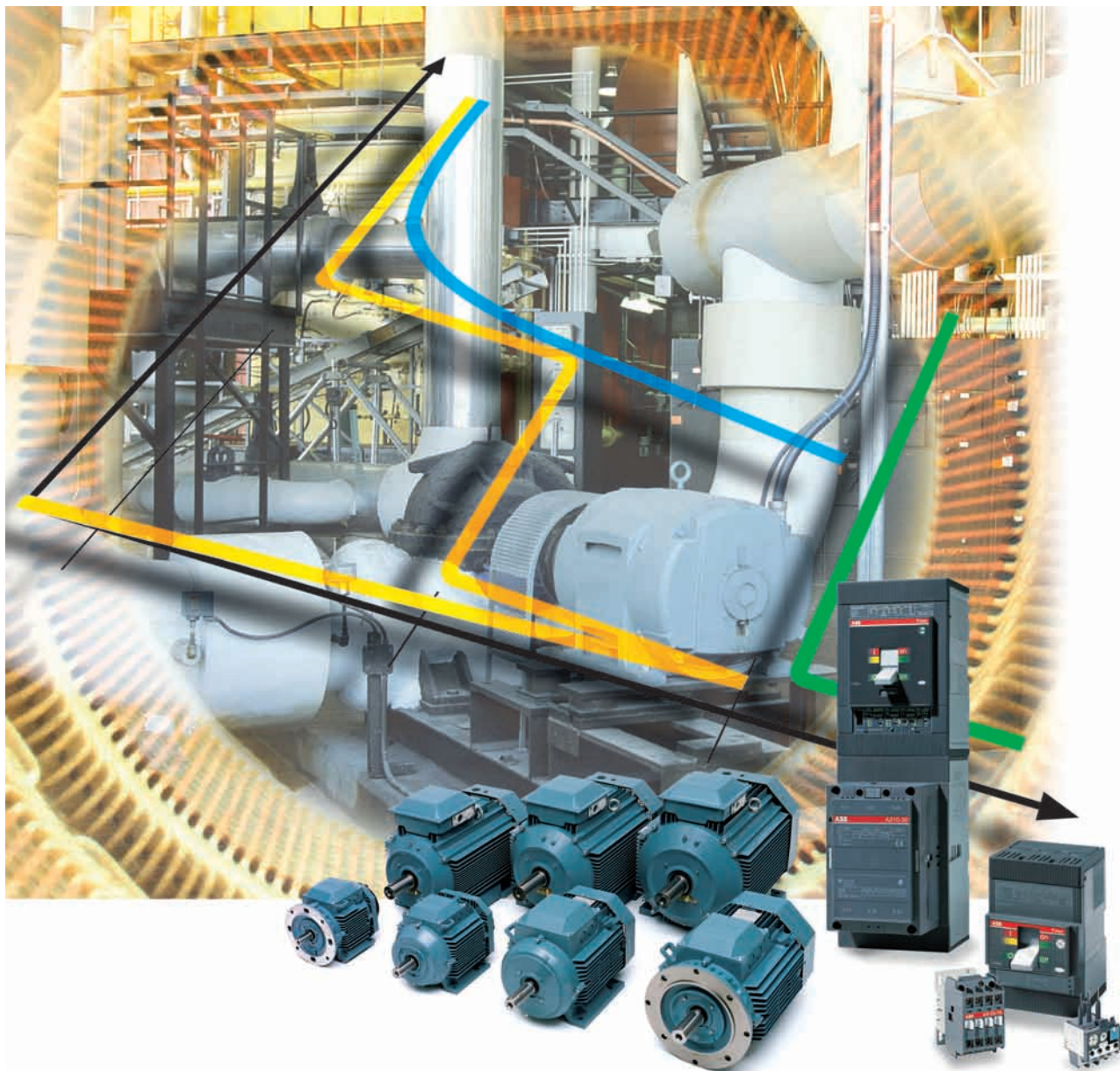# Three-phase asynchronous motors

Generalities and ABB proposals for the coordination of protective devices

ABB

Three-phase asynchronous motors
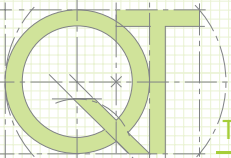## Generalities and ABB proposals for the coordination of protective devices

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Introduction

Three-phase asynchronous motors can be considered among the most reliable electrical machines: they carry out their function for many years with reduced maintenance and adapt themselves to different performances according to the requirements of both production as well as service applications.

As already said, these motors find their application in the most different industrial sectors, such as food, chemical, metallurgical industries, paper factories or water treatment and extractive systems. The applications concern the equipment with machine components running at fixed or variable speed such as for example lifting systems as lifts or good hoists, transporting systems as conveyors, ventilation and air conditioning installations, without forgetting the commonest use with pumps and compressors.

From the above considerations it is easily deduced how three-phase asynchronous motors can be considered the most widespread electric machine for industrial applications (the power consumption of electrical motors is about 75% of the total consumption in the industrial field). Considering this datum it is possible to understand how a reduction in power consumptions can be important for both the business management (the cost of a motor in its whole life is due to power consumption for about 98% and to purchase and maintenance costs for the remaining 2%) as well as for the improvement of the power efficiency in general; for example, such reduction can be obtained by using variable-speed drives with inverters or by implementing power factor correction to get a $\cos\varphi$ suitable to avoid incurring fines or, even more directly, by using the high-efficiency motors, identified by the code "EFF1", which have particularly advanced constructional characteristics and materials, allowing to reduce energy consumption up to 20%.

This Technical Paper (the seventh volume of the series of Technical Papers issued by ABB SACE) can be divided into five parts; after a survey of the motor structure, the main prescriptions of the Standards about coordination are considered. Then general information about the main starting typologies is offered, giving in the following part an overview of the products manufactured by ABB for motor starting, with a reading example of ABB official coordination tables. The last part is constituted by an analysis of some of the most important ratings of motors. Five annexes complete the document with:
- a hint to the theory of asynchronous motors with the purpose of giving the basic elements to understand their operating principle
- an example for the calculation in first approximation of the starting time as a function of the characteristics of the motor and of the load
- some considerations about motor running in case of "phase loss"
- a thorough analysis of the concept of "duty type" making reference to the Standard prescriptions
- a short account of motor coordination according to the prescriptions of the UL Standards.

1 Three-phase asynchronous motor

1.1 Typologies and use

A three-phase asynchronous motor can have
- a slip-ring rotor or
- a short-circuit rotor, more commonly defined squirrel-cage rotor.

The main difference between these two types derives from the structure of the rotor. More precisely, the first type of rotor is constituted by real windings as those of the stator, it presents a more complex and fragile structure (brushes sliding on the rotor, with the possible interposition of resistances for the control of the starting phase), it needs periodical maintenance and has big overall dimensions; the second type, instead, is made of a rotor with rods short-circuited at both ends and consequently, thanks to its higher constructional simplicity, it originates a type of motor very simple, sturdy and cost-effective.

Thanks to the development of control electronics, which allows the adjustment of speed in a very simple and effective way, all those applications using motors which foresee the possibility of speed regulation (d.c. motors or slip-ring motors) have been replaced by asynchronous motors, in particular the squirrel-cage ones, which are commonly used to control pumps, fans, compressors and many other industrial applications.

ABB manufactures and markets a complete range of low voltage motors, from the simple to the most complex application. ABB offers always the most suitable and profitable solution for all sort of use. With reference to the most common applications, it is possible to identify an application field defined "General Purpose", the motors of which are intended for OEMs' applications and can be requested directly from the distributors all over the world.

The motors which belong to this category are characterized by a high constructional quality and are intended in particular for the manufacturers of fans, pumps, compressors, lifting systems etc.
Complying with efficiency class "EFF2", they are available in class "EFF1" as option.

ABB range of "General Purpose" motors includes the following typologies:

- Aluminum motors from 0.06 to 95 kW
- Steel motors from 75 to 630 kW
- Cast iron motors from 0.25 to 250 kW
- Open drip-proof motors from 75 to 800 kW
- Brake motors from 0.055 to 22 kW
- Single phase motors from 0.065 to 2.2 kW
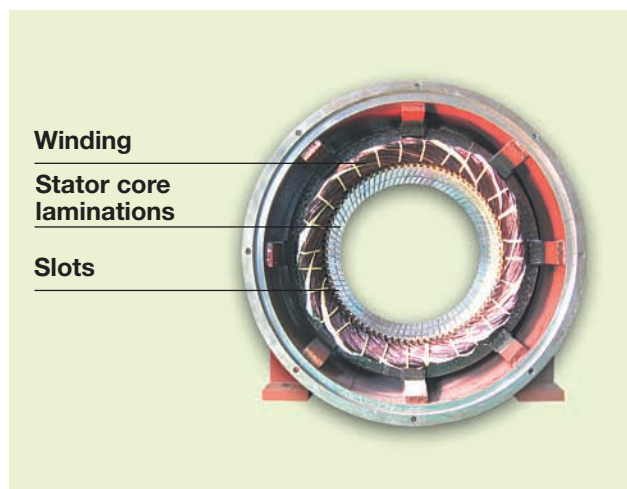- Integral motors from 0.37 to 2.2 kW

ABB motors have obtained CE mark and comply with the main international Standards of this sector, such as for example the Standards IEC 60034-1, IEC 60034-2, IEC 60034-8, IEC 60034-12, as regards the electrical characteristics, and the Standards IEC 60034-5, IEC 60034-6, IEC 60034-7, IEC 60034-9, IEC 60034-14, and IEC 60072, as regards the mechanical field.

1.2 Structure of the asynchronous motor

In order to understand better how a three-phase asynchronous motor is structured, here is a brief description of the main parts which constitute the rotating machine, i.e. the parts where the electrical phenomena generating the operation originate.

The first element we describe is the stator, which can be defined as the assembly of the fixed parts performing the function of supporting - at least partially - the motor, but fundamentally it constitutes the part of the magnetic circuit which includes the inductor windings housed in special slots made in correspondence with its internal surface. The stator, shown in Figure 1, is constituted by silicon steel alloy or by steel laminations, insulated one from the other. From its structure it depends how much it is affected by time-variable magnetic flows which cause losses due to hysteresis (linked to the nonlinear magnetization of the material) and to induced "eddy currents".

In the slots obtained in the structure of the laminations, three primary windings are inserted (each of them constituted by more coils differently connected between them), to which the supply voltage is applied and which generate the magnetic field. The three-phase stator windings can be star- or delta-connected; this can be achieved with motors equipped with terminal box with 6 terminals, so that it is possible to feed the same motor with different three-phase network voltages. An example of double indication could be 230VΔ - 400VY or 400VΔ - 690VY, where the symbol Y or Δ refer to the connection of the stator windings; for example, taking into consideration the second case (400VΔ - 690VY), the indication means that the delta-windings of the motor can be connected to a three-phase network at 400V (phase-to-phase voltages), whereas, if for the same motor the windings are star-connected, the motor itself can be connected to a supply network at 690V (the star-windings shall be subjected to the network voltage reduced by $\sqrt{3}$ times).

The second element is the rotor, which is positioned inside the stator and constitutes the induced circuit of the motor. For a squirrel-cage motor, the rotor - as represented in Figure 2 – is constituted by a system of bars (in copper or aluminum), which are coaxial to the rotation axis and directly die-cast in the slots made along the external periphery of the ferromagnetic; they are closed in short-circuit by two rings located on the extremities and

Figure 2: Rotor of a three-phase asynchronous motor
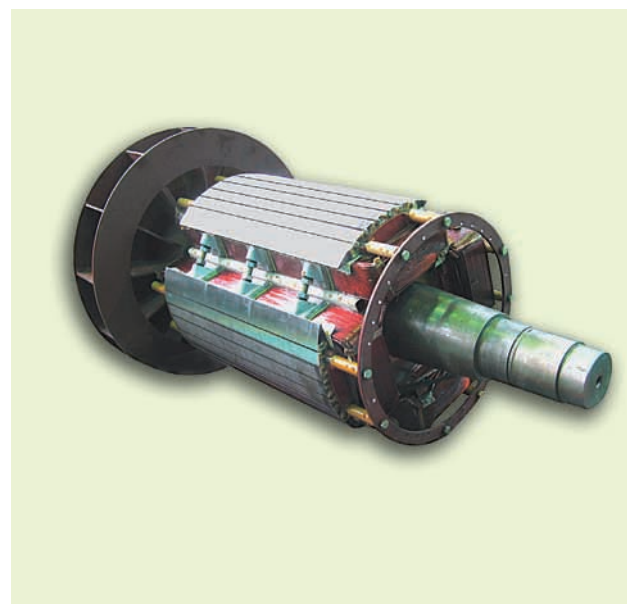
constituting also a mechanical fixing. Thus, an extremely compact and robust rotor is obtained, to which also the motor shaft is fixed.

The induced magnetic field, which constitutes the operation principle of the motor, makes the motor shaft rotate, thus converting the electrical energy into mechanical energy.

Figure 1: Stator of a three-phase asynchronous motor

Winding

Stator core laminations

Slots

There are other mechanical components which constitute the motor. The main ones are:
- the two bearings mounted on the stator and having the function to support the motor shaft;
- the chassis which, thanks to the cooling fins, dissipate the heat produced especially by the stator and which houses also the connection terminal box;
- the fan, which provides for cooling.

A general representation of the assembly together with a section plane of the asynchronous three-phase motor is given in Figure 3.

Figure 3: Overall view and cross section of an asynchronous motor

Terminal box

Stator with stator windings

Cooling fan

Cooling air flow

Motor shaft

Bearing

Squirrel-cage rotor

Cooling fins

Chassis
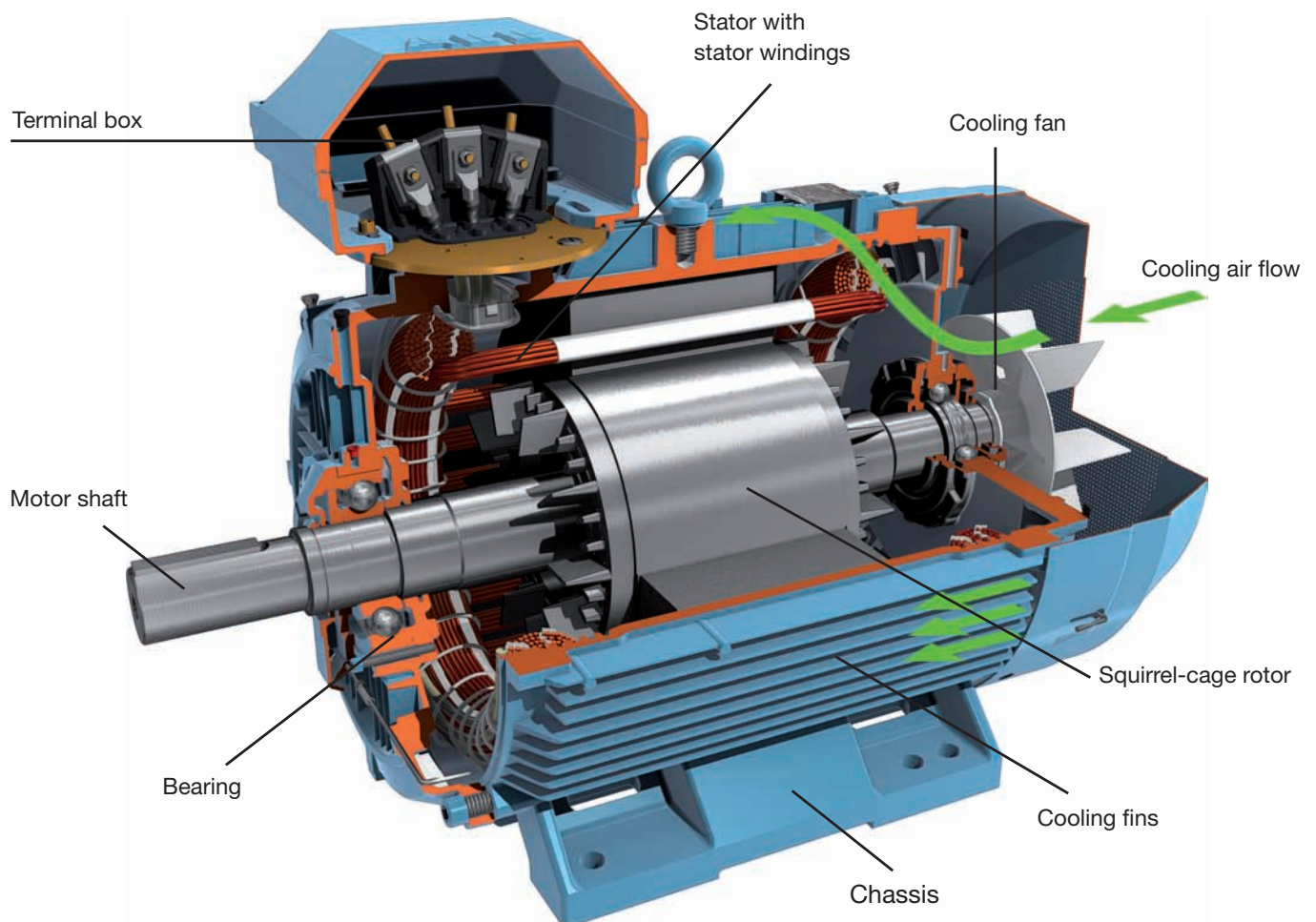
2 Protection and switching of the asynchronous motor

An important aspect to be taken into consideration in the choice and realization of a system for motor starting and control is the safety and reliability of the solution to be obtained. The main causes of motor failure are due to short-circuits which occur, for example, owing to humidity, grease, dust between the windings, or because of overloads. The overcurrents resulting from faults cause temperature-rises which can damage the motor irreversibly and which could also originate fires in the surrounding environment. As a consequence, starting constitutes a phase particularly critical for the motor and the plant supplying it and also the rated operation requires to be adequately monitored and protected in the face of possible maloperations. To this purpose it is necessary and important to dimension and choose correctly the electrical apparatus to realize motor starting and switching. The first step to be taken in this field is identifying the reference Standard, which is IEC 60947-4-1 *"Electromechanical contactors and motor-starters"* and which applies to a.c. and d.c. contactors and to a.c. starters whose contacts are intended to be connected to circuits with rated voltages not exceeding 1000 Vac or 1500 Vdc.

2.1 Main Standard definitions of general character

Making reference to Standard IEC 60947-4-1, here are given some definitions of general character aimed at a better understanding of the meaning and the function of the main electrical components used for motor control.

AC motor-starters
Combination of all the means intended to start and accelerate motors to normal speed, to ensure continuous operation of motors, to switch off the supply from the motor and to provide means for the protection of motors and associated circuits against operating overloads.
Overload relays for starters, including those based on solid state technology, shall meet the requirements of this Standard.

Direct-on-line starters
Starters which connect the line voltage across the motor terminals in one step, intended to start and accelerate a motor to normal speed. They shall ensure switching and protection functions as prescribed in the general definition.
In addition, two further specifications are given according to the changeover modality permitted for the motor and in particular to reverse the direction of rotation.

Reversing starters
Starters intended to cause the motor to reverse the direction of rotation of the motor by reversing the primary connections also when the motor is running.

Two-direction starters
Starters intended to cause the motor to reverse the direction of rotation of the motor by reversing the primary connections only when the motor is not running.

Reduced voltage a.c. starters
Reduced voltage a.c. starters intended to start and accelerate a motor to normal speed by connecting the line voltage across the motor terminals in more than one step or by gradually increasing the voltage applied to the terminals.
They shall ensure switching and protection functions as prescribed in the general definition. To control the successive switching operations from one step to the other, time-delay contactor relays or equivalent products may be used. The most common type of reduced voltage a.c. starters are start-delta starters as defined in the above mentioned Standard.

Star-delta starters
Star-delta starters intended to start a three-phase motor in the star connection, to ensure continuous operation in the delta connection. They shall ensure switching and protection functions as prescribed in the general definition.
The star-delta starters considered in this Standard are not intended for reversing motors rapidly and, therefore, utilization category AC-4 does not apply.

This Standard takes into consideration also other types of starters (auto-transformer starters – rheostatic stator starters) for the definition of which reference shall be made to the Standard itself.
The starters dealt with in this Standard are not usually provided for the breaking of short-circuit currents. Therefore an adequate protection against short-circuit must be provided for in the installation.

After defining starters according to their functions and components, the Standard offers a further classification and categorization of them in combination with protection devices against short-circuit; in this case reference is made to their assembling and wiring modalities with the starter itself, as indicated below.
The first step is defining the protection device typically used, i. e. the circuit-breaker, in compliance with the Std. IEC 60947-2 *"Low-voltage switchgear and controlgear - Part 2: Circuit-breakers"* as:
a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short-circuit.
Then, the whole of the switching and protection devices is defined and differentiated as follows:

Combination starter

Equipment consisting of a starter and a short-circuit protective device, mounted and wired in a dedicated enclosure. The switching and short-circuit protective devices may be a fuse combination unit, a switch with fuses or a circuit-breaker with or without an isolating function.

Protected starter

Equipment consisting of a starter and a short-circuit protective device, enclosed or unenclosed, mounted and wired according to the instructions of the starter manufacturer.

The manually operated switching device and the short-circuit protective device may be one single device and may incorporate the overload protection as well.

The definition of "starter" introduces a switching device, which can be identified with a contactor, and a protection device against operation overloads, which can be identified with a thermal relay. Let's consider now how the Std. IEC 60947-4-1 defines these two devices constituting the starter.

Contactor (mechanical)

A mechanical switching-device having only one position of rest, operated otherwise than by hand, capable of making, carrying and breaking currents under normal circuit conditions including operating overload conditions.

Thermal overload relay or release

Multipole thermal overload relay or release which operates in the case of small overcurrents (overloads) in the motor supply circuit. For this application, a device operating also in case of loss of phase in accordance with specified requirements is often required, so that the protection of the motor, which could be find itself running under anomalous conditions is ensured.

The Standard specifies different application fields for contactors and starters, by introducing the concept of utilization categories.

Utilization category

Different utilization categories are identified: they are characterized by the applications summarized in the Table 1. Each utilization category identifies for the contactor the minimum required performances (for example, application field or rated breaking capacity) according to the values of current, voltage power factor, or time constant and test conditions specified by the Standard.

Table 1: Utilization categories

Kind of current	Utilization category	Typical applications [1]
Alternating current	AC-1	Non-inductive or slightly inductive loads, resistance furnaces
	AC-2	Slip-ring motors: starting, switching off
	AC-3	Squirrel-cage motors: starting, switching off motors during running (2)
	AC-4	Squirrel-cage motors: starting, plugging, inching
	AC-5a	Switching of electric discharge lamp controls
	AC-5b	Switching of incadescent lamps
	AC-6a	Switching of transformers
	AC-6b	Switching of capacitor banks
	AC-7a	Slightly inductive loads in household appliances and similar applications
	AC-7b	Motor-loads for household applications
	AC-8a	Hermetic refrigerant compressor motor control with manual resetting of overload releases
	AC-8b	Hermetic refrigerant compressor motor control with automatic resetting of overload releases
Direct current	DC-1	Non-inductive or slightly inductive loads, resistance furnaces
	DC-3	Shunt motors: starting, plugging, inching
		Dynamic breaking of d.c. motors
	DC-5	Series-motors: starting, plugging, inching
		Dynamic breaking of d.c. motors
	DC-6	Switching of incandescent lamps

(1) As regards the application field with reference to motor starting, those applications for which starters belong to one or more utilization categories identifiable with AC-3, AC-4, AC-7b, AC-8a and AC-8b are to be considered of common use for direct-on-line starters, those applications for which starters belong to the utilization category identifiable with AC-3 are to be considered of common use for star-delta starters.

(2) The most common applications usually provide direct-on-line starters for the switching of three-phase squirrel-cage asynchronous motors; therefore, in this case too, reference shall be made to category AC-3 only. For this application, the Standard prescribes working conditions slightly different from those prescribed for category AC-3 and admits a use of such apparatus or sporadical inching or plugging for limited periods as those related to motor positioning; during such limited periods the number of these operations should not exceed the number of five/minute or ten over a period of 10 min.

2.2 Main Standard prescriptions regarding co-ordination

The devices which can be identified by the previous definitions and which are commonly used to realize a protected starter result to be:

- a protection device against short-circuit, typically a magnetic only circuit-breaker (the use of fuses is possible)
- a switching device, such as a contactor
- a protection device against overload, such as a thermal relay or release.

These devices shall be properly chosen to achieve correct motor switching and protection, but also coordinated one another to ensure protection for the starter elements in order to guarantee the plant safety. The performances of the protection device against short-circuit shall be adequate and verified with reference to the characteristics of the components used for each application. The verifications of protection between the different devices are carried out by the manufacturer making reference to the experimental data and to the characteristics of the products which are not reported on the technical/commercial catalogues. As a consequence, the manufacturer usually makes available for the designer the coordination tables reporting the components to be used to obtain the characteristics prescribed for the coordination. The use of either a component of the starter (contactor or thermal protective device) or of a protection device against short-circuit not complying with the prescriptions of the manufacturer can make the coordination used not suitable.

Besides being referred to the rated current of the motor to be switched and besides being valid for a determined voltage and short-circuit current, a coordination for motor starting (circuit-breaker + contactor + thermal relay) is classified as "normal" or "heavy" and "type 1" or "type 2". As regards the first classification it is possible to affirm that the distinction between normal or heavy starting is linked to the starting time and to the tripping characteristic of the thermal protection, whereas the distinction between type 1 or 2 coordination is linked to the different ways in which a device protects the switching apparatus (contactor) against short-circuit and the protection apparatus against overload (external thermal relay). Here are some details to differentiate one starting typology from the other.

2.2.1 Normal and heavy starting

A classification of the starting typology is linked to the characteristics required by the load and by the consequent behaviour of the thermal relay. Compensated thermal relays are normally used, that is relays having an operating principle for which their behavior remains unchanged also when the working temperature varies. According to whether the thermal relay is compensated as regards temperature, the Standard gives some prescriptions for the relay characterizing the tripping curve, but, in particular, the Standard establishes the tripping times corresponding to 7.2 x Ir (Ir setting current of the thermal protection), based on which the concept of trip class or starting class is introduced, as shown in Table 2.

Table 2: Starting classes

Trip class	Tripping time Ti [s] for 7.2 x Ir	Tripping time Ti [s] for 7.2 x Ir (band E)
2	–	Ti ≤ 2
3	–	2 < Ti ≤ 3
5	0.5 < Ti ≤ 5	3 < Ti ≤ 5
10A	2 < Ti ≤ 10	–
10	4 < Ti ≤ 10	5 < Ti ≤ 10
20	6 < Ti ≤ 20	10 < Ti ≤ 20
30	0.5 < Ti ≤ 30	20 < Ti ≤ 30
40	–	30 < Ti ≤ 40

The meaning of the different terms of this table can be better explained making reference to the following considerations.

The parameter 7.2 x Ir is the multiple of the current set on the protection relay and the multiplying factor 7.2 is fixed by the product Standard.

"Ir" usually coincides with the rated current of the motor "Ie", the value 7.2 x Ir may be considered the current which the motor absorbs during the starting phase.

The trip classes usually considered and most commonly used are 10A –10 – 20 – 30 referred to the time "Ti" of the middle column. It is quite common speaking of normal starting and associate to it the trip classes 10A and 10, or of heavy starting making reference to the trip classes 20 and 30. The other trip classes and the tripping time indicated with band "E" have been recently introduced in an amendment of the Standard IEC 60947-4-1 and are characterized by a restricted trip range due to the increase of the minimum non-tripping time.

The limits fixed for "Ti", which is the generic tripping time of the thermal protection, have the following meaning:

- the lower limit represents the minimum time under which the relay mustn't trip in order not to interfere during starting;

- the upper limit is the time within which the relay shall surely trip. Such limit is fixed with reference to the standard characteristics of the machine allowing the stator windings, or however the motor in general, to withstand the starting current and the thermal effects generated by the current for quite short times.

Using an easy numerical example, the meaning of the information reported in the table results clearer. By assuming to have a motor for a specific application which needs a starting time of 5s, the choice of a thermal protection device classified as trip class 10A and 10 would not be correct because, from a theoretical point of view, it could trip already at 2s or 4s; therefore it is necessary to choose a relay in class 20, which up to 6s does not trip, thus allowing complete starting of the motor.

Figure 4 below shows a typical example of protection curves of a relay for motor starting; from their analysis it is evident the correspondence between the trip time value which "Ti" assumes and the division into the different classes 10A – 10 –20 – 30 which characterizes the relay. Actually it is possible to see how in correspondence with 7.2 x Ir (the value established by the Standard), the relay declared in class 30 has a tripping time of about 23s (item A), thus in compliance with the indications of Table 2 above.

Figure 4: Tripping curves with thermal relays for different starting classes
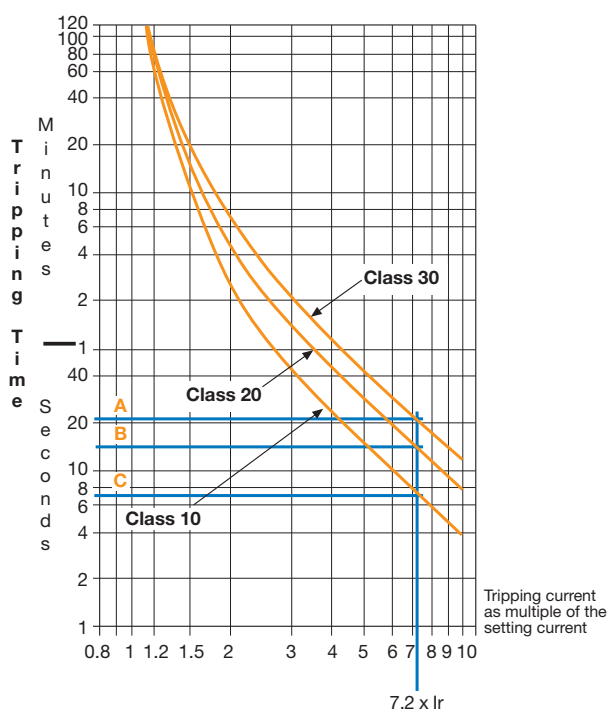
The characteristics of the load to be driven by the motor, the motor type and the starting modality are elements which influence the starting time and consequently the choice of the thermal protection device. With the only purpose of offering an indication linked to real applications, it is possible to state that ship propellers, compressors and centrifugal pumps may be included in the category of normal starting, therefore with thermal protection class 10 or 10A, whereas – for example – centrifugal fans, mixers and mills can be considered part of heavy starting, therefore with thermal protection class 30.

It is evident how it is important to define the operating conditions to ensure a correct choice of the motor, and also of the protection device in order to obtain optimum working and protection conditions.

2.2.2 Co-ordination type 1 and type 2

The co-ordination typologies admitted by the Standard with reference to the behavior of the protection device against short-circuit towards the starter components are classified as "type 1" and "type 2".

Under short-circuit conditions, the coordination of type "1" allows the contactor and the overload relay to be damaged; as a consequence they could not be able to operate without repairing or replacement of parts. However, the Standard prescribes that these devices do not cause damages to people or installations, for example with parts of the components ejected outside the enclosure.

Under short-circuit conditions, the coordination of type "2" allows the risk of contact welding, provided that the contacts themselves can be easily separated (for example through a screwdriver) without important deformations. This type of coordination requires that the contactor or the starter do not cause damages to people or installation and that they are able to resume operation after restoring of the standard conditions.

From the definition of the two coordination typologies it is possible to deduce how "type 1" coordination permits the use of devices of lower sizes, thus with an initial cost saving and reduced dimensions, but to the disadvantage of a high safety and however with subsequent costs for maintenance and replacement in case of faults. "Type 2" coordination meets higher safety requirements and the possible greater initial cost can be amortized considering that, in case of fault, the switching and protection equipment could start operating again without being replaced.

3 Main starting modalities of a three-phase asynchronous motor with squirrel-cage rotor

Independent of the previous classifications, the starting of a three-phase asynchronous motor for applications which do not require a speed change of the machines can be obtained through plant engineering solutions differentiating according to the modality through which the voltage is applied across the stator windings and according to the various electrical and mechanical parameters. These parameters of different entity generate more or less violent stresses on the electrical machine, but make available inrush torque parameters with very different values.

Now let's go into details by identifying the most common starting typologies.

3.1 Direct-on-line starting

Direct-on-line starting, which is often abbreviated as DOL, is perhaps the most traditional system and consists in connecting the motor directly to the supply network, thus carrying out starting at full voltage. Direct-on-line starting represents the simplest and the most economical system to start a squirrel-cage asynchronous motor and it is the most used. As represented in Figure 5, it provides the direct connection to the supply network and therefore starting is carried out at full voltage and with constant frequency, developing a high starting torque with very reduced acceleration times.

The typical applications are relevant to small power motors also with full load starting.

These advantages are linked to some problems such as, for example, the high inrush current, which - in the first instants - can reach values of about 10 to 12 times the rated current, then can decrease to about 6 to 8 times the rated current and can persist to reach the maximum torque speed. The effects of such currents can be identified with the high electro-dynamical stresses on the motor connection cables and could affect also the windings of the motor itself; besides, the high inrush torques can cause violent accelerations which stress the transmission components (belts and joints) generating distribution problems with a reduction in the mechanical life of these elements. Finally, also the possible electrical problems due to voltage drops on the supply line of the motor or of the connected equipment must be taken into consideration.

Figure 5: *Principle diagram for DOL starting*
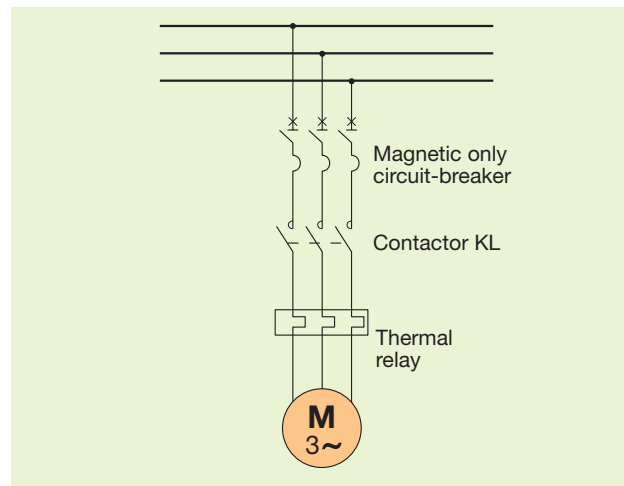
3.2 Reduced voltage starting

The reduced voltage starting systems consist in connecting directly the motor to the electrical supply network, thus carrying out a reduced voltage starting. This involves a reduction of the starting current, but unfortunately also a reduction in the inrush torque. The most common types of starting are starting with reactors and stator resistors, star-delta starting, starting with auto-transformer or starting with soft starter, which intervenes on the motor torque curve to adapt it to the load characteristics.

3.2.1 Star-delta Y/Δ starting

Star-delta starting is the best known system and perhaps the commonest starting system at reduced voltage; it is used to start the motor reducing the mechanical stresses and limiting the current values during starting; on the other hand, it makes available a reduced inrush torque. This system can be used for motors with terminal box with 6 terminals and double supply voltage. It is particularly suitable for no-load starting or with low and constant load torque or lightly increasing load torque, such as in the case of fans or low power centrifugal pumps.

Making reference to the diagram of Figure 6, the starting modality foresees the initial phase with star-connection of the windings to be realized through the closing of the circuit-breaker, of the line contactor KL and of the star contactor KY. After a suitable predetermined period of time, the opening of the contactor KY and the closing of KΔ allow switching to delta-connection, which is also the configuration of normal running position. These apparatus are affected by currents related to the different starting phases; these currents result to be lower than the rated current of the motor, as illustrated below. Also

the thermal protection, which is usually positioned on the load side of the Y/Δ changeover node, shall be set at a current value lower than the rated current of the motor. Besides, the thermal protection installed in this position is sensitive to the third-harmonic currents generated due to iron saturation and which remain closed in the delta circuit.

Now let's analyze the different phases of starting in details:

Star phase (Y)

It is the starting phase: the motor windings are star-connected and the voltage on them is $\dfrac{V_L}{\sqrt{3}}$. The current in the motor winding and on the line results to be $I_{MY} = \dfrac{V_L}{\sqrt{3} \ x \ Z_W}$.

Z_W is the winding impedance.

As already said, this phase of starting coincides with the acceleration phase and shall last enough so that the steady-state speed can be almost reached. A too short duration would not allow that reduction in stresses which characterize this starting typology; as a consequence, such stresses would present themselves again in the subsequent delta phase, thus reproducing starting conditions similar to those of direct-on-line starting.

Changeover phase

It is the phase in which through the opening and closing of the dedicated contactors the switching from the star position to the delta position occurs. Duration and calibration of the changeover phase are important: the changeover time must be such as to guarantee the extinction of the electric arc on the star contactor and to prevent that a short-circuit condition is caused by a too advance closing of the delta contactor. On the other hand a too long time to pass from Y to Δ position would cause the deceleration of the motor, resulting in large current peaks in the delta phase.

The switching is regulated by analog or digital timers and, just as an indication, the switch-over time can be set at an average value of 50ms. On the timer also the duration of the star phase is set, that is the acceleration or the starting time which, generally speaking, can be considered as a function of the difference between the average driving torque of the motor and the average load torque of the motor–machine unit.

A good commutation, which is necessary to make effective the advantages which in theory characterizes Y/Δ starting, must be made taking into consideration the rotation direction and the sequence of the wiring connections on the clamps of the motor passing from Y to Δ position. If the commutation occurs when the residual magnetism of the rotor is in phase opposition with the magnetic field

generated by the stator current, the current requirement could also be very high with values which could reach also 20 times the rated current. The consequences deriving from a commutation not well calibrated affect not only the motor but also the behavior of the apparatus which constitute the coordination and cause inappropriate and unpredictable running.

Delta phase (Δ)

When the changeover has been carried out, the final phase of starting is reached; it represents also the steady-state running condition in which the stator windings are delta-connected and are subject to the full network voltage V_L and the motor reaches again the full torque, whereas the current flowing through the windings is:

$$I_{M\Delta} = \dfrac{V_L}{Z_W}$$

and the current absorbed by the line (rated current "Ie" of the motor) is

$$I_{LM\Delta} = \dfrac{V_L}{Z_W} \ x \ \sqrt{3} \ .$$

Figure 6: Principle diagram for star-delta starting
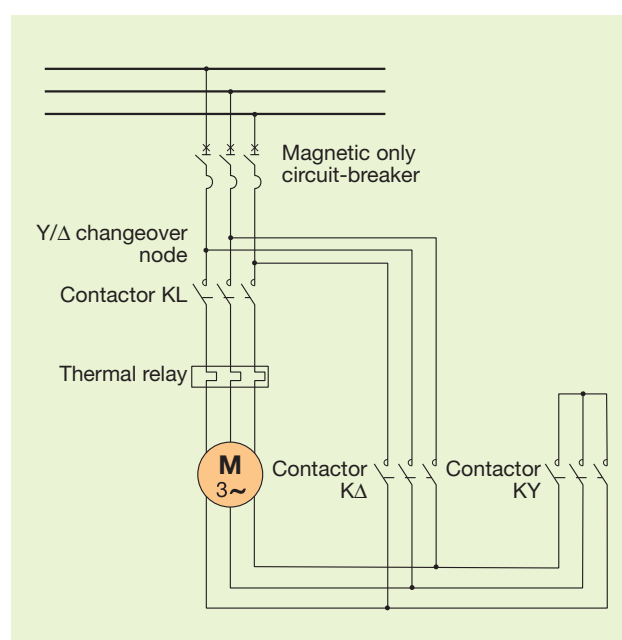
By analyzing the current and voltage formulas previuosly given, it can be seen how Y starting phase occurs at a voltage value equal to 0.577 times the line voltage V_L and requires a current absorption (both from the line as well as in the Y windings) which results 0.33 times lower than the current which the motor would absorb from the line in case of direct-on-line starting and delta-connected motor. From the relation above referred to the current in the phase Y and to the line current in the phase Δ, it can be deduced that $I_{MY} = \dfrac{V_{LM\Delta}}{3}$.

From the electrotechnical laws, it can be deduced that the reduction in the currents absorbed reduces by the same amount the electrodynamical stresses, whereas voltage drop reduces quadratically the initial torque (i.e. by 3 times).

In some treatises or technical comments, the reasons and the characteristics previuosly adduced for the use of the starting system Y/Δ, (i.e. the reduction of the high voltage drop caused by the inrush current and the reduction of the initial torque, which would cause damages to the coupling joint of the machine tool) are often not considered important and substantial elements to deem Y/Δ a good starting method. However the point is that such method is frequently used in the most classic industrial applications which provide the use of asynchronous motors.

3.2.2 Autotransformer starting

The reduction of the supply voltage is obtained by means of a fixed tap auto-transformer or of a more expensive multiple tap auto-transformer, or even by means of a variable voltage transformer.

During starting with auto-transfomer (see diagram of Figure 7) the motor is connected to one tap of the autotransformer (magnetic only circuit-breaker closed, KA closed, KY closed) which reduces the network voltage by the factor "k" and which draws in the motor a current reduced by the same factor compared to the current that the motor would absorb when supplied directly at the full rated voltage. The current on the primary of the transformer, and consequently on the line, results to be reduced by k2. Consequently to the voltage reduction by factor k, also the inrush torque is reduced by k2 compared to starting at full voltage.

When the motor has reached approximately 80% to 90% of its steady-state speed, the contactor KY is opened and the motor continues to be supplied at reduced voltage by the inductance of the auto-transformer windings. At this point, the contactor KL is closed and the contactor KA is opened so that the motor is supplied directly from the network. Starting with auto-transfomers is to

be considered quite expensive, certainly more than Y/Δ starting, and is applied to medium/high power squirrel-cage motors with high inertia.

Figure 7: Principle diagram for autotransformer starting
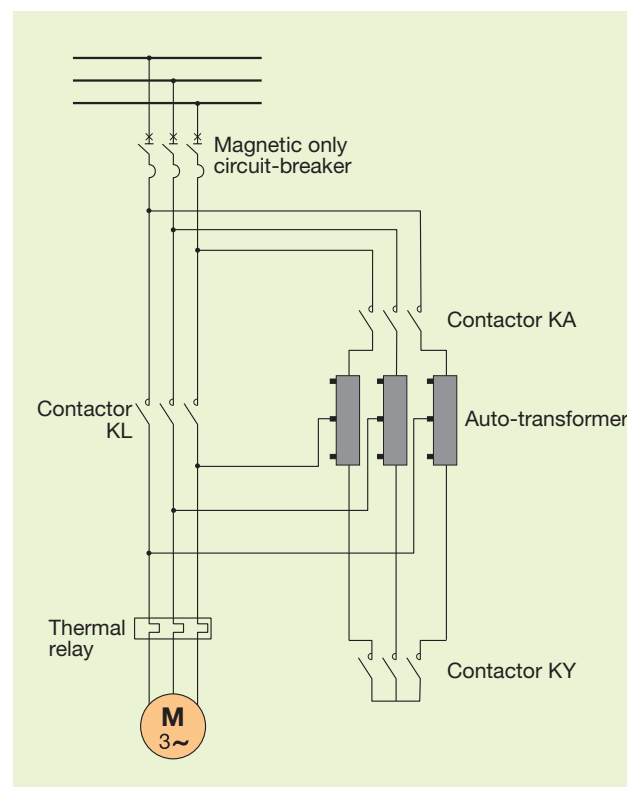
3.2.3 Starting with stator resistors or reactors

This starting method, whose diagram is shown in Figure 8, is suitable for squirrel-cage rotors. In this case the voltage drop is achieved by using reactors or resistors in series to the stator during starting (KL closed, KB open); consequently the voltage supplying the motor in the initial phase is reduced by factor "k" compared to the network voltage, to which a torque reduction by k2 corresponds. The starting current is limited to about half the current necessary for starting at full voltage. Once the acceleration phase is finished, the reactors or resistors are excluded (closing of KB) and the motor returns to the parameters related to the full voltage.

It is possible to achieve also a lot of step-by-step exclusions of resistors and reactors by means of time-delayed control devices. This method implies some consequences in the starting phase, such as for example the remarkable fall in the power factor because of the reactors, or a high temperature-rise produced by power dissipation on the resistors. This is a system which is typically used for machines which have strong inertia

and which do not need particulary high torque values and currents at starting.

Figure 8: *Principle diagram for starting with stator resistors or reactors*
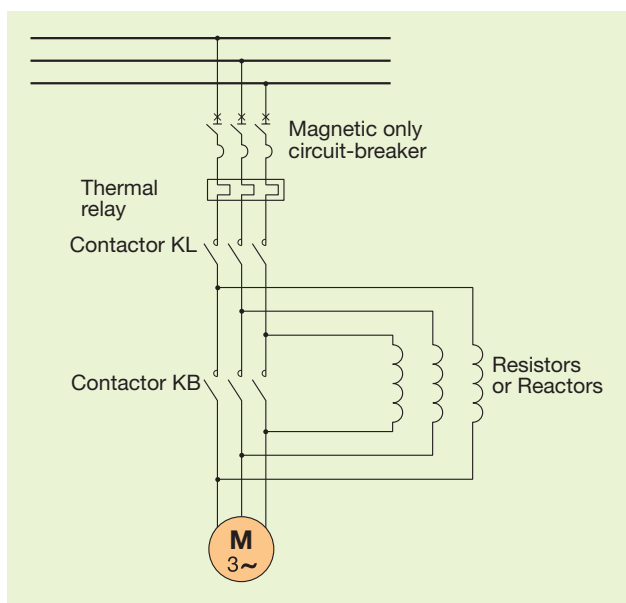
3.2.4 Soft starting

A modern method to perform starting maybe requiring a quite high intial investment, is represented by the use of electronic static starters, usually called soft starters. The use of these devices, with the diagram shown in Figure 9, allows to limit the starting current, to determine the torque and to set the starting time thus making possible a very soft motor supply which is increased during the whole process in order to get a soft starting avoiding the electrical and mechanical stresses which characterize DOL and Y/Δ starting. Soft stsarters are mainly constituted by two parts, a power unit and a control unit. The main components of the power unit are the heat dissipater and the thyristors, which are controlled by logic implemented on a circuit card which constitutes the control unit, usually a microprocessor-based one. The diagram typically used is represented hereunder and is defined "on-line". The fuses can be often replaced by a circuit-breaker which however does not allow to guarantee a suitable protection for the thyristors in case of fault; besides, when the soft starter typology does not provide a thermal protection implemented inside itself, an external thermal relay shall be used to be mounted on the supply side of the bypass connection. With reference to the Y/Δ connection diagram, the soft starter could also be inserted into the changeover node by a "delta" connection. The starting phase typically occurs with KL closed and KB open so

that the soft starter can control starting; afterwards, KB is closed with the exclusion of the power unit inside the soft starter whereas the control unit is left active.

Figure 9: *Principle diagram for soft starting*
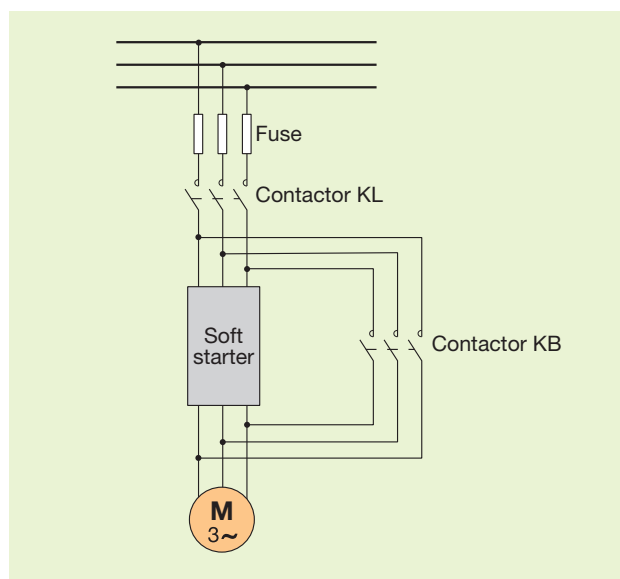
With reference to direct-on-line, star/delta and soft starter starting Figure 10 shows a typical curve of the starting current and of the torque required by the motor. It is clear that direct-on-line starting constitutes the heaviest modality in terms of current, but the most performing one in terms of torque and that with Y/Δ starting it is possible to reduce the starting current even if, as already pointed out, a very high peak value presents at the changeover although with a modest value of initial torque. The most balanced starting results definitely that obtained with soft starters.

Figure 10: *Curves relevant to current and motor torque for different starting methods*
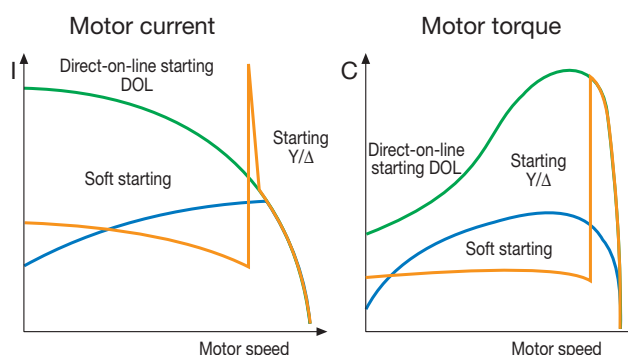
4 ABB equipment and solutions for co-ordination

4.1 Theoretical considerations about coordination equipment

The behaviour of three-phase squirrel-cage asynchronous motors is represented by some significant parameters:

- the rated current "Ie" linked to the rated power "Pe" through the rated efficiency and power factor. The Standard IEC 60947-4-1 (with its amendement dated November 2006) reports a table where the rated operational power of the motor is linked with a rated operational current at different installation voltages. The reference rated currents are determined for a 4-pole squirrel-cage motor at 400V, 1500 rpm and 50Hz. The rated operational currents for the other voltages are calculated on the basis of these values.
- the inrush current "Isp" to which a value of about 12 x Ie is assigned and which represents the maximum current required by the motor in the very first instants of feeding;
- the starting current "Iavv" to which a value of about 7.2 x Ie is assigned in compliance with the Std. IEC 60947-4-1 and which represents the required current during starting persisting during the starting time.

In principle these parameters, as illustrated in the scheme of Figure 11, relate to the characteristics of the different coordinating devices as follows:
- **the inrush current Isp** influences the choice of the protective device which shall have such a magnetic tripping threshold to permit the inrush phase. In addition to this parameter, the circuit-breaker shall have a breaking capacity suitable for the short-circuit current at the installation voltage;
- **the starting current Iavv** and the starting time permits to identify the type of thermal protection fit for the required duty type; besides, the setting range of the relay shall be suitable for the rated current of the motor.
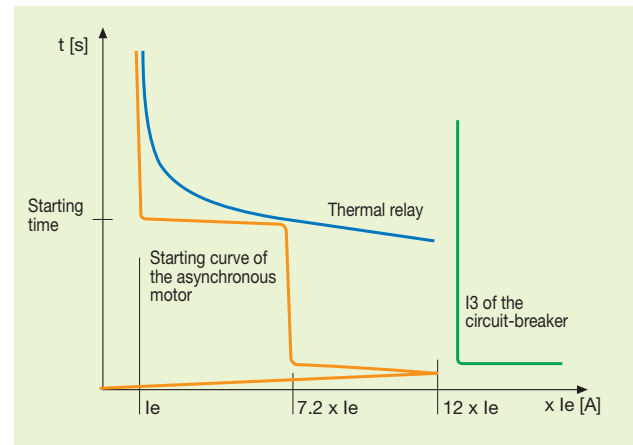
Apart from these characteristics to comply with, both the thermal relay as well as the contactor must be coordinated with the protection device against short-circuit so that an adequate protection is guaranteed if a short-circuit occurs in order to comply with the prescriptions for type 2 coordination.

4.1.1 Devices normally used and relevant combinations

Making reference to the description and to the previous scheme representing the behaviour of the motor in relation to control and protection devices, the typical solution offered by ABB foresees the use and combination of magnetic only circuit-breaker – contactor – external thermal relay. Hereunder are some elements which characterize the mentioned components:

- magnetic only circuit-breaker
It allows to have a magnetic trip threshold I3 (up to 13 times In) higher than that available on a thermomagnetic circuit-breaker which has a standardized value of 10 x In. This allows to face better the possible problems linked to the particularly high current which the motor draws during the first instants of its starting phase without necessarily

turn to bigger circuit-breaker frame sizes. To this purpose the molded case circuit-breakers series Tmax or the circuit-breakers defined "miniature circuit-breaker", such as the MO325 shown in Figure 12, can be used.

Figure 12: Magnetic only circuit-breakers

- contactor

it is the device (see Figure 13) intended to carry out the switch on/switch off operations of the motor under normal conditions and also to disconnect the motor from the supply network in case of overcurrents detected by the thermal relay which commands the tripping. Besides, the contactor shall be chosen so as to be suitable to carry the rated current of the motor with reference to the category AC-3. The contactor carrying out motor operations allows to realize a number of operations much higher than those which the circuit-breaker could perform.

Typically, the contactor allows an electrical life higher than that guaranteed by a circuit-breaker. The electrical life of a contactor can be determined with the aid of the curves made available by the manufacturer and being valid for specified conditions; as illustrated in the following example, taking into consideration a three-phase squirrel-cage asynchronous motor which absorbs a current of 79A at 400Vac, it is possible to determine the number of possible operations (about 1.5 millions) from the graph of Figure 14, in correspondence to the curve of the contactor assumed to be used for starting (e.g. A110).

Figure 13: Contactor

Figure 14: Curves showing the electrical life for the category AC-3 – voltage <440V – ambient temperature <55°C
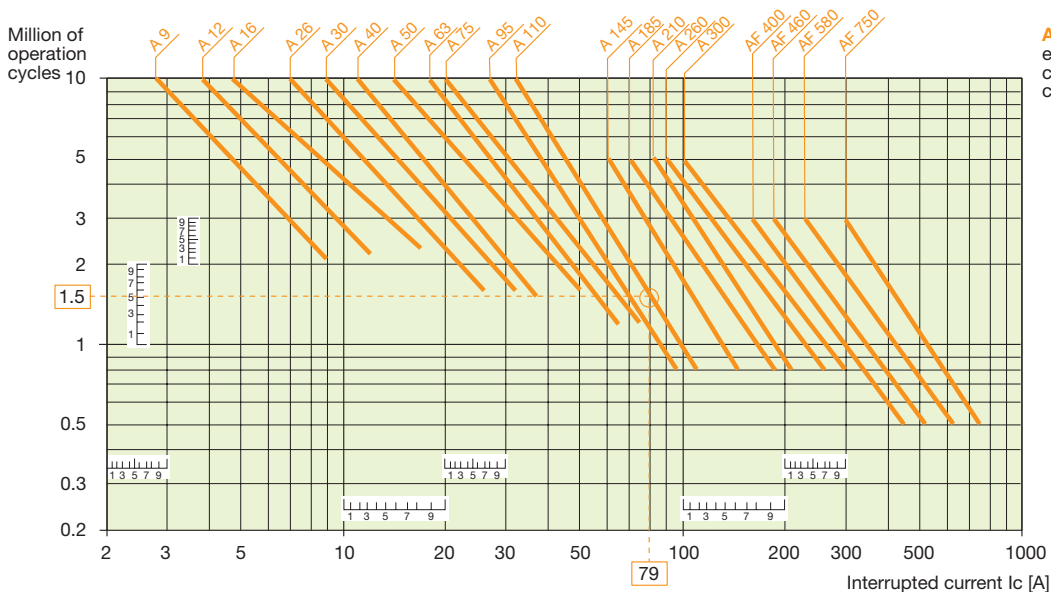
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-external thermal relay

it is the device intended to realize the protection against motor overload and it has usually the function of commanding the opening of the contactor for those overcurrents lower than the magnetic trip threshold of the circuit-breaker.

It is a simple external (that is not mounted on the circuit-breaker, which is the magnetic type only) bimetal or electronic relay carrying out the above mentioned protection function and therefore with tripping and protection curves (for example temperature-compensated and sensitive to the lack of phase) complying with the Std. IEC 60947-4-1.

Also more complex devices can be used, which offer more advanced protection and monitoring functions for remote control too, such as, for example, Insum or UMC. An overview of the different typologies of apparatus is given in Figure 15.

Figure 15: Thermal relays

The combination of the three apparatus cabled as shown in Figure 16 and realized making reference to the concepts previously illustrated allows to obtain a compact solution fully complying with the main requirements regarding the overall dimensions and taking into account the needs of the machine during starting (inrush and starting currents), operating (high number of operations) and protection while running

Figure 16: Compactness of the solution with magnetic only circuit-breaker, contactor and thermal relay

The above configuration allows to cover the most part of the applications requiring the control of a three-phase asynchronous motor; however, different configurations are possible and available, for example:

- solution with switch-disconnector and fuse

the combination of these two devices, see Figure 17, is used to replace a magnetic only circuit-breaker.

Figure 17: Switch-disconnectors with fuses

- solution with a circuit-breaker having both therm–al as well as magnetic protection

this solution, which provides thermal and magnetic protection integrated on the circuit-breaker, is realized with the moulded-case circuit-breakers of Tmax series equipped with the electronic relay type PR222MP dedicated to motor starting. In this way it is possible to realize magnetic protection and thermal protection sensitive to phase loss and temperature-compensated through a single device (then, by combining only the contactor intended for the operations, an extremely compact starter can be obtained). Instead, the thermomagnetic protection which is obtained by means of standard distribution circuit-breakers and relays presents a typical protection curve not typically suitable for motor protection when considered from the thermal and magnetic point of view. As explained afterwards, the relay named "motor protection" allows in addition the implementation of dedicated protections to manage anomalous situations which might present with motors.

A more simplified version of PR222MP which performs the pure and simple thermal and magnetic protection functions is the relay type PR221MP mounted on Tmax circuit-breakers type T2; thanks to this solution, also motors with relatively small rated currents can be protected by molded-case circuit-breakers with the thermal (complying with the classes 3E – 5E – 10E - 20E) and magnetic protection implemented on board the circuit-breaker.

The same solution, integrated in the circuit-breaker, as simple magnetic protection and thermal protection sensitive to phase loss and temperature-compensated, can be obtained also by using the thermomagnetic miniature circuit-breakers called "manual motor starters", such as for example MS325.

With these circuit-breakers, in the coordination, the external thermal protection shall be no longer used whereas the contactor shall still be present.

Figure 18 points out the compactness of the solution which can be obtained by using a moulded-case circuit-breaker equipped with a PR222MP or a thermomagnetic circuit-breaker directly connected to the switching device only.

Figure 18: Realization of functional and compact solutions

Here are illustrated the protection functions which characterize the relay PR222MP in addition to the classic protections against overload (L) - implemented through a thermal model simulating copper and iron temperature-rises inside motors – and against short-circuit (I).

Protection against rotor block (R):
it protects the motor against a possible rotor block during normal operation. This function is able to distinguish whether the fault occurs during start-up, that is when it is inhibited during the starting time, or whether the fault occurs during normal running, i.e. when it is active. As regards time this function can be set from 1s to 10s and as regards current from 3 to 10 times the current I1 and intervenes when at least one of the phase currents exceeds the set values. This protection can be excluded.

Protection against unbalanced phase (U):
it intervenes when the value of one or two currents drops below the setting and remains below it for longer than the set time. The manual setting has fixed current threshold equal to 0.4 x I1 and fixed time threshold of 4s, whereas in case of electronic setting the current threshold is adjustable from 0.4 to 0.9 times I1 and the time threshold from 1s to 10s. This function can be excluded.

Protection by means of a PTC sensor:
against the temperatures exceeding those accepted for the motors.

The following diagram shows how the protection curve obtained using the relay type PR222MP is positioned on the time-current plane in comparison with the typical curve which schematizes the starting phase of the motor.
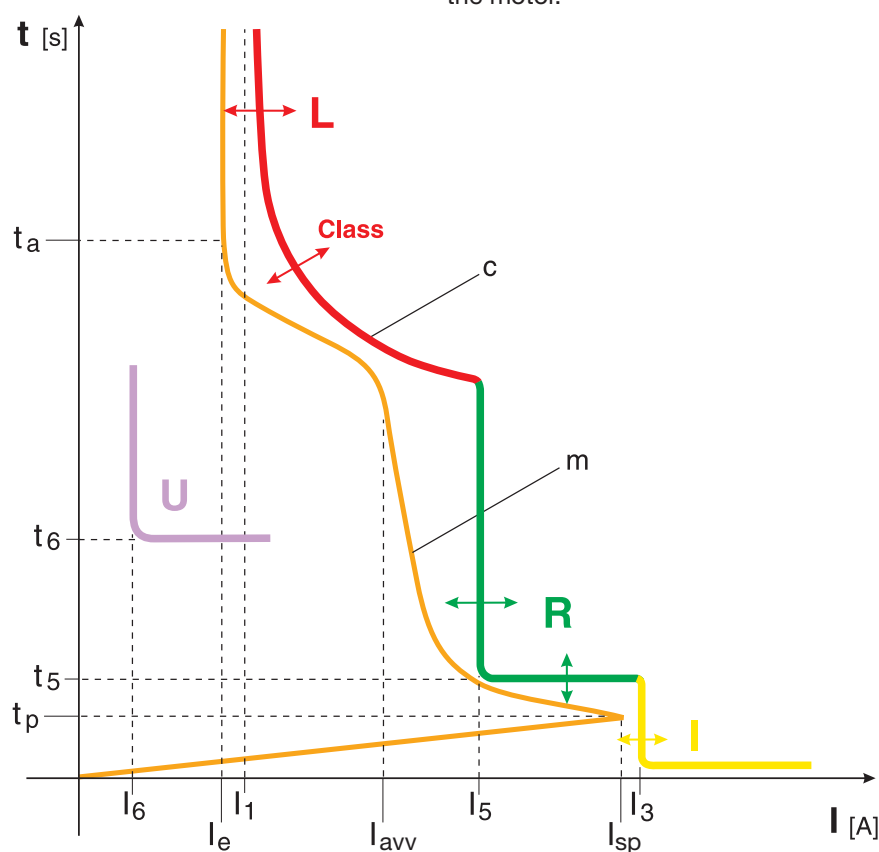
I_1 = function L trip current
I_3 = function I trip current
I_5 = function R trip current
t_5 = function R trip time
I_6 = function U trip current
t_6 = function U trip time
I_e = rated service current of the motor
I_{avv} = motor starting current
I_{sp} = peak value of the sub-transient starting current
t_a = motor starting time
t_p = duration of the sub-transient starting phase
m = typical motor starting curve
c = example of trip curve of a motor protection circuit-breaker with electronic release
The different curves of the functions, with numerous threshold and time settings, allow an overall trip curve to be drawn which is really close to the motor starting curve, thereby optimising its protection.

- solution with air circuit-breaker (Emax series)

all the above mentioned functions performed by three different devices are assigned to the circuit-breaker only. This solution is to be used in particular cases: for example when a high number of operations is not required, which is typical of big size motors (just as an indication with power output exceeding 300kW), or to satisfy particular specification requirements.

- solution with soft starters

as a control component of the motor, this device bases its functioning on power semiconductors, also called tyristors, which allow to control and slowly increase the voltage applied to the motor, making it start slowly and limiting the starting currents.

Once the ramp time has elapsed, the tyristors are usually by-passed with a contactor, and the line is directly connected to the motor. This means that tyristors do not remain constantly in function, thus reducing any possible problem due to temperature-rise. Figure 19 shows some types of soft starters.

Figure 19: Soft Starters

4 ABB equipment and solutions for co-ordination

4.1.2 Special applications

- Protection against earth fault

In addition to the classic thermomagnetic protection functions, a residual current protection on the motor is often required, so that a possible earth leakage can be detected in due time to protect the motor before the fault may evolve and generate dangerous conditions with overheating and short-circuits. Thus, damages on the machine are minimized.

This protection can be implemented through an external residual current device which detects the currents in the plant by means of a toroidal transformer; if compared with the use of a pure residual current device, this allows to get rid of the verification of its protection against short-circuit performed by the circuit-breaker. The residual current device usually acts through a changeover contact on the contactor, which is the device physically tripping the fault circuit; the action of the residual current device could also command the tripping coil of the circuit-breaker and consequently assign the task of breaking the fault circuit to this latter.

- Speed control

For particular project requirements or for applications in the automation field, where a sophisticated motor control becomes necessary, it is possible to use variable-speed drivers (inverters) which allow to modulate the power supply frequency of the motor as a function of the load (example: in order to control the load of a pump without resorting to a classic system which uses reducing valves). Together with control and management of the electrical and mechanical parameters of the application, the use of inverters allows to obtain also energy saving from 20% to 50%. ABB can supply a wide range of frequency converters for industrial applications. These systems are characterized by semiconductors and converters which are in the forefront of technology and able to offer highy reliable systems, together with high efficiency and limited maintenance requirements.

4.1.3 ABB equipment for co-ordination

Here is a schema that sums up some of the main characteristics of the devices[1] included in the coordination tables for classic starting drown up by ABB SACE to satisfy the most common and typical requirements. For a more complete and detailed overview on the various devices reference must be made to the information given in the relevant technical catalogues.

Circuit-breakers

The circuit-breakers for motor protection can belong both to the family of miniature circuit-breakers (MO… MS…), as well as to that of moulded-case circuit-breakers (Tmax), the main characteristics of which are summarized respectively in Tables 3 and 4. They can be of thermomagnetic or classic magnetic type or with electronic relay, typically in four-pole version. As regards moulded-case circuit-breakers the sizes of the relevant relays are reported in Table 5.

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[1] The products here described are those ones available on the market at the moment of issue of this document. For further future updating of the product range reference shall be made to the product catalogues.

Table 3: Types of miniature circuit-breakers, MO series – rated current In – breaking capacity Icu at 400Vac. Types of manual motor starters, MS series – rated current In – breaking capcity Icu at 400Vac – starting class

Magnetic only circuit-breaker "mcb"		
Type	**In**	**Icu @ 400Vac**
MO325	0.4 - 25	100
MO450	16 - 50	50
MO495	40 - 100	50
MO496	16 - 100	100

Thermomagnetic circuit-breaker "mms"			
Type	**In**	**Icu @ 400Vac**	**class**
MS116	0.16 - 16	50*	10
MS225	0.16 - 25	50**	10
MS325	0.16 - 25	100***	10
MS450	16 - 50	50	10
MS451	16 - 50	50	20
MS495	40 - 100	50	10
MS496	40 - 100	100	20
MS497	16 - 100	100	10

* In12 Icu=25kA In16 Icu=16kA
** In=9A Icu=40kA ; In=12.5A and 16A Icu=30kA ; In=20A and 25A Icu=10kA
*** In=12.5A Icu=75kA ; In=16A Icu=60kA ; In=20A Icu=55kA ; In=25A Icu=50kA

Table 4: Moulded-case circuit-breakers series Tmax – available versions, breaking capacities and coupling with motor protection relays

|	Moulded-case circuit-breakers Tmax series																						
	T2				T3		T4					T5					T6				T7			
Iu	160				250		250 / 320					400 / 630					630 / 800				800 / 1000 / 1250			
Version	N	S	H	L	N	S	N	S	H	L	V	N	S	H	L	V	N	S	H	L	S	H	L	V
415Vac	36	50	70	85	36	50	36	50	70	120	200	36	50	70	120	200	36	50	70	100	50	70	120	150
440Vac	30	45	55	75	25	40	30	40	65	100	180	30	40	65	100	180	30	45	50	80	50	65	100	130
500Vac	25	30	36	50	20	30	25	30	50	85	150	25	30	50	85	150	25	35	50	65	40	50	85	100
690Vac	6	7	8	10	5	8	20	25	40	70	80	20	25	40	70	80	20	22	25	30	30	42	50	60
MF		■																						
MA		■				■			■															
PR221DS-I		■							■					■					■					
PR231DS-I																							■	
PR222MP									■					■					■					
PR221MP		■																						

Table 5: Moulded-case circuit-breakers series Tmax – availability of relay sizes – relative value for magnetic protection

T2…160												
Fixed magnetic only release MF	**In**	1	1,6	2	2,5	3,2	4	5	6,5	8,5	11	12,5
	I3=13 x In	13	21	26	33	42	52	65	84	110	145	163
Adjustable magnetic only release MA	In	20	32	52	80	100						
	I3=(6…12) x In	120…240	192…384	314…624	480…960	600…1200						
Electronic release PR221MP L-I function*	In	63	100	160								

* I1=(0.65…1) x In I3= (2.5..17.5) x In

T3…250					
Adjustable magnetic only release MA	**In**	100	125	160	200
	I3=(6..12) x In	600…1200	750…1500	960…1920	1200…2400

T4…250								
Adjustable magnetic only release MA	In	10	25	52	80	100	125	160	200
	I3=(6..14) x In	60…140	150…350	314…728	480…1120	600…1400	750…1750	960…2240	1200…2800

Electronic release magnetic only PR221DS-I*		In				
T2…160	10	25	63	100	160
T4…250	100	160	250		
T4…320	320				
T5…400	320	400			
T5…630	630				
T6…630	630				
T6…800	800				

* I3= (1..10) x In

Electronic release magnetic only PR231DS-I*	**In**
T7…800	800
T7…1000	1000
T7…1250	1250

* I3= (1..12) x In

Electronic release PR222MP*	**In**		
T4…250	100	160	200
T5…400	320	400	
T6…800	630		

* I1=(0.4…1) x In I3= (6..13) x In ; availability of dedicated protection functions as R U

Contactors

ABB offers different types of contactors, but the most used ones for the control and switching of three-phase asynchronous motors are the three-pole contactors belonging to the series identified by the letter "A" or "AF" and characterized by types from A9 up to AF1650, the main characteristics of which are indicated in Table 6. They are three-pole apparatus with a.c. control circuit and laminated magnetic core for type "A" contactors or a.c. or d.c. control circuit with wide voltage range electronic coil for type "AF" contactors. They offer a wide range of accessories with auxiliary contacts to be both side- and front-mounted.

Relays for thermal protection

ABB offers different types of thermal overload relays, from the classic bimetal ones, identified by the ab-

breviation "TA...DU…" or "TA...SU…", to the electronic ones, identified by the abbreviation "E...DU..", the main characteristics of which are summarized in Table 7. These relays - available in three-pole version - are sensitive to the lack of phase, are temperature-compensated, offer the possibility of automatic reset and can be equipped with auxiliary contacts.

More sophisticated units are also available, such as INSUM or UMC, which guarantee more complete protection functions in comparison with that of a conventional thermal relay: they offer global better efficiency thanks to bigger monitored values, wide setting range, possibility to select the protection more suitable for the different starting conditions, low absorption and high tripping precision and possibility of being integrated in a supervision and control system.

Table 6: Contactors of the series A and AF – main electrical characteristics

	A9	A12	A16	A26	A30	A40	A45	A50	A63	A75	A95	A110	A145	A185	A210	A260	A300	AF400	AF460	AF580	AF750	AF1350	AF1650
Max rated oper. voltage Vmax	690Vac						1000Vac								690Vac								
Max rated oper. cur. Ie 415Vac*	9	12	17	26	32	37	37	50	65	75	96	110	145	185	210	260	300	400	460	580	750	860	1050
Max rated oper. cur. Ie 690Vac*	7	9	10	17	21	25	25	35	43	46	65	82	120	170	210	220	280	350	400	500	650	800	950
Icw 1sec**	250	280	300	400	600	600	1000	1000	1000	1000	1320	1320	1800	2000	2500	3500	3500	4600	4600	7000	7000	10000	12000
Icw 10sec**	100	120	140	210	400	400	650	650	650	650	800	800	1200	1500	1700	2400	2400	4400	4400	6400	6400	8000	10000
Icw 30sec**	60	70	80	110	225	225	370	370	370	370	500	500	800	1000	1200	1500	1500	3100	3100	4500	4500	6000	7500
Icw 60sec**	50	55	60	90	150	150	250	250	250	250	350	350	600	800	1000	1100	1100	2500	2500	3500	3500	4500	5500
Pdl 440Vac***	250	250	250	420	820	820	820	1300	1300	1300	1160	1160	1500	2000	2300	2600	3000	4000	5000	6000	7500	10000	12000
Pdl 690Vac***	90	90	90	170	340	340	490	630	630	630	800	800	1200	1600	2000	2400	2500	3500	4500	5000	7000	-	-

*) utilization category AC-3 with Tamb< 55°C
**) referred to Tamb of 40°C starting from cold condition
***) cosφ=0.45 cosφ=0.35 for Ie>100A

Table 7: Thermal bimetal relays and thermal electronic relays – setting range and coupling capabilities with the contactors

	TA25DU..*	TA42DU..	TA75DU..	TA80DU..	TA110DU..	TA200DU..	TA450DU..	TA450SU..
Class	10A							30
	20				-	-	-	-
Smaller setting range* [A]	0.1-0.16	18-25	18-25	29-42	65-90	66-90	130-185	40-60
Greater setting range [A]	24-32	29-42	60-80	60-80	80-110	150-200	220-315	220-310
Direct mounting with	A9…A40	A30,A40	A50…A75		A95,A110	A145,A185	A210,A300	

*) In class 20 starting from TA25DU1.8 type, setting range 1.3A to 1.8A

	E16DU	E45DU **	E80DU **	E140DU **	E200DU	E320DU	E500DU	E800DU	E1250DU
Class	10-20-30 *	10 o 10-20-30			10-20-30***				
Smaller setting range* [A]	0.1-0.32	9-30	27-80	50-140	60-200	100-320	150-500	250-800	375-1250
Greater setting range [A]	5.7-18.9	15-45							
Direct mounting with	A9…A16	A26…A40	A50…A75	A95,A110	A145,A185	A210…A300	AF400,AF460	AF580,AF750	AF1350,AF1650

*) each starting class is identified by a dedicated ordering code
**) device with starting class 10 or with adjustable class (10-20-30) have different ordering codes
***) adjustable trip class available on the same device

Switch-disconnectors with fuses

Switch-disconnectors with fuses used as protection and switching devices, as shown in Table 8, can be divided into the series OS, which includes sizes from 32A to 200A, and OESA, with sizes from 200A to 800A. They are combined with a fuse used as element of protection against short-circuit. They fulfill the main requirements in terms of safety, ease of installation and functional practicality.

Soft starters

ABB offers three different types of soft starters to meet the requirements of each customer for applications ranging from 3A to 1050A at 400Vac with line connection mode. The main characteristics of the different versions are illustrated in the following summary and in Table 9:

- PSR3…45: range of soft starters for motors with rated currents from 3A up to 45A at 400Vac with line connection mode. It is extremely compact and easy to mount both clamped on a DIN rail as well as screwed on a switchboard panel. It offers the possibility of coordination with manual motor starters MS type and has a flexible communication system. It replaces the series PSS3…25.

- PSS18…300: range of soft starters for motors with rated currents from 18A to 300A at 400Vac with line connection mode, which offer a solution adaptable to every type of application thanks to its flexibility and reliability also under the heaviest working conditions. This soft starter series gives the possibility to exploit the same device to obtain either an in-line connection or a delta connection, i.e. in a Y/Δ starting the same device can be connected inside the delta circuit, so that the current affecting it results to be reduced of about 42%. This possibility can be verified in the code identifying the type of apparatus; e.g. the code PSS60/105 indicates that the maximum controllable current of the motor for an in-line connection results to be 60A, whereas for a delta connection the controlled motor can have a maximum current of 105A.

- PST30…300 and PSTB370….1050: new range of soft starters for motors with rated currents from 30A to 1050A at 400Vac with line connection mode, offering various advanced integrated functions (e.g.; protection against rotor block, unbalanced phase, phase reversal). The same unit gives the possibility to realize an in-line or a delta connection (in this lay-out the possible maximum current for the motor results to be 1810A), it has a very flexible communication system and easy interfaceability through a simple LCD display.

Table 8: Switch-disconnectors with fuses - choice parameters

		OS32	OS50	OS63	OS100	OS125	OS160	OS200	OESA200	OESA250	OESA315	OESA400	OESA630	OESA800
Rated current* [A]		32	50	63**	100**	125**	160**	160**	200	250	315	400	630	720
power*** [W]	**415Vac**	15	22	30	55	55	75	75	110	132	180	200	355	400
	690Vac	22	37	55	90	110	132	132	160	200	250	355	560	710

* Rated operational current in AC-23A up to 690Vac
** For utilizzation category B: not frequent service
*** Rated operational power: suitable asyncronus power motor

Table 9: Soft starters – general characteristics

	PSR 3	PSR 6	PSR 9	PSR 12	PSR 16	PSR 25	PSR 30	PSR 37	PSR 45
Rated current*	3,9	6,8	9	12	16	25	30	37	45
Line contactor	A9	A9	A9	A12	A16	A26	A30	A40	A50
By-pass contactor	Built-in	Built-in	Built-in	Built-in	Built-in	Built-in	Built-in	Built-in	Built-in
Thermal protection	TA25DU							TA42DU	TA75DU

* SS in Line connection mode. V=400V

	PSS18/30	PSS30/52	PSS37/64	PSS44/76	PSS50/85	PSS60/105	PSS72/124	PSS85/147	PSS105/181	PSS142/245	PSS175/300	PSS250/430	PSS300/515
Rated current*	18	30	37	44	50	60	72	85	105	142	175	250	300
Rated current*	30	52	64	76	85	105	124	147	181	245	300	430	515
Line contactor	A26	A30	A40	A50	A50	A63	A75	A95	A110	A145	A185	A260	A300
By-pass contactor	A9	A16	A26	A26	A30	A40	A50	A50	A63	A75	A110	A145	A210
Thermal protection	TA25DU	TA42DU	TA75DU					TA110DU		TA200DU		TA450DU	

* SS in Line connection mode. V=400V
** SS in Delta connection mode. V=400V

	PST30	PST37	PST44	PST50	PST60	PST72	PST85	PST105	PST142	PST175	PST210	PST250	PST300
Rated current*	30	37	44	50	60	72	85	105	142	175	210	250	300
Rated current*	52	64	76	85	105	124	147	181	245	300	360	430	515
Line contactor	A30	A40	A50	A50	A63	A75	A95	A110	A145	A185	A210	A260	A300
By-pass contactor	A16	A26	A26	A30	A40	A50	A50	A63	A95	A110	A145	A145	A210
Thermal protection	Overload protectionwith the motor temperature simulation based on the measurements of the flowing current; adjustable starting current for 10-10A-20-30 class												

* SS in Line connection mode. V=400V
** SS in Delta connection mode. V=400V

	PSTB370	PSTB470	PSTB570	PSTB720	PSTB840	PSTB1050
Rated current*	370	470	570	720	840	1050
Rated current*	640	814	987	1247	1455	1810
Line contactor	AF400	AF460	AF580	AF750	-	-
By-pass contactor	integrato	integrato	integrato	integrato	integrato	integrato
Thermal protection	Overload protectionwith the motor temperature simulation based on the measurements of the flowing current; adjustable starting current for 10-10A-20-30 class					

* SS in Line connection mode. V=400V
** SS in Delta connection mode. V=400V

Frequency converters

Here is a quick and concise survey of some of the available frequency converters; however, reference must be made to the specific documents for a thorough analysis of the availability and of the technical characteristics of these products.

The frequeny converters of the series "machinery drives" from ACS50 up to ACS350 (through types ACS55 - ACS100 – ACS140 – ACS150) or of the series "standard drives" with ACS550 or ACH550 intended for applications in heating, ventilation and air conditioning systems (HVAC) represent the ideal choice for the situations which require drives easily installed, put into service and used, suitable for accurate speed and torque control of squirrel-cage motors with powers ranging from 0.55kW and 355kW. These converters - based on PWM technology - can be used in a wide field of industrial sectors, both for the simplest applications with quadratic torque (pumps and fans) as well as to obtain more sophisticated dynamics.

The frequency converters of the series "industrial drives" with ACS800 - based on DTC technology (Direct Torque Control) - offer a quick reply to the variations of the motor load in order to guarantee a more constant functioning. ACS 800 devices, equipped with EMC filters and inductances already built-in the drive, offer better performances and a greater ease of putting into service and programming, thanks to which these drives result suitable for a wide application range. The series of ACS800 converters allow the control of motors with a wide range of powers from 0.55 kW to 5600 kW and supply voltages from 380 V to 690 V.

4.2 How to read ABB motor coordination tables

For the different possible suggested solutions and for the different starting methods (DOL or Y/Δ - normal or heavy - type 2) ABB SACE makes available some coordination tables which derive from experimental tests and, whenever possible, from the extension of the obtained results. This support helps the customers in the choice of the different devices so that they result coordinated, protected and suitable to motor operation and protection. The tables are referred to the most common voltages and short-circuit currents of a plant (415Vac, 440Vac, 500Vac, 690Vac, 35kA, 50kA, 65KA and over).

The most commonly used tables meeting the typical requirements of customers as regards motor starting are collected in the document "Coordination tables", code 1SDC007004D0206 dated March 2008 (see hereunder

a picture of the cover), where it is possible to find the necessary reference for back-up and discrimination coordination between ABB circuit-breakers at 415Vac.
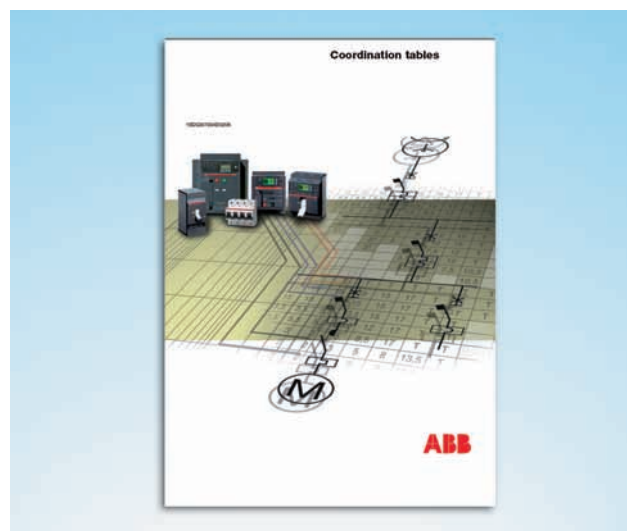
A more complete overview of the different solutions for motor coordination can be found at the web address http://www.abb.com/lowvoltage following the path "Support - Online Product Selection Tools - Coordination Tables for Motor Protection" up to the following page:

and then, through the entry "selection", to the search form for the coordination of one's own interest:

Now let's go into the details of the structure of these table by giving an example of how to read them, illustrating the meaning of the different fields (identified by numbers from 1 to 6) and of the useful information which can be deduced from them and which characterize the suggested solution, but are also common to all other tables. In the reading example, reference is made to Tables 10 and 11 here shown as they can be found in the above mentioned document "Coordination tables".

Table 10: *Motor coordination table, DOL starting – reading example*

DOL @ 400/415 V - 50 kA -Type 2 - Normal starting ①

Motor		MCCB		Contactor	Thermal release			Group
Rated power Pe [kW]	Rated current Ie [A]	Type	Setting of the magnetic release [A]	Type	Type	Current setting min [A]	max [A]	I max [A]
0,37	1,1	T2S160 MF 1.6	21	A9	TA25DU1.4	1	1,4	1,4
0,55	1,5	T2S160 MF 1.6	21	A9	TA25DU1.8	1,3	1,8	1,6
0,75	1,9	T2S160 MF 2	26	A9	TA25DU2.4	1,7	2,4	2
1,1	2,8	T2S160 MF 3.2	42	A9	TA25DU4	2,8	4	3,2
1,5	3,5	T2S160 MF 4	52	A16	TA25DU5	3,5	5	4
2,2	5	T2S160 MF 5	65	A26	TA25DU6.5	4,5	6,5	5
3	6,6	T2S160 MF 8.5	110	A26	TA25DU8.5	6	8,5	8,5
4	8,6	T2S160 MF 11	145	A30	TA25DU11	7,5	11	11
5,5	11,5	T2S160 MF 12.5	163	A30	TA25DU14	10	14	12,5
7,5	15,2	T2S160 MA 20	210	A30	TA25DU19	13	19	19
11	22	T2S160 MA 32	288	A30	TA42DU25	18	25	25
15	28,5	T2S160 MA 52	392	A50	TA75DU42	29	42	42
18,5	36	T2S160 MA 52	469	A50	TA75DU52	36	52	50
22	42	T2S160 MA 52	547	A50	TA75DU52	36	52	50
30	56	T2S160 MA 80	840	A63	TA75DU80	60	80	65
37	68	T2S160 MA 80	960	A75	TA75DU80	60	80	75
45	83	T2S160 MA 100	1200	A95	TA110DU110	80	110	96
55	98	T3S250 MA 160	1440	A110	TA110DU110	80	110	110
75	135	T3S250 MA 200	1800	A145	TA200DU175	130	175	145
90	158	T3S250 MA 200	2400	A185	TA200DU200	150	200	185
110	193	T4S320 PR221-I In320	2720	A210	E320DU320	100	320	210
132	232	T5S400 PR221-I In400	3200	A260	E320DU320	100	320	260
160	282	T5S400 PR221-I In400	4000	A300	E320DU320	100	320	300
200	349	T5S630 PR221-I In630	5040	AF400	E500DU500	150	500	400
250	430	T6S630 PR221-I In630	6300	AF460	E500DU500	150	500	430
290	520	T6S800 PR221-I In800	7200	AF580	E800DU800	250	800	580
315	545	T6S800 PR221-I In800	8000	AF580	E800DU800	250	800	580
355	610	T6S800 PR221-I In800	8000	AF750	E800DU800	250	800	750
②		③	③a	④	⑤	⑤a	⑤b	⑥

① defines the validity of the table in terms of installation data and starting type; the information given is:
- type of starting: direct on line (DOL)
- electrical characteristics of the plant for which the coordination is valid (400V/415V voltage, 50kA short-circuit current)
- coordination characteristics: (type 2 – normal starting)

② defines the characteristics of the motor in terms of power and rated current, making reference to the standard data of ABB motors

③ identifies the type of protection device against short-circuit and gives information about:
- family and frame size (T2...160 or T5...400)
- version referred to the electrical data of the plant (version "S" which at 400V / 415V has a breaking capacity suitable to the 50kA of the plant)
- type and rated current of the protection device against short-circuit (...MF11 - ...MA100 - ...PR221-I In400); the field ③a suggests the settings for the magnetic trip threshold

④ defines the contactor type by name (A95 – AF750)

⑤ dentifies the typology of the protection device against overload, and includes information about :
- typology (either bi-metal type TA25...- TA200...or electronic type E320...)
- compliance with normal starting characteristics (...DU for bi-metal releases or with adjustable trip class for electronic relays)
- maximum non-tripping current (....2.4 - ...175 - ...320). By putting together the different parts the complete name of the thermal protection device is obtained (TA25DU2.4 – TA200DU175 – E320DU320); the fields ⑤a and ⑤b show the minimum and maximum values of the possible current settings

⑥ defines the reference current for the choice of the cable to be used in the coordination complying with the Std. IEC 60947-4-1.

Table 11: Motor coordination table, Y/Δ starting – reading example

Star-delta - Type 2 @ 400/415 V - 35 kA - 50/60 Hz ①

Motor		MCCB			Contactor			Thermal release	
Pe [kW]	Ie [A]	type	Im [A]	line type	delta type	star type	type	[A]
18,5	36	T2N160 MA52	469	A50	A50	A26	TA75DU25	18-25
22	42	T2N160 MA52	547	A50	A50	A26	TA75DU32	22-32
30	56	T2N160 MA80	720	A63	A63	A30	TA75DU42	29-42
37	68	T2N160 MA80	840	A75	A75	A30	TA75DU52	36-52
45	83	T2N160 MA100	1050	A75	A75	A30	TA75DU63	45-63
55	98	T2N160 MA100	1200	A75	A75	A40	TA75DU63	45-63
75	135	T3N250 MA160	1700	A95	A95	A75	TA110DU90	66-90
90	158	T3N250 MA200	2000	A110	A110	A95	TA110DU110	80-110
110	193	T3N250 MA200	2400	A145	A145	A95	TA200DU135	100-135
132	232	T4N320 PR221-I In320	2880	A145	A145	A110	E200DU200	60-200
160	282	T5N400 PR221-I In400	3600	A185	A185	A145	E200DU200	60-200
200	349	T5N630 PR221-I In630	4410	A210	A210	A185	E320DU320	100-320
250	430	T5N630 PR221-I In630	5670	A260	A260	A210	E320DU320	100-320
290	520	T6N630 PR221-I In630	6300	AF400	AF400	A260	E500DU500	150-500
315	545	T6N800 PR221-I In800	7200	AF400	AF400	A260	E500DU500	150-500
355	610	T6N800 PR221-I In800	8000	AF400	AF400	A260	E500DU500	150-500

② ③ ③a ④ ⑤ ⑤a

① defines the validity of the table in terms of installation data and starting type; the information given is:
- type of starting: star/delta Y/Δ
- electrical characteristics of the plant for which the coordination is valid (400V/415V voltage, 35kA short-circuit current)
- coordination characteristics: (type 2)
The fields ② ③ ③a give the same information already given for Table 10.

④ gives some indications regarding contactors; it is possibile to verify how line contactors and delta contactors are identical; as regards starting, it must be remembered that these contactors do not see the full rated current of the motor (but the current reduced by 1.73 times), even if often the size of the apparatus is conditioned by the coordination with the protection device against short-circuit. The third contactor is that of the star phase: it sees the motor current diminished by 0.33 times, but, owing to the pe culiarity of the star connection, the protection against short-circuit is not required and consequently the size of this contactor can be reduced.

⑤ identifies the typology of the protection device against overload, the information about the type of relay is the same already given; only one remark is necessary about the setting field ⑤a of the rated current which must be fit for the motor current reduced by 1.73 times in compliance with the current seen by the thermal release.

5 Identity card of an asynchronous motor: main parameters

A motor is characterized by different electrical and constructional parameters which identify its correct application field. The whole of all these parameters constitutes the rating of the machine and is reported on a nameplate positioned on the motor itself.

Hereunder is a short description of the main parameters included in the nameplate rating with simple information about the electrical parameters which are the most known ones and those more easily explained, whereas particular attention is paid to those which are less common and refer to working and environmental conditions.

The electrical and mechanical parameters which constitute the rating of a motor identify its rated performances and are:

- the power in kW, which represents the rated mechanical power made available by the shaft; in many countries it is common to express the available mechanical power of the motor shaft also in horsepower: 1hp (UK and US horsepower) is equivalent to 745.7W, 1hp (metric horsepower) is equivalent to 736W)
- the supply voltage of the motor, e.g. 230VΔ, 400VY.

With a three-phase distribution system at 400V (phase-to-neutral voltage 230V, phase-to-phase voltage 400V) the motor can be only star-connected. In case of delta connection the motor windings would be subject to 400V, when they have been dimensioned for 230V; as a consequence, the considered motor does not result suitable for connection to the network in the example with delta-connected windings.

To summarize: a motor having double operating voltage could be used in the following configurations

- windings with delta-connection only supplied at the lower voltage;
- windings with star-connection only supplied at the higher voltage);
- windings with Y/Δ connection (with six conductors to the motor) with Y configuration at motor starting and Δ configuration during motor running, possible when the lower value of the rated voltage of the motor coincides with the voltage of the supply;
- the rated current linked to the power and to the voltage through the rated efficiency parameters "η" and the power factor "$\cos\varphi$";
- the rotation speed in rpm linked to the frequency (50Hz or 60Hz) and to the number of poles.

The other information on the nameplate, with a meaning less clear or not easily recognizable, are referred to:

- duty type: to be declared by the purchaser of the motor (classifications given by the Std. IEC 60034-1 *"Rotating electrical machines. Part 1: "Rating and performance"*) and necessary to define the rating that the motor must guarantee according to the application type. Where a duty is not declared, the manufacturer shall assume that duty type S1 (continuous running duty) applies. For a thorough analysis on duty types, please refer to Annex D;

- degree of protection (IP code classification): it indicates the degree of protection provided by the enclosures of electrical rotating machines (prescriptions and classification complying with the Std. IEC 60034-5 Part 5: *"Degrees of protection provided by the integral design of rotating electrical machines"*). The first characteristic numeral indicates the degree of protection provided by the enclosure both to persons as well as to the parts of the machine inside the enclosure. It gives information about protection against approach to or contacts with live parts and against contact with moving parts inside the enclosure and protection of the machine against ingress of solid foreign objects.
  The second characteristic numeral indicates the degree of protection provided by the enclosure with respect to harmful effects due to ingress of water.

- thermal class: it indicates the temperature limits for motor windings. It is expressed through insulation classes identified by letters, to which the maximum permitted temperature for the windings is associated as represented in Table 12. Systems with insulation class F are often used; for them a temperature rise referred to thermal class B is allowed, which guarantees a margin of safety on the insulation life.

Table 12: References for thermal class and relevant temperature

Thermal class	Temperature class
A	105
E	120
B	130
F	155
H	180

Other codes which allow to go further into details on motor typology, but which result to be quite complex to intepret and relevant to problems not closely connected to the purpose of this technical paper may be:

- IC code: it is a designation relevant to the methods of cooling and is formed by numerals and letters representing the circuit arrangement, the coolant and the methods of movement of the coolant itself. For further details please refer to the Std. IEC 60034-6 *"Rotating electrical machines. Part 6: Methods of cooling"*.

- IM code: it is a designation relevant to the classifications of types of constructions (arrangement of machine components with regard to fixings, bearing arrangement and shaft extensions) and mounting arrangements (orientation on site of the machine as the whole with regard to shaft alignment and position of fixings) of rotating electrical machines. For further details please refer to the Std. IEC 60034-7 *"Rotating electrical machines. Part 7: Classification of types of constructions and mounting arrangements (IM Code)"*.

Annex A: Theory of three-phase asynchronous motors

In this Annex, without going into the details of a precise theoretical treatment, the main concepts regarding the operating principle of asynchronous motors are illustrated.

Asynchronous motors are a type of alternating current electric motor in which the rotation frequency results to be not equal to, but lower than the network frequency; in other words, the two frequencies are not "synchronous", from which the origin of the name.

Due to the electrical supply of the stator circuit, a rotational magnetic field is created with a speed (synchronous speed n_0) related to the supply network frequency. The rotor, closed in short-circuit and subject to the stator magnetic field, is seat of an induced electromotive force; this force generates currents which produce a driving torque inducing the rotation of the rotor to counterbalance the cause which has generated the phenomenon (Lenz's law). The rotor accelerates, ideally tending to the synchronous speed, the driving torque developed is zero and thus an instability condition for the motor is created. However, in practice, the rotor reaches a lower speed (concept of slip as difference between the speed of the stator magnetic field and that of the rotor speed) such that with no load (i.e. without an external load connected to the motor shaft) the driving torque equals the frictional and ventilation torques, whereas at full load the driving torque equals the sum of the previously mentioned torques plus the braking torque applied to the shaft.

As already said, the speed at which the motor does not produce torque is called synchronous speed. It is related to the supply frequency and to the number of pole pairs by the following formula:

$$n_0 = \frac{60 \times f}{p} \text{ where}$$

n_0 is the synchronous speed expressed in rpm

f is the frequency of the supply system

p is the number of pole pairs

(the pole pairs are calculated dividing by two the pole number characteristic of the motor).

Through the above formula, for example taking into consideration a 8-pole motor (4 pole pairs) supplied at 50 Hz, it is possible to obtain the synchronous speed "n_0" which results:

$$n_0 = \frac{60 \times 50}{4} = 750 \text{ rpm.}$$

As an example, Table A1 reports the values of the synchronous speed calculated for motors with different number of poles at the two typical installation frequencies: 50Hz and 60Hz.

Table A1: *Synchronous speed of three-phase asynchronous motors as function of number of poles and frequency*

No. of poles	Synchronous speed n_0 50Hz	Synchronous speed n_0 60Hz
4	1500	1800
6	1000	1200
8	750	900
10	600	720

Under normal operating conditions the rotor (and consequently the motor shaft integral with it) has a lower speed. Also during no-load operation, that is when no loads are connected, the synchronous speed is not reached due to the inherent motor losses linked for example to the friction on the bearings which support the shaft and which therefore produce a small frictional torque.

From the difference between the rotation speed of the rotor "n" and the rotation speed of the stator magnetic field "n_0" it is possible to calculate a relative speed "ns", expressed as ns = n_0 - n and more properly termed "slip speed".

From this, the slip "s" is defined as $s = \dfrac{n_0 - n}{n_0}$

and can take all the values between the limit values 0 and 1 according to the operating conditions, and more precisely:

n = 0 rotor not running, therefore s = 1 (rotor locked)

n = n_0 rotor with synchronous speed, therefore s = 0 (in theory only).

Just as an indication, it is possible to consider that the slip which characterizes asynchronous motors operating at full load has values ranging from 3% to 7%, whereas lower values are typical of high power motors.

Always making reference to the motor of the previous example, characterized by a synchronous speed of 750 rpm, and assuming a slip of 4%, the actual speed under rated conditions becomes:

$$n = n_0 - (s \times n_0) = 750 - (0.04 \times 750) = 720 \text{ rpm}$$

As an example, considering the most common three-phase asynchronous motors with different pole number, Table A2 shows the typical values which efficiency, power factor and rated current can take at 415Vac for some output powers.

Table A2: Typical values of efficiency, power factor and rated current (referred to the supply voltage V_L = 415Vac)

Rated output power [kW]	Efficiency η at full load %			Power factor at full load Cosφ			Rated current [A] $Ie = \dfrac{P_e \times 1000}{\sqrt{3} \times V_L \times \cos\varphi \times \eta}$		
Pe	2P	4P	6P	2P	4P	6P	2P	4P	6P
75	94.8	95.0	94.9	0.87	0.82	0.80	127	134	137
90	95.1	95.2	95.3	0.89	0.83	0.83	148	158	158
110	95.1	95.3	95.3	0.85	0.83	0.83	189	193	193
132	95.7	95.5	95.4	0.87	0.84	0.84	221	229	229
160	96.1	96.0	95.5	0.89	0.85	0.83	260	273	281
200	96.3	96.2	95.8	0.90	0.85	0.83	321	340	350
250	96	96.2	96.0	0.88	0.85	0.80	412	425	453
315	96.4	96.4	96.0	0.89	0.85	0.82	511	535	557
355	96.5	96.6	96.5	0.87	0.85	0.84	588	601	609
400	96.8	96.6	96.5	0.88	0.86	0.84	653	670	687

Annex B: Calculation of the starting time as first approximation

The problems connected to motor starting operations are fundamentally linked to the type of motor which a determined motor operational torque "C_M" offers, to the starting modality and to the connected load which has a determined load torque "C_L". The necessary starting torque "Ca" can be expressed as $Ca = C_M - C_L$ and shall be well calibrated to prevent it from being either too low, so as starting is not too long and heavy - which causes risks of temperature rise for the motor - or from being too high on the joints or on the operating machines. A generic curve of the above mentioned quantities is shown in the Figure B1.

Figure B1: *Torque typical curves*
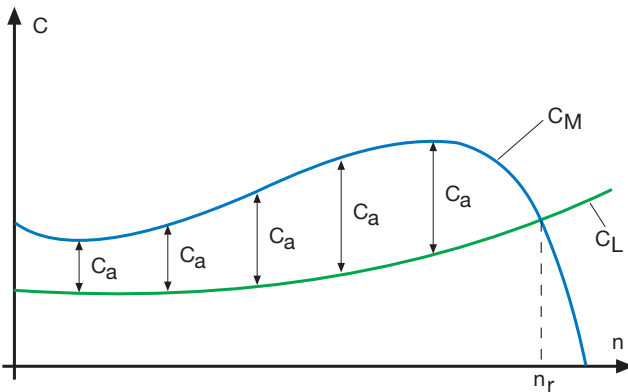
The concept of starting time "ta" can be associated to this concept of properly calibrated starting and can be evaluated making reference to concepts linked to the motion dynamics, but also by introducing simplifying hypotheses which allows, however, an evaluation with a good approximation.

It is possible to relate the acceleration torque, expressed as a difference between the motor operational torque and the load torque, to the moment of inertia of the motor "J_M", of the load "J_L" and to the motor angular speed, to obtain the following formula:

$$(C_M - C_L) = (J_M + J_L) \times \frac{d\omega}{dt}$$

where the expression of "$d\omega$" assumes the following form $d\omega = \frac{2 \times \pi \times dn}{60}$ and it is obtained by differentiating the well known expression for the motor angular speed

$$\omega = \frac{2 \times \pi \times n}{60}.$$

Through simple mathematical operations and applying the method of integral calculus, it is possible to make the unknown quantity "ta" explicit by the following expression:

$$ta = \int_0^{n_0} \frac{2 \times \pi \times (J_M + J_L)}{60} \times \frac{dn}{(C_M - C_L)}$$

To express the value of the acceleration torque, it is necessary to introduce some simplifications:

- the first one consists in considering an average value for the motor operational torque to be expressed as $C_M = 0.45 \times (C_s + C_{max})$ where C_s represents the inrush torque and C_{max} the maximum torque;

- the second one concerns the torque due to the load and which can be correct by applying the multiplying factor K_L linked to the load typology as in Table B1 below.

Table B1: *Values of factor K_L*

	Type of comparable loads			
Load coefficient	Lift	Fans	Piston pumps	Flywheel
K_L	1	0.33	0.5	0

In order to better understand the significance of the co-efficient K_L we associate to the type of load indicated in the table the torque characterizing the starting phase of the load by means of the following assumptions:
Lift = load torque constant during acceleration
Fans = load torque with square law increase during acceleration
Piston pumps = load torque with linear increase during acceleration
Flywheel = zero load torque.

With these assumptions, the acceleration torque can be expressed as:

$$(C_M - C_L) = C_{acc} = 045 \times (C_s + C_{max}) - K_L \times C_L$$

These hypotheses allow to obtain the starting time with the aid of the following formula

$$t_a = \frac{2 \times \pi \times n_0 \times (J_M + J_L)}{60 \times C_{acc}}$$

The starting time allows to define whether a normal or a heavy duty start must be realized and to choose correctly the protection and switching devices.

The above mentioned parameters relevant to the motor are given by the manufacturer of the motor. As an example, Table B2 below shows the values that these parameters can take for three-phase asynchronous motors of common use and typically present on the market. Obviously the parameters relevant to the load characterize each single application and must be known by the designer.

Table B2: *Typical values of some electrical and mechanical parameters of a three-phase asynchronous motor*

Rated output power [kW]	Speed at full load [rpm]	Starting current Rated current Ratio	Full load torque Rated torque C_N [Nm]	Inrush torque Rated torque Ratio	Max. torque Rated torque Ratio	Efficiency at full load	Inertia of the rotor J 1/4GD² [Kgm²]	Max. starting time DOL starting [s]
75	1485	6.8	483	2.4	2.8	95	1.15	18
90	1486	7.1	579	2.7	2.9	95.2	1.4	18
110	1488	6.9	706	2.1	2.8	95.3	2	18
132	1487	6.7	848	2.2	2.7	95.5	2.3	18
160	1487	7.2	1028	2.4	2.9	96	2.9	18
200	1487	7.2	1285	2.5	2.9	96.2	3.5	20
250	1489	7.5	1603	2.2	2.6	96.2	5.7	20
315	1489	7.3	2022	2.3	2.8	96.4	6.9	20
355	1490	7.5	2277	2.4	2.7	96.6	6.9	20
400	1490	7.7	2564	2.5	2.8	96.6	8.4	20

Making reference to the data of the table, here is an example of calculation of the starting time of a motor, according to the theoretical treatment previously developed.

Example:

Three-phase asynchronous motor – 4 poles	160kW
Frequency	50Hz
Rated speed	1500 rpm
Speed at full load	1487 rpm
Moment of inertia of the motor	$J_M = 2.9 Kgm^2$
Moment of inertia of the load	$J_L = 60 Kgm^2$
Load torque	$C_L = 1600 Nm$
Rated torque of the motor	$C_N = 1028 Nm$
Inrush torque	Cs = 2467Nm (Cs=2.4x1028)
Max. torque	$C_{max} = 2981 Nm$ (C_{max}=2.9x1028)
Load with constant torque	$K_L = 1$

C_{acc}= 0.45 x (C_S + C_{max}) - K_L x C_L = 0.45 x (2467 + 2981) – (1 x 1600) = 851.6Nm

from which $t_a = \dfrac{2 \times \pi \times 1500 \times (2.9 + 60)}{60 \times 851.6} = 11.6s$

Load with quadratic rising torque K_L = 0.33
C_{acc}= 0.45 x (C_S + C_{max}) - K_L x C_L = 0.45 x (2467 + 2981) – (0.33 x 1600) = 1923.6Nm

from which $t_a = \dfrac{2 \times \pi \times 1500 \times (2.9 + 60)}{60 \times 1923.6} = 5.14s$

For both typologies of load, the esteemed starting time results to comply with the instruction given by the manufacturer regarding the maximum time admitted for DOL starting. This indication can be also taken as a cue for a correct evaluation of the thermal protection device to be chosen.

Annex C: Thermal protection and operation in case of "phase loss"

Among the many causes of "phase-loss" operation of a three-phase asynchronous motor it is possible to mention as example the interruption of a phase in the supply line (operation in case of "loss of a supply phase") or the interruption of a winding (operation in case of "loss of a winding"). The general and most common consequences can be overheating of the motor, functioning with a strong humming noise and mechanical vibrations.

Hereunder we shall analyze how operation under "phase loss" conditions affects the motor with star- and delta-connected windings in terms of power and current.

In a three-phase asynchronous motor the relationship between the nominal operation parameters under normal service conditions (three-phase supply) can be expressed by the following formula:

$$1) \qquad Pe = \sqrt{3} \times Vn \times Ie \times \cos\varphi$$

Star-connected motor

We analize first the condition of a star-connected motor, running both in case of "loss of winding" as well as of "loss of supply phase". If, due to a malfunctioning, the motor should run when a "phase loss" happens, the relation among the operation parameters can be expressed by the formula:

$$2) \qquad P^* = V^* \times I^* \times \cos\varphi^*$$

By " * " we indicate the electric quantities referred to running in case of "phase loss".

Running in case of loss of supply phase

Running in case of loss of a winding
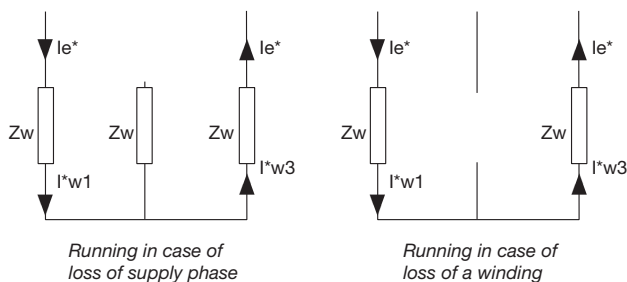
By assuming that both under standard operation conditions as well as under anomalous conditions, the motor shall deliver the same power, by keeping unchanged the supply voltage (Vn=V*) and the power factor (cosφ= cosφ*) and equating the previous formulas 1) and 2) it is possible to obtain:

$$3) \qquad \sqrt{3} \times Vn \times Ie \times \cos\varphi = V^* \times Ie^* \times \cos\varphi^* \quad \hookleftarrow$$
$$\rightarrow \quad \sqrt{3} \times Ie = Ie^* \quad \rightarrow \quad Ie^* = 1.73 \times Ie$$

From an analysis of the derived formula, it results that when functioning under "phase loss" conditions, if the motor is required to deliver the same power which it can guarantee in three-phase operation, the current "Ie*" absorbed by the motor results to be $\sqrt{3}$ times the current "Ie" required under normal working conditions. Thus, in order to deliver the same power, a motor running in case of "loss of phase" should absorb a current which results to be 73% bigger than the rated current in three-phase operation; that is, it should work under overload conditions, which would result critical for the temperature-rise level and, generally speaking, for the electrical life of the motor itself.

As a matter of fact, running with such high currents is however blocked by the presence of the thermal protection, the trip threshold of which is set at the rated current "Ie" of the motor. This protection trips, thus safeguarding the motor against the effects due to an absorbed current exceeding the set threshold "Ie".

Now, assuming that in the two different cases (normal three-phase supply and under "phase loss" conditions) the motor absorbs the same current value "Ie", by keeping unchanged the supply voltage and the power factor, let us consider the relationship between the deliverable power under these two operating conditions:

By making the current value explicit in the previous equations 1) and 2) and equating the two relations, the following is obtained:

$$4) \qquad \frac{Pe}{\sqrt{3} \times Vn \times \cos\varphi} = \frac{P^*}{V^* \times \cos\varphi^*} \quad \hookleftarrow$$
$$\rightarrow \quad \frac{Pe}{\sqrt{3}} = P^* \quad \rightarrow \quad 0.58 \times Pe = P^*$$

that is, with "loss of phase" and with absorption of the current "Ie", the motor delivers a power reduced by 42% in comparison with the three-phase rated power.

In a motor with star-connected windings the current seen by the motor windings is the same as that seen by the thermal protection under any operation condition. Therefore, the thermal relay protects the motor in case of higher absorption than the rated current "Ie" in both the operation modalities taken into consideration.
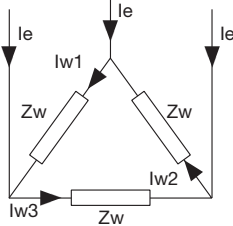
In this case, if, during normal functioning, the loss of one phase in the supply line or the loss of one winding occured, the three-phase motor would run single-phase because the windings would result to be passed through by a single current (i.e. there are no differences in values and phase displacement).

As a consequence during general running in case of "phase loss" the motor operational torque decreases and, if the stall torque keeps constant, there is reduction in the motor speed. This implies an increase in the slip with a consequent rise of the current absorption causing an excessive and harmful overheating of the motor. It is to signal that, according to the operation principle of the rotational magnetic field, when a three-phase asynchronous motor runs single-phase there is no starting torque and consequently it results impossible to start the motor under "phase loss" conditions. On the contrary, if the motor is put to rotate by means of any device, then it will start to rotate in the direction imposed by the external action, thus running with the limits and the problems previously mentioned.

Delta-connected motor
In case of a delta-connected motor, the equivalence between the formulas 1) and 2) is valid in case of "loss of supply phase" only.
As already mentioned, during normal three-phase operation, the motor absorbs a line current equal to the rated current "Ie", which means that through the three delta-connected windings a current value flows equal to:

5) $\quad I_{w1} = I_{w2} = I_{w3} = I_w = \dfrac{Ie}{\sqrt{3}}$

Normal running

During operation in case of "loss of the supply phase", assuming that the motor always absorbs a line current equal to the rated current "Ie", the current is distributed in the phases as follows:

6a) $\quad I^*w1 = I^*w2 = \dfrac{V}{2 \times Zw}$

6b) $\quad I^*w3 = \dfrac{V}{Zw}$

Running in case of loss of the supply phase
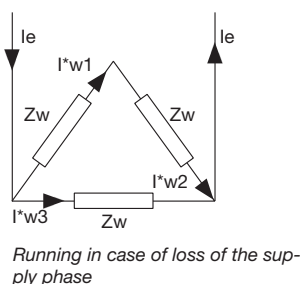
By expressing the voltage as a function of the total impedance of the windings, it is obtained:

7) $\quad V = \dfrac{2 \times Zw}{3} \times Ie$ (the equivalent impedance

results to be $\dfrac{(Zw + Zw) \times Zw}{(Zw + Zw) + Zw} = \dfrac{2 \times Zw}{3}$)

Replacing "V" in the above expressions 6a) and 6b) with the relation 7), it is possible to express the current in the windings as function of the rated current:

8a) $\quad I^*w1 = I^*w2 = \dfrac{1}{2 \times Zw} \times \dfrac{2 \times Zw}{3} \times Ie = \dfrac{Ie}{3}$

8b) $\quad I^*w3 = \dfrac{1}{Zw} \times \dfrac{2 \times Zw}{3} \times Ie = \dfrac{2}{3} \times Ie$

Calculating the ratio between the currents in the windings determined during normal operation, expressed by the formula 5, and during operation in case of "loss of the supply phase", expressed by the formulas 8a) and 8b), the following relations are obtained:

9a) $\quad \dfrac{I_{w1}}{I^*w1} = \dfrac{I_{w2}}{I^*w2} = \dfrac{Ie}{\sqrt{3}} \times \dfrac{3}{Ie} = \dfrac{3}{\sqrt{3}} = 1.73$ ↵

$\quad \longrightarrow \dfrac{I^*w1}{I_{w1}} = \dfrac{I^*w2}{I_{w2}} = 0.578$

9b) $\quad \dfrac{I_{w3}}{I^*w3} = \dfrac{Ie}{\sqrt{3}} \times \dfrac{3}{2 \times Ie} = \dfrac{3}{2 \times \sqrt{3}} = 0.876$ ↵

$\quad \longrightarrow \dfrac{I^*w3}{I_{w3}} = 1.153$

As already mentioned, during normal three-phase operation, the motor absorbs the line current "Ie" and the current $I_w = \dfrac{Ie}{\sqrt{3}}$ in the windings; as a consequence, from the relations 9a) and 9b), it can be deduced that during running in case of "loss of supply phase", even if the line current "Ie" is absorbed, one of the windings (in the given example winding 3) absorbs about 15% more than with normal operation.

This analysis leads to say that the thermal relay does not trip because it is affected by the current "Ie", even if in fact one winding results to be overcharged (15% more than with normal operation, as already said) without this being
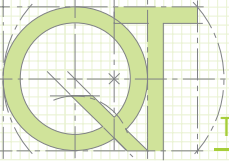
detected by the thermal protection. As a consequence, the motor could result not properly protected.

Under "loss of supply phase" conditions, being equal the delivered power, functioning can be dealt with making the same considerations as for star-connected motors in compliance with the relation 4.

In case of a delta-connected motor and running under "loss of winding" conditions, the equivalence between the formulas 1) and 2) is no more valid and a new equivalence element shall be considered, i.e. the relation:

2a) $\quad P^* = 2 \times V^* \times Ie^* \times \cos\varphi^*$
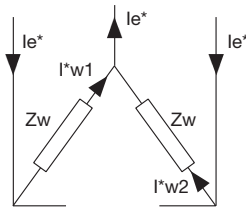
Running in case of loss of a winding

By assuming that the motor has to deliver the same power, keeping constant the supply voltage (Vn=V*) and the power factor ($\cos\varphi = \cos\varphi^*$), equating the formulas 1) and 2a) above, the following result is obtained:

10) $\quad \sqrt{3} \times Vn \times Ie \times \cos\varphi = 2 \times V^* \times Ie^* \times \cos\varphi^*$

$\sqrt{3} \times Ie = 2 \times Ie^* \rightarrow Ie^* = \dfrac{\sqrt{3}}{2} \times Ie \rightarrow Ie^* = 0.866 \times Ie$

"Ie*" is the current absorbed by the motor and flowing through the single winding during running with "loss of one winding" $Ie^* = I^*w$ and it is also the current seen from the thermal protection. During normal three-phase functioning, the current flowing through the winding has a value equal to $Iw = \dfrac{Ie}{\sqrt{3}}$, whereas the current seen from the thermal protection is exactly "Ie". Introducing this concept in the formula 10), the following relation is obtained:

11) $\quad \sqrt{3} \times \sqrt{3} \times Iw = 2 \times I^*w$

$\rightarrow I^*w = \dfrac{3}{2} \times Iw = 1.5 \times Iw$

From the above, it is evident that with this anomalous functioning the winding of the motor is passed through by a current "I*w" which results to be higher than the maximum current admitted in the winding under standard running conditions, without thermal protection tripping since, as it can be seen from formula 10), the protection results to be passed through by a current lower than the rated current of the motor during normal functioning.

It is evident that this implies for the motor particularly heavy operation.

Instead, by assuming that the motor absorbs a line current equal to the rated current "Ie" of normal operation, equating the expression of the current which can be derived from the formulas 1) and 2a), keeping the supply voltage (Vn=V*) and power factor ($\cos\varphi = \cos\varphi^*$) unchanged, the following relation is obtained:

12) $\quad \dfrac{P}{\sqrt{3} \times Vn \times \cos\varphi} = \dfrac{P^*}{2 \times V^* \times \cos\varphi^*}$

$\rightarrow P^* = \dfrac{2 \times P}{\sqrt{3}} = 1.15 \times P$

Therefore, when running in case of "loss of winding", the motor delivers a power which results 15% higher than that delivered by the motor under normal operating conditions. This makes the windings passed through by a current which exceeds of about 73% the current affecting the windings in case of normal three-phase running. This condition results to be still heavier than the previous one and does not cause the tripping of the thermal protection because, as assumed, it is interested by the rated current "Ie".

In a motor with delta-connected windings, functioning with the loss of one phase of the supply line, leads the three-phase motor to run single-phase, because the windings are passed through by currents having different values, but the same phase displacement. This does not allow the generation of the rotational magnetic field; consequently the motor cannot even be started, if not initially forcing its rotation.

Functioning in case of loss of one winding, instead, leads the asynchronous motor to run two-phase, in fact the windings are passed through by currents having the same values $\left(|Iw| = \dfrac{|V|}{|Zw|}\right)$ but different phase displacement ($\phi_1 - \varphi_V = \varphi_w$).

The previous treatment illustrates the operation conditions of the motor in case of "loss of phase" through a theoretical approach based on the operation conditions with same delivered power and same absorbed current as normal three-phase running. But the real operation conditions are characterized by the formation of harmonics generating direct or inverse magnetic rotational eddy fields which affect efficiency, rotation speed and power delivered. Therefore the real functioning situation cannot be the subject of a linear and simple treatment as set out above, even if this is however valid to give an indication of the currents interesting the motor and to understand how functioning in case of "loss of phase" have consequences causing damages to the motor.

Annex D: Different duty types

The term duty defines the load cycle to which the machine is subjected, including, if applicable, starting, electric braking, no-load and rest de-energized periods, and including their durations and sequence in time. Duty considered as generic term, for example, can be classified as continuous duty, short-time duty or periodic duty. The percentage ratio between the period of loading and the total duration of the duty cycle is defined cyclic duration factor.

It is the responsibility of the purchaser to declare the duty. Where the purchaser does not declare the duty, the manufacturer shall assume that duty type S1 (continuous running duty) applies. The duty type shall be designated by the appropriate abbreviation and the purchaser may describe the type of duty based on the classifications according to the indications given below.

When the rating is assigned to the motor (values declared, usually by the manufacturer, for a specified working condition of a machine), the manufacturer must select one of the rating classes. If no designation is given, the rating relevant to the continuous running duty shall be applied.

In compliance with the classification of Std. IEC 60034-1 here are some indications regarding the duty types which are typically considered as reference to indicate the rating of the motor.

Continuous running duty:

for a motor suitable to this duty type, the rating at which the machine may be operated for an unlimited period is specified. This class of rating corresponds to the duty type whose appropriate abbreviation is S1.

The duty type S1 can be defined as operation at a constant load maintained for sufficient time to allow the machine to reach thermal equilibrium.
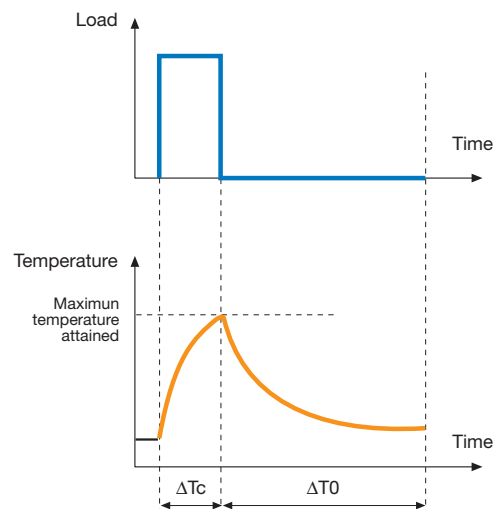
Continuous running duty: Duty type S1
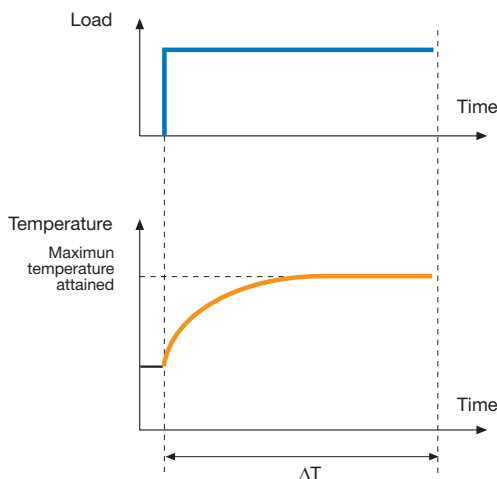
ΔT: Time sufficient to allow the machine to reach thermal equilibrium

Short-time duty:

for a motor suitable to this duty type, the rating at which the machine, starting at ambient temperature, may be operated for a limited period is specified. This class of rating corresponds to the duty type whose appropriate abbreviation is S2.

The duty type S2 can be defined as operation at constant load for a given time, less than that required to reach thermal equilibrium, followed by a time de-energized and at rest of sufficient duration to re-establish the equilibrium between the machine temperature and that of the coolant temperature. A complete designation provides the abbreviation of the duty type followed by an indication of the duration of the duty (S2 40 minutes).

Short-time duty: Duty type S2

ΔTc: operation time at constant load
ΔT0: time de-energized

Periodic duty: for a motor suitable to this duty type, the rating at which the machine may be operated in a sequence of duty cycles is specified. With this type of duty, the loading cycle does not allow the machine to reach thermal equilibrium. This set of ratings is linked to a defined duty type from S3 to S8 and the complete designation allows identification of the periodic duty. If no otherwise specified, the duration of a duty cycle shall be 10 minutes and the cyclic duration factor shall have one of the following values: 15%, 25%, 40%, 60%. The cyclic duration factor is defined as the ratio between the period of loading, including starting and electric braking, and the duration of the duty cycle, expressed as a percentage.

The duty type S3 is defined as a sequence of identical duty cycles, each including a time of operation at constant load and a time de-energized and at rest. The contribution to the temperature-rise given by the starting phase is negligible. A complete designation provides the abbreviation of the duty type followed by the indication of the cyclic duration factor (S3 30%).
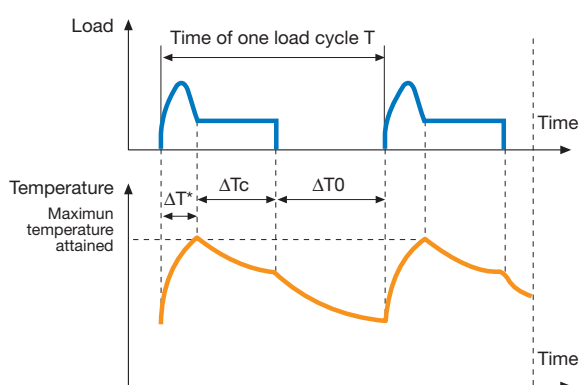
Intermittent periodic duty: Duty type S3
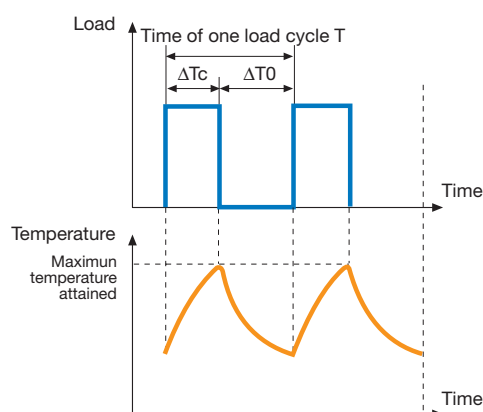
ΔTc: operation time at constant load
$\Delta T0$: time de-energized and at rest
Cyclic duration factor = $\Delta Tc/T$

The duty type S4 is defined as a sequence of identical duty cycles, each cycle including a significant starting time, a time of operation at constant load and a time de-energized and at a rest.
A complete designation provides the abbreviation of the duty type followed by the indication of the cyclic duration factor, by the moment of inertia of the motor J_M and by the moment of inertia of the load J_L, both referred to the motor shaft (S4 20% J_M = 0.15 kg m^2 J_L = 0.7 kg m^2).
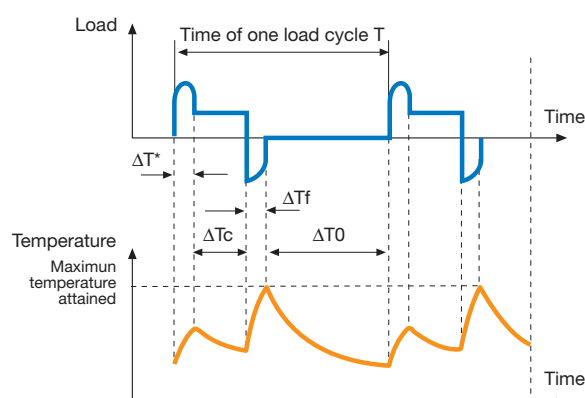
Intermittent periodic duty with starting: Duty type S4

ΔT^*: starting/accelerating time
ΔTc: operation time at constant load
$\Delta T0$: time de-energized and at rest
Cyclic duration factor = $(\Delta T^* + \Delta Tc)/T$

The duty type S5 is defined as a sequence of identical duty cycles, each cycle consisting of a starting time, a time of operation at constant load, a time of electric braking and a time de-energized and at a rest.
A complete designation refers to the duty type and gives the same type of indication of the previous case.

Intermittent periodic duty with electric braking: Duty type S5

ΔT^*: starting/accelerating time
ΔTc: operation time at constant load
ΔTf: time of electric braking
$\Delta T0$: time de-energized and at rest
Cyclic duration factor = $(\Delta T^* + \Delta Tc + \Delta Tf)/T$

The duty type S6 is defined as a sequence of identical duty cycles, each cycle consisting of a time of operation at constant load and a time of operation at no-load. There is no time de-energized and at rest. A complete designation provides the abbreviation of the duty type followed by the indication of the cyclic duration factor (S6 30%).

Continuous-operation periodic duty: Duty type S6
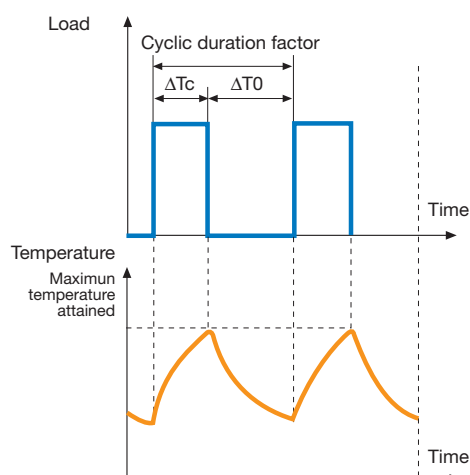
ΔTc: operation time at constant load
$\Delta T0$: operation time at no load
Cyclic duration factor = $\Delta Tc/\Delta T0$

The duty type S7 is defined as a sequence of identical duty cycles, each cycle consisting of a starting time, time of operation at constant load and a time of electric braking. There is no time de-energized and at rest. A complete designation provides the abbreviation of the duty type followed by the indication of both the moment of inertia of the motor J_M and the moment of inertia of the load J_L (S7 J_M = 0.4 kg m^2 J_L = 7.5 kg m^2).
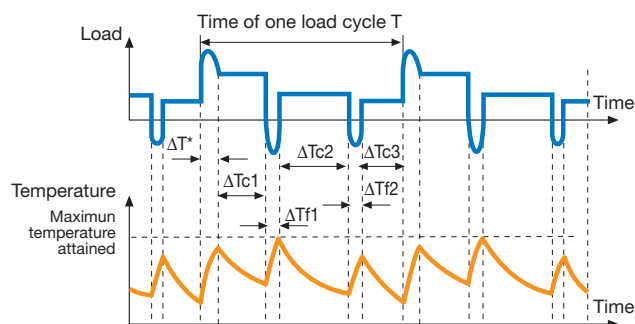
Continuous-operation periodic duty with electric braking: Duty type S7
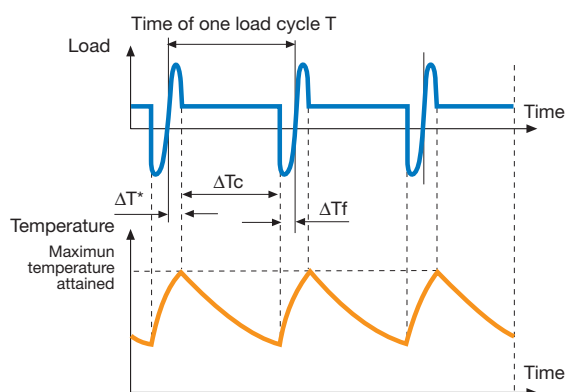
ΔT*: starting/accelerating time
ΔTc: operation time at constant load
ΔTf: time of electric braking
Cyclic duration factor = 1

The duty type S8 is defined as a sequence of identical duty cycles, each consisting of a time of operation at constant load corresponding to a predetermined speed of rotation, followed by one or more times of operation at other constant loads corresponding to different speeds of rotation. There is no time de-energized and at rest. A complete designation provides the abbreviation of the duty type followed by the indication of the moment of inertia of the motor J_M and by the moment of inertia of the load J_L, together with the load, speed and cyclic duration factor, for each speed condition (S8 J_M = 0.7 kg m^2 J_L = 8 kg m^2 25 kW 800 rpm 25% 40 kW 1250 rpm 20% 25 kW 1000 rpm 55%).

*Continuous-operation periodic duty with related load/speed: Duty type S8*

ΔT*:   starting/accelerating time
ΔTc1; ΔTc2; ΔTc3: operation time at constant load
ΔTf1; ΔTf2: time of electric braking
Cyclic duration factor = (ΔT*+ΔTc1)/T; (ΔTf1+ΔTc2)/T; (ΔTf2+ΔTc3)/T

Non-periodic duty:
for a motor suitable to this duty type, the rating at which the machine may be operated non-periodically is specified. This class of rating corresponds to the duty type whose appropriate abbreviation is S9.
The duty type S9 is defined as a duty in which generally load and speed vary non-periodically within the permissible operating range. This duty includes frequently applied overloads which may greatly exceed the reference load.

Duty with non-periodic load and speed variations: Duty type S9
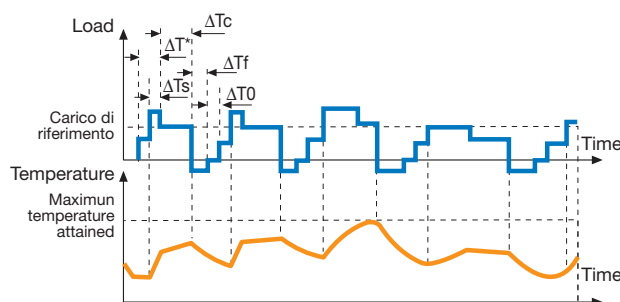
ΔT*: starting/accelerating time
ΔTs: time under overload
ΔTc: operation time at constant load
ΔTf: time of electric braking
ΔT0: time de-energized and at rest

Duty with discrete constant loads (and speeds):
for a motor suitable to this duty type, the rating at which the machine may be operated with a specific number of discrete loads for a sufficient time to allow the machine to reach thermal equilibrium is specified.
The maximum permissible load within one cycle shall take into consideration all parts of the machine (the insulation system, bearings or other parts with respect to thermal expansion).
The maximum load shall not exceed 1.15 times the value of the load based on duty type S1. Other limits as regards the maximum load may be given in terms of limits of temperature of the winding. The minimum load may have the value zero, when the machine operates at no-load or is de-energized and at rest.
This class of rating corresponds to the duty type whose appropriate abbreviation is S10.
The duty type S10 is defined as the operation characterized by a specific number of discrete values of load maintained for a sufficient time to allow the machine to reach thermal equilibrium. The minimum load during a duty cycle may have value zero and be relevant to a no-load or rest condition. A complete designation provides

the abbreviation of the duty type followed by the indication of the per unit quantities $p/\Delta t$ for the partial load and its duration, and by the indication of the per unit quantity T_L which represents the thermal life expectancy of the insulation system related to the thermal life expectancy in case of duty type S1 with rated output, and by the quantity r which indicates the load for a time de-energized and at rest (S10 $p/\Delta t$ = 1.1/0.4; 1/0.3; 0.9/0.2; r/0.1 T_L = 0.6).

Duty for equivalent loading:
for a motor suitable to this duty type, the rating, for test purposes, at which the machine may be operated at constant load until thermal equilibrium is reached and which results in the same stator winding temperature rise as the average temperature rise during one load cycle of the specified duty type. This class of ratings, if applied, corresponds to the duty type designated "equ".

Duty with discrete constant loads and speeds: Duty type S10
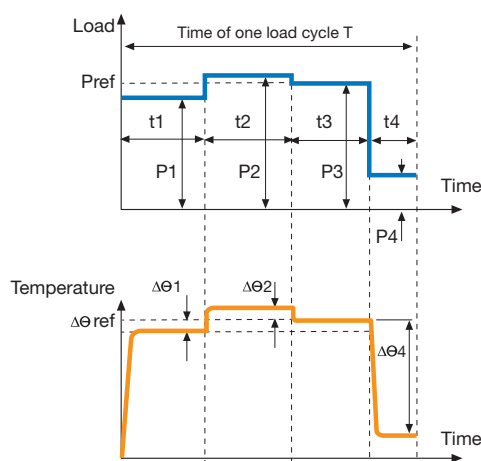
$\Delta\Theta 1$; $\Delta\Theta 2$; $\Delta\Theta 4$: difference between the temperature rise of the winding at each of the various loads within one cycle and the temperature rise based on duty cycle S1 with reference load

$\Delta\Theta$ ref: temperature at reference load based on duty type S1
t1; t2; t3; t4: time of a constant load within a cycle
P1; P2; P3; P4: time of one load cycle
Pref: reference load based on duty type S1

Annex E: Some considerations about UL coordination

This Annex is aimed at giving a brief survey and a short account of the main modalities and prescriptions regarding the coordination of motors for applications or projects intended for the North American market.

In the automation field, the European market – with IEC Standard references – and the North American market – with UL Standard references – have very different foundations from a normative and juridical point of view; as a consequence, the concepts explained in the previous chapters lose their validity when considered in an American context.

The American reference Standard as regards motor coordination is UL 508 "Industrial Control Equipment". The requirements of this Standard cover industrial control apparatus and relevant accessories for starting, stopping, regulating, controlling, or protecting electric motors.

Generalities
The American Standard prescriptions do not deal with the topic of motor coordination in accordance with the parameters and the definitions given by the Standard IEC and previously analyzed. As a consequence, the classification into "type 1" and "type 2" coordinations or "normal starting" and "heavy starting" does not exist in the UL Standard, which instead describes the different modalities to obtain starters, named "combination motor controllers" and classified in different typologies called "construction types".

The "combination motor controller" is a device or combination of devices designed to start and stop a motor by making and breaking the motor current. It is a controller constituted by one or more devices assembled together providing a disconnecting means, branch circuit (short-circuit and ground fault) protection, motor controller (usually with a contactor), and motor overload protection.

The circuit disconnecting means and motor branch-circuit protection (short-circuit and ground-fault) usually consist of a circuit-breaker. The circuit-breaker can be either an instantaneous trip or inverse time breaker. The instantaneous trip breaker provides short-circuit protection, whereas the inverse time breaker provides both short-circuit protection and overload protection.
The magnetic motor controller function can be generally carried out by a contactor. The overload relay provides protection from overload conditions.

This Standard gives very severe prescriptions as regards the testing procedures and values, for which also the concept of "enclosure", i.e the cubicle where the "combination motor controller" is housed.

The different "construction types" are identified according to the different components admitted and to the distribution modalities of the fundamental protection and control functions.

The classification foresees constructions of types A-B-C-D-E-F and it is illustrated in a table which, according to the type, gives indications about the different components admitted, about the relevant reference Standard defining their characteristics and about the function they have to fulfil.
The most common construction types, characterized by having single components replaceable with other ones with suitable characteristics, are those classified from A through D, whereas those ones providing the use of a circuit-breaker are classified as type C and D, which in details foresee the use of the following components:

Type C

- "Inverse time circuit breaker", identifiable as a thermal magnetic circuit-breaker, complying with the Std. UL 489 and performing a disconnecting and circuit protecting function
- "Magnetic or solid state motor controller", identifiable as a contactor complying with the Std. UL 508 and operating as a "motor controller", i.e. having a motor control function
- "Overload relay", identifiable as a thermal protective device complying with the Std. UL 508 and having a function defined as "motor overload", i.e. a protection function against overload.

Type D

- "Instantaneous trip circuit breaker", identifiable as a magnetic only circuit-breaker complying with the Std. UL 489 and carrying out a disconnecting and circuit protecting function
- "Magnetic or solid state motor controller", identifiable as a contactor complying with the Std. UL 508 and operating as a "motor controller", i.e. having a motor control function
- "Overload relay", identifiable as a thermal protective device complying with the Std. UL 508 and having a function defined as "motor overload", i.e. a protection function against overload.

A particular construction type is identified as **Type E** and called "Self-Protected Control Device", introduced by the Standard UL as from 1990. The Type E controller is a manual self-protected combination motor controller that provides both overload and short-circuit protection in a compact device. This design does not require upstream a circuit-breaker or fuses.

In this construction type all the functions "Disconnect" - "Branch Circuit Protection" - "Motor Control" - "Motor Overload" are carried out by a single component complying with the prescriptions of the Std. UL 508.

By using a contactor combined with the Type E, a new construction type originates, which in 2002 was introduced in the Standard and was classified as **Type F**, but this device is not considered "Self-Protected".
As far as short-circuit is concerned, the construction types A through D, and F are tested under the same conditions and with the same testing modalities, whereas the Standard specifies dedicated testing modalities for type E.

Here is a short analysis which also offers some further elements characterizing the components of the different control and protection functions, starting with the definition of "Enclosure" or cubicle as contained in the Std. UL508.

Enclosure

An "enclosure" for industrial control equipment shall be constructed and assembled so as to have the strength and sturdiness necessary to resist the abuses to which it is likely to be subject, without total or partial collapse resulting in a risk of fire, electric shock, or injury to persons due to reduction of spacings, loosening or displacement of parts, or other serious defects.
Practically speaking, these are the characteristics which the enclosure housing the "combination motor controller" shall have; the enclosure constitutes an integral part of the motor controller and consequently influences its performances.

Protection against overload

For each motor an individual protection against overload shall be provided. External overload relays – either mechanical or electrical – or the thermal relays of the motor starters "type E" can be used, but however equipment all complying with UL 508. The setting of the overload protection shall not exceed 115% of the nameplate current rating of the motor at full load.

Protection against short-circuit

To obtain protection against short-circuit, magnetic only or thermomagnetic circuit-breakers complying with the Std. UL 489 can be used; combined with a contactor and an overload protection, they allow to achieve a motor protection system type C or D in compliance with the Std. UL 508. Alternatively also the circuit-breakers identified by the Std. UL 508 as "self-protected combination motor controller" may be chosen.

Control function

Either the generic contactors as defined by the Std. UL 508 or other more complicated components such as the controllers and inverters complying with the Std. UL 508C can be used as control equipment.

The contactor shall be chosen according to the type of load which it shall control and shall have a size (i.e. a current carrying capacity) not lower than the current or the sum of the currents of the motors calculated with reference to the standardized values reported in the Std. UL 508.

Glossary

Ir	setting current of the thermal protection
Ti	tripping time of the thermal protection
V_L	network voltage between lines (phase-to-phase)
Zw	impedance of the winding
Ie	rated current of the motor
Iw	current in the motor windings under standard conditions
Iw*	current in the motor windings under anomalous conditions
Pe	rated power of the motor
Isp	inrush current 12 x Ie
Iavv	starting current 7.2 x Ie
I3	magnetic tripping threshold
In	rated current of the relay
η	rated efficiency
$\cos\varphi$	rated power factor
Y	star connection
Δ	delta connection
n_0	synchronous speed or speed of the magnetic field of the stator
f	frequency of the supply network
p	number of pole pair
n	rotation speed of rotor
ns	slip speed
s	slip
C_M	motor operational torque
C_L	load torque
Ca	starting torque
ta	starting time
J_M	moment of inertia of the motor
J_L	moment of inertia of the load
ω	motor angular speed
$\dfrac{d\omega}{dt}$	angular acceleration
C_S	inrush torque
C_{max}	maximum torque
C_{acc}	acceleration torque
K_L	multiplying factor
S..	duty type
ϕ_I	current phase displacement
φ_V	voltage phase displacement
φ_w	phase displacement of the winding impedance

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