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n° 165

control/ monitoring and protection of HV motors

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control/monitoring and protection of HV motors

Unit power of rotating machines frequently exceeds 100 kW in industry and large tertiary. In such cases and/or if the length of the supply line is particularly long (voltage drops, losses…), use of high voltage motors is advantageous.
The purpose of this Cahier Technique is to analyse and compare these motors, their starting systems and the various protection devices which may be used, in order to simplify technical choices.

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1. reminder of the various types of AC motors

Both high and low voltage AC motors, offer a large variety of electrical, dynamic and technological characteristics. However, except for a small number of motors used for highly specific applications, they can be divided into three families, namely:

- asynchronous cage motors;
- asynchronous slipring rotor motors;
- synchronous motors.

They differ from each other in:

- starting current and torque values;
- speed variation in normal operation;
- power factor and efficiency values as a function of load.

HV motors are supplied with a voltage rarely exceeding 7.2 kV, their power ranges from 100 kW to over 10 MW, with an average of 800 kW.

asynchronous cage motors

These HV motors fall into two main categories according to their rotor composition which can be single or double cage.
This enables choice of starting current and torque characteristics:

- single cage rotors have:
  - a relatively low starting torque (0.6 to 1 C_n),
  - a maximum torque of around 2 to 2.2 C_n,
  - a starting current ranging from 4.5 to 5.5 I_n,

(C_n: rated torque, I_n: rated current);

- double cage or deep slot rotors have:
  - a slightly higher starting torque (0.8 to 1.2 C_n),
  - a maximum torque of around 2 to 2.2 C_n (slightly higher for deep slots),
  - a starting current ranging from 5 to 6.5 I_n.

Figures 1 and 2 show the form of these curves as a function of speed (N/N_s).

Note that:

- single cage motors have a minimum torque (0.5 to 0.6 C_n), whereas the torque curve, varying according to the speed of the double cage or deep slot motors, continues to increase up to maximum torque.
- these motors are ideal for intensive use and dangerous environments, due to:

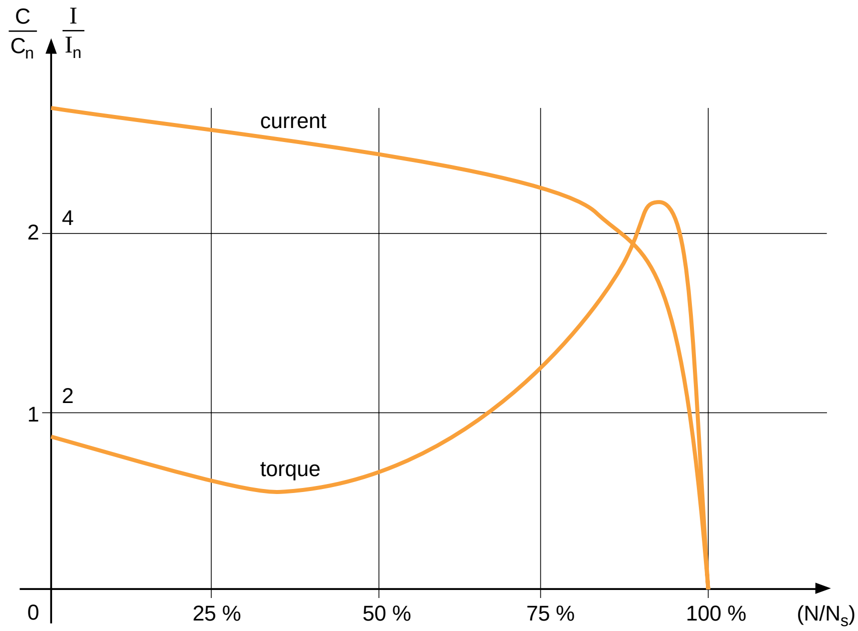


fig. 1: curves C (N) and I(N) of an asynchronous single cage motor.

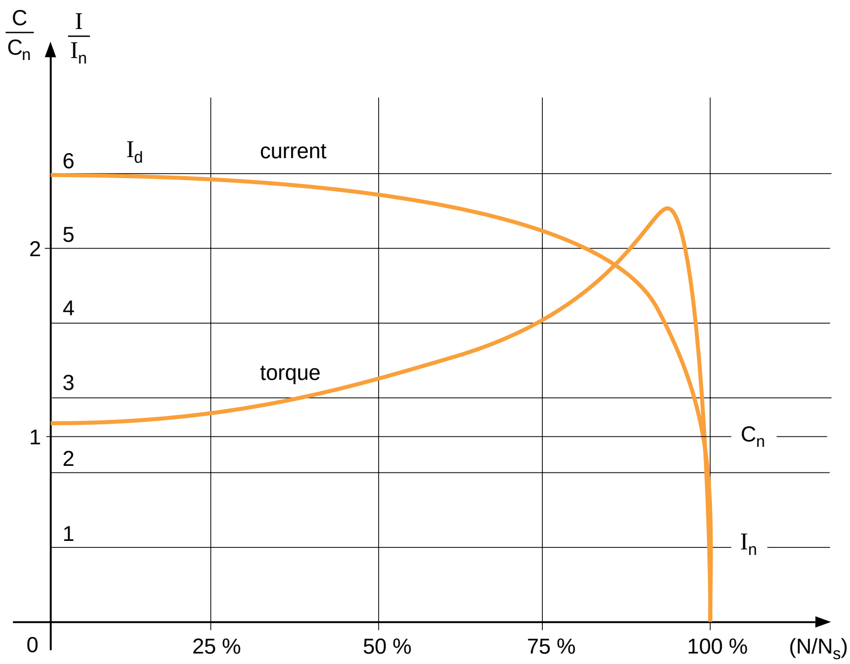


fig. 2: curves C(N) and I(N) of an asynchronous double cage motor.

□ the simplicity of rotor design in short-circuit providing them with an excellent mechanical and electrical robustness,
□ absence of brushes.
These two features allow maintenance to be reduced to a minimum.

The torque characteristics of asynchronous cage motors are especially suitable for machines such as centrifugal pumps, compressors, converter sets, machine-tools and fans.

However, all these motors have the drawback of a relatively low power factor, around 0.8 to 0.9 on full load, and even less when they are running on low load (see fig. 3).

If asynchronous motor installed power is high, reactive power compensation is required. This may either be global, for each set of motors or for each motor (large units).

asynchronous slipring rotor motors

The rotor winding of these motors connected to sliprings means the resistance of this circuit can be modified by introducing external resistances.
In the motor stability zone, corresponding to the positive slope of curve C = f (g) (see fig. 4), the slippage "g" is proportional to the rotor resistance:

$$g = \frac{1}{A} R_r \ C$$

where $g\,\% = \dfrac{N_s - N}{N_s} 100$

where:
N_s : synchronous speed,
N : operating speed.

$$A = 3V^2 \frac{p}{\omega} \frac{M}{L_1} = \text{constant}$$

where:
V: phase to neutral supply voltage,
p: number of pole pairs,
ω: pulsation of supply currents,
M: reciprocal stator-rotor inductance,
L_1: total stator choke,
($L_1 = M + L_s$)
R_r: rotor resistance = rotor inherent resistance + external resistances,
C: motor torque.

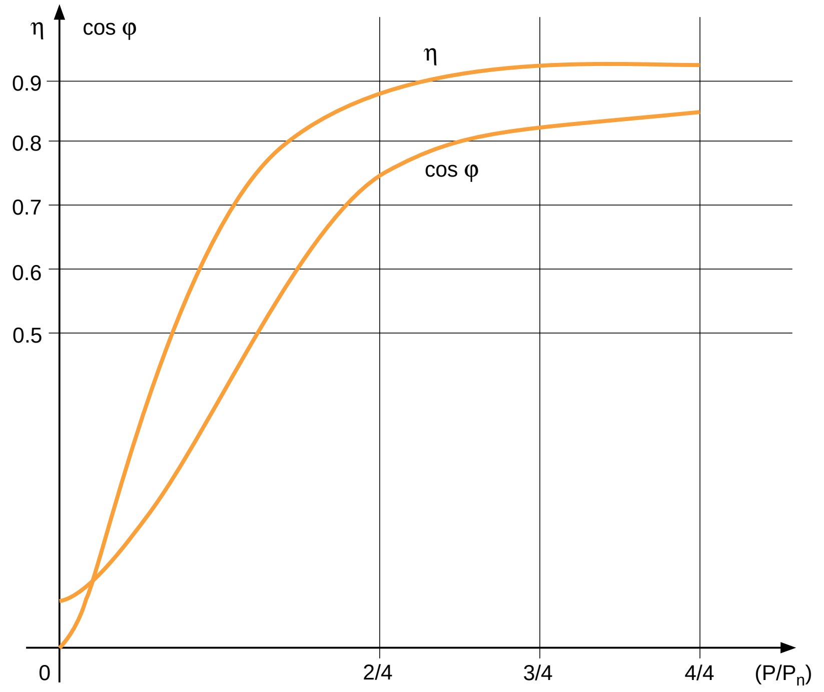


fig. 3: efficiency curves η (P) and power factor curves cos φ (P) of an asynchronous double cage motor.

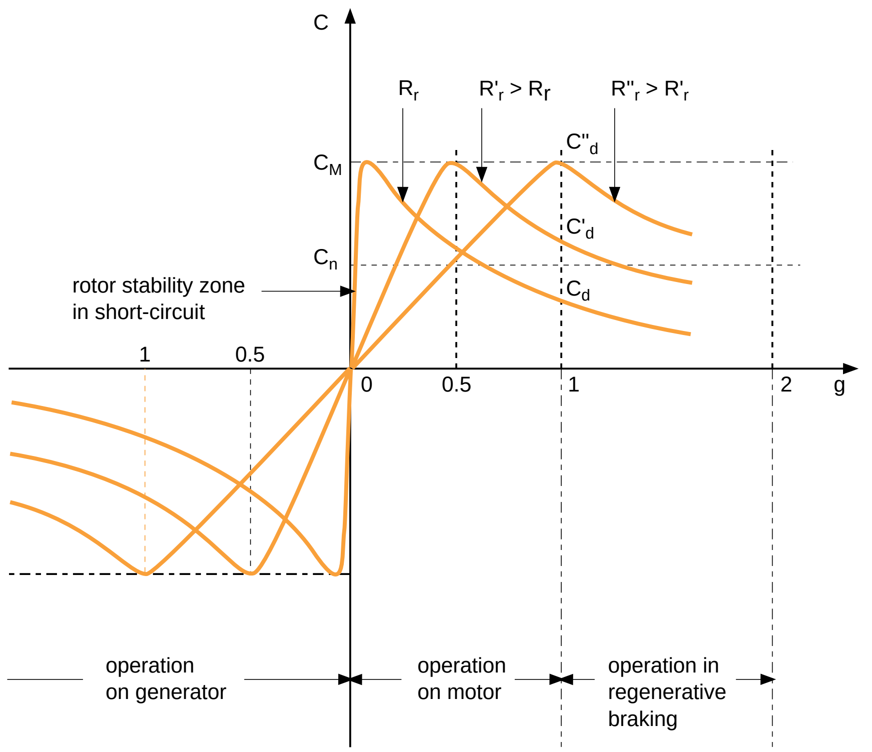


fig. 4: curves C (g) of an asynchronous slipring rotor motor.

By decreasing external resistance on starting, the characteristic C (g) is translated and the starting torque adapted to the torque of the machine being driven. Note that maximum torque value does not depend on rotor resistance.

Moreover, for small slippages, rotor current is inversely proportional to rotor resistance. Its amplitude is given by:

$$I_2 = B \frac{g}{R_r}$$

where

$$B = V \frac{M}{L_1}.$$

Stator current follows the same law, except for the winding ratio and the magnetising current.

Consequently, the choice of initial rotor resistance solves virtually all the problems concerning high starting torque and inrush current on the network and ensures these two requirements are satisfied. The various possibilities for using asynchronous slipring rotor motors make them suitable for driving machines with high starting torque such as crushers, mixers, conveyors, etc.

Moreover, machines requiring high regenerative braking also use this type of motor.

Just as for asynchronous cage motors, the power factor in normal operation is relatively low: this characteristic and the presence of sliprings and rotor resistances mean these motors are increasingly replaced by double cage or deep slot motors.

Figure 4 represents the characteristic C (g) curves, according to rotor resistance value and the stability zones. These curves show the advantage of introducing a high resistance in the rotor circuit as a means of obtaining efficient regenerative braking.

synchronous motors

The main differences with asynchronous motors are:

■ their constant speed (synchronous speed);
■ the rotor circuit supplied with DC;
■ the power factor which may be set by the exciting current.

Technologically, they are identical to AC generators.

In order to obtain asynchronous torque and avoid oscillations, the rotors are equipped with a damping cage. This cage means synchronous motors can be started with a low load torque in similar fashion to asynchronous single cage motors (they have practically the same characteristic torque and current curves). To avoid surge voltages in the exciting circuit, this circuit is shunted during starting and on tripping by a resistance with a value chosen between 5 and 10 times the resistance of the exciting circuit.

In view of the fact that the asynchronous torque tends to zero on approaching synchronous speed, coupling to the network when motor starting is complete cannot take place at synchronous speed as is the case for AC generators. The result is invariably a transient state varying according to the speed acquired at the end of starting and motor power. To limit this transient state:

■ either use a relay to monitor slippage by measuring frequency of the rotor current passing through the starting resistance. This relay controls exciting circuit supply when slippage is at its lowest.
This device is practically indispensable when the synchronous motor accounts for a large part of total installed power.
■ or apply the exciting current in two stages, automatically or manually.

The exciting sources can be either separate:

■ motor set, exciter;
■ thyristor rectifier;

or placed at the end of the motor shaft:

■ reversed generator;
■ rotating "diode rectifier and armature" reversed AC generator.

The techniques most frequently used are the thyristor rectifier and the "rotating diodes".
The latter does away with brushes, removes the exciting cubicle and, in addition, is often fitted with a synchronisation and recoupling mechanism should synchronism fail.

These motors can supply reactive energy by increasing the exciting current. This characteristic, which enables compensation of network reactive loads, is one of the main reasons these motors are chosen.

The curves in figure 5 show stator current variation as a function of exciting current for a given constant load (Mordey curves). Use of this type of motor for small powers is fairly rare. On the other hand, it is frequently used above 2,000 kW for its excellent efficiency and control of its power factor. In the case of highly regular movements, synchronous motors are a necessity. However, the machines being driven must have a relatively low load torque during starting, and sizing of the dampening cage limits starting rate.

sizing tolerances

The electromechanical characteristics of motors are defined by standard IEC 34-1. In the case of certain rated characteristic values, the standard defines the tolerances to be complied with by the manufacturer. It is useful to be familiar with these tolerances since, for certain characteristics, they directly affect the choice of motor and equipment power and the setting of the protection devices.

The table in figure 6 gives the tolerances of the main characteristic values.

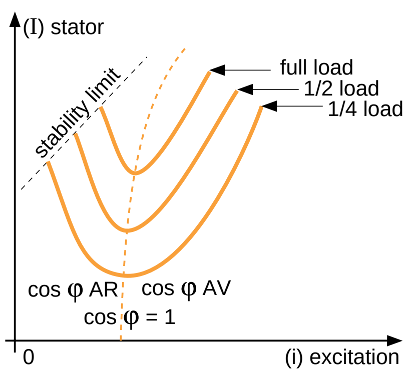


fig. 5 synchronous motor: Mordey curves.

dielectric withstand and tests

Motors, just like all electrical network components, are subjected to a variety of surge voltages. They are particularly sensitive to steep front surge voltages or high frequency since they are "jammed" by the first turns of the stator windings.

Switching surge voltages

These are the result of transient phenomena occurring during changes in status in the supply network.
The following phenomena, specific to inductive circuits and thus to motors, must be taken into consideration:

- current pinch-off on current breaking;
- multiple re-ignitions on breaking and prearcing on current making if the breaking device is capable of breaking the high frequency currents corresponding to these phenomena.

Steep front surge voltages

These are the result of direct or indirect lightning strokes. They spread onto the network, creating a dielectric stress which, even when limited by the use of surge arresters, can be considerable. Surge voltage is studied in detail in "Cahier Technique" n° 151 "Overvoltages and insulation coordination in MV and HV" and special motor sensitivity in "Cahier Technique" n° 143 "Behaviour of the SF6 MV circuit-breakers Fluarc for switching motor starting currents".
To check the motor's capacity to withstand to these various surge voltages, the motors undergo standardized tests performed as defined by IEC 34-1 standard.

The test voltage is applied between the winding being tested and the body of the machine to which the magnetic circuits and all the other stator and rotor windings are connected.

Two types of tests are stipulated in the standards: standard frequency tests and impulse withstand tests.

Standard frequency test

Withstand to switching surge voltages is checked in compliance with standard IEC 71, by the standard frequency withstand test. Testing commences with a voltage of less than U/2 which is gradually increased up to 2 U + 1,000V, at which level it is applied for one minute.

For the stator, U is the specified supply voltage. For the rotor, U is the voltage which appears, with the rotor circuit open, when the specified stator supply voltage is applied with the rotor locked in rotation. If the motor is reversible (change of rotation direction of motor already started), the test voltage applied to the rotor will be 4 U + 1,000 V.

Impulse withstand test

This test consists in applying an impulse voltage representative of lightning:

- buildup time: 1.2 µs;
- dropdown time at $U_{peak}/2$: 50 µs;
- test voltage:
U_{peak} = 4 U + 5,000 V.

The windings are subjected to a number of positive and negative waves.

Impulse withstand tests are not currently mandatory in standards, as they can lead to early ageing of armature and winding insulation.
More generally, the dielectric tests must not be repeated; if a second test is performed, it will be carried out at 80 % of the voltages indicated above.

value	tolerance
asynchronous motors	
current with locked rotor and short-circuited	+ 20 % of current (no lower limit)
torque with locked rotor	- 15 % to + 25 % of torque guaranteed
minimum torque during starting	- 15 % of torque guaranteed for cage motors $C_d \geqslant$ at a third of rated torque and $\leqslant$ at half of torque with locked rotor, at full voltage
maximum torque	- 10 % of torque guaranteed provided that once this tolerance is applied, the torque remains $\geqslant$ 1.6 times rated torque
synchronous motors	
current with locked rotor	+ 20 % of value guaranteed
torque with locked rotor	- 15 % to + 25 % of value guaranteed
pull-out torque	- 10 % of value guaranteed provided that once this tolerance is applied, the torque remains $\geqslant$ 1.35 times rated torque (1.5 for synchronous motors with salient poles)

fig. 6: tolerances on the main characteristic values as in standard IEC 34-1.

2. classical HV starting processes

The main HV motor starting processes are as follows:
- direct stator starting on full voltage;
- stator starting on reduced voltage by star-delta connection, by reactance or by autotransformer;
- stator starting by capacitors;
- rotor starting.

direct stator starting on full voltage

This starting mode is used for asynchronous motors with cage rotor and for synchronous motors.

Current peak on starting is around 4 to 7 I_n, according to motor characteristics, and can last for roughly 1 to 10 seconds depending on the moment of total inertia (motor + machine), motor torque and load torque.

If this starting mode is used, the network must be able to withstand the above current overload without disturbing the other loads, and the machine being driven must be able to withstand the mechanical impact due to the motor torque. The simplicity of both equipment and motor and the resulting savings mean that this mode is very popular and even recommended provided that voltage drop on the network on start up is acceptable. The decisive factor lies in the motor power/ short-circuit power ratio.

stator starting on reduced voltage

Star-delta starting

This starting mode is used to reduce:
- current in a ratio of $\sqrt{3}$;
- starting torque by a third.

It is used in LV and for low powers, but rarely in HV due to the high current peaks when moving to delta. In this case it is replaced by reactance starting.

Voltage reduced by resistance

Commonly used in LV, it is rarely used in HV due to the Joules to be dissipated and resistance insulation problems.

Voltage reduced by reactance

This starting mode (refer to power diagram, figure n° 8) is the one which reduces current inrush on the network in the simplest manner. Since motor starting torque is low, the machines being driven must have a relatively low load torque during start up: compressors, centrifugal pumps, converter sets, etc.

In point of fact, asynchronous motor torque varies according to square of the supply voltage , whereas the absorbed current remains proportional to this voltage.

$$C'_d = C_d \left(\frac{U_d}{U_n}\right)^2$$

where :
C'_d: starting torque with reduced voltage,
C_d: starting torque with full voltage,
U_d: starting voltage,
U_n: rated operating voltage.

$$I'_d = I_d \frac{U_d}{U_n}$$

where:
I'_d: starting current with reduced voltage,
I_d: starting current with full voltage.
These relationships can also be expressed using the rated characteristics as follows:

$$\frac{I'_d}{I_n} = \frac{I_d}{I_n}\frac{U_d}{U_n}.$$

The curves in figure 7 give the ratio variations as a function of

the ratio $\frac{U_d}{U_n}$.

Voltage at the motor terminals increases gradually during starting. The resulting start up is smooth.
- operation and schematic diagram:
  - □ first stage: operation on reduced voltage by closing the line contactor C_L,
  - □ second stage: normal operation by closing the short-circuit contactor C_C;
- determining a starting reactance (see fig. 9)

Starting voltage is determined by the maximum current inrush I'd authorised on the network:

$$U_d = U_n \frac{I'_d}{I_d}.$$

The phase-to-phase voltage drop in the reactance has the following value:

$$\vec{U_n} - \vec{U_d} = j\,\sqrt{3}\,L\,\omega\,\vec{I'_d}.$$

The diagram in figure 9 shows that this relationship can be expressed in an arithmetic form for asynchronous motors, since the power factor at the initial moment start up moment is initiated is virtually the same as the power factor of the starting inductance. Therefore:

$$L\,\omega = \frac{U_n - U_d}{\sqrt{3}\,I'_d}.$$

Knowledge of start up time and operation rate is required to determine reactive power.

Voltage reduced by autotransformer

This starting mode sometimes makes it possible to reconcile reduction of current inrush on the network and motor torque value. In point of fact, it has the advantage of reducing current inrush according to the square of the winding ratio:

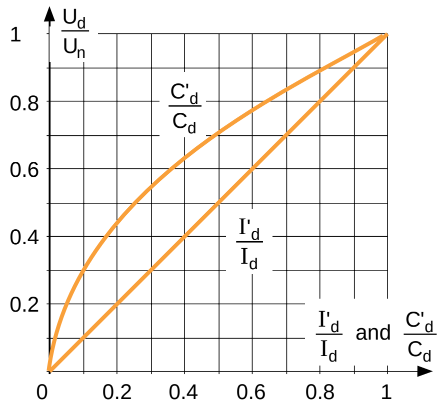


fig. 7: graphs showing start-up on reduced voltage (by reactance or star-delta).

$$\frac{I'_d}{I_n} = \frac{I_d}{I_n}\left(\frac{U_d}{U_n}\right)^2$$

$$\frac{C'_d}{C_n} = \frac{C_d}{C_n}\left(\frac{U_d}{U_n}\right)^2$$

where:
I'_d: starting current on network side with reduced voltage.

These relationships are used to determine the value of reduced voltage authorised on the network, as a function of the ratio $\frac{I'_d}{I_n}$ or of the ratio $\frac{C'_d}{C_n}$ authorised by the machine being driven.

The curve in figure 10 gives the variation of $\frac{U_d}{U_n}$ as a function of $\frac{I'_d}{I_n}$ or $\frac{C'_d}{C_n}$.

■ operation and schematic diagram (see fig. 11)
C_L: line contactor,
C_C: short-circuit contactor,
C_{PN}: HV neutral point formation contactor,
AT: autotransformer
□ first stage
operation on reduced voltage by closing C_{PN} which causes C_L to close,
□ second stage
operation in inductance by opening C_{PN},
□ third stage
operation on full voltage by closing C_C.

Remarks:

■ in theory the second stage is short (around one second) since in most cases it is a slowing-down time;
Use of an autotransformer with air gaps considerably reduces this fault, but requires knowledge of the value of the current absorbed by the motor at the end of the first stage;

■ the move to full voltage invariably results in a transient state whose duration varies according to the speed acquired at the end of the first stage and the value of the current absorbed;

■ the current flowing through the neutral point on start up is equal to the difference between the motor current and the line current, excluding the magnetising current of the autotransformer. This enables the rating of the neutral point contactor to be reduced;

■ there is an alternative version of this configuration in which the neutral point contactor is removed. This version is not recommended since the move from reduced to full voltage necessites the motor-network link be cut. In view of the relatively short switching time, and the residual voltage at the motor terminals, a current inrush exceeding starting current can ocur on transfer to normal operation. This is unacceptable for both the network and the motor and can lead to the tripping of the protection devices.

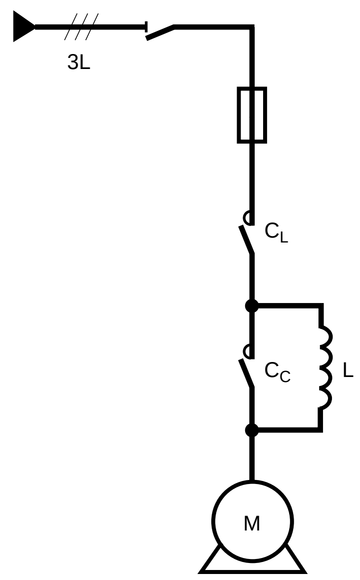


fig. 8: power diagram: starting by reactance.

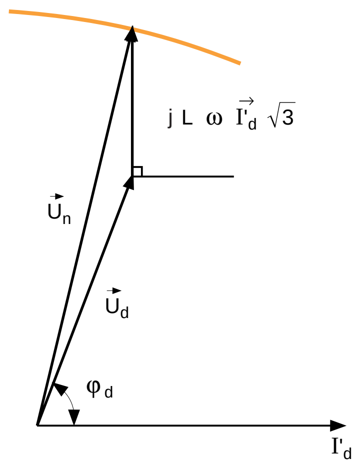


fig. 9: vectorial diagram to determine L.

stator starting with capacitors

This process enables motor full voltage starting characteristics to be maintained. It is mainly used for keeping the starting torque of synchronous motors constant during start up, for example in cement works and crushing plants.

Capacitors, as well as motor, supply part of the reactive energy during the starting phase: the motor power factor is small at this stage. Power inrush on

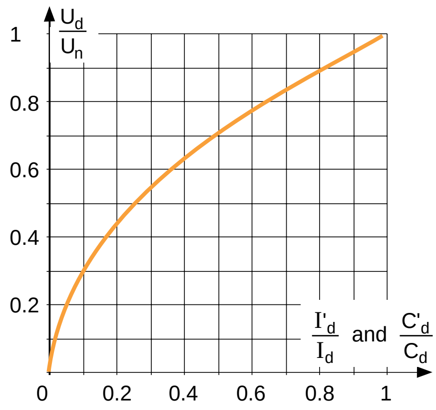


fig. 10: graphs showing start up by autotransformer on reduced voltage.

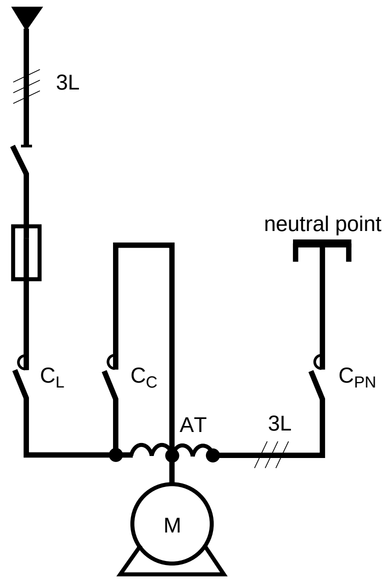


fig. 11: power diagram: starting by autotransformer.

the network is reduced accordingly (see fig. 12).

This technique is tricky to implement and calls for a study of the motor and capacitors to avoid resonance and surge voltage (due to motor self-excitation), as well as mechanical oscillations on the transmission system.

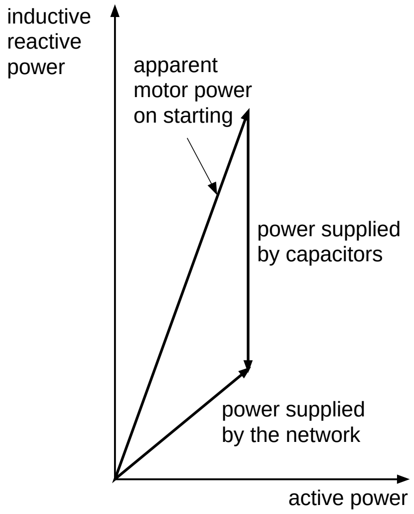


fig. 12: vectorial diagram for starting by capacitor.

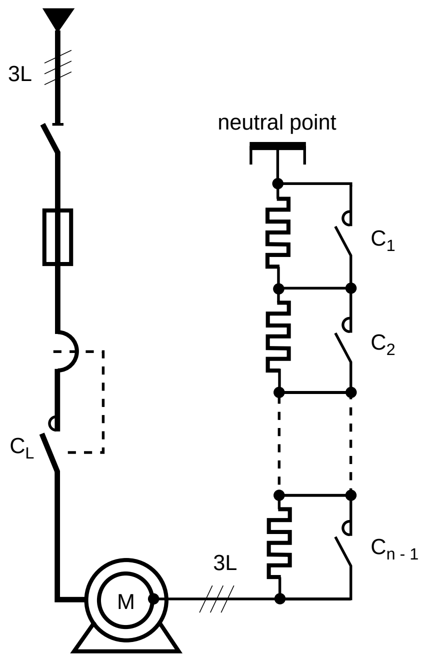


fig. 13: power diagram: rotor starting.

Moreover, control equipment must be chosen especially for capacitor switching.

rotor starting

This starting mode solves virtually all the problems which may occur on starting, namely:

- reduction of current inrush on the network with increase in motor torque;
- adaptation of motor torque to load torque;
- long, progressive starting (e.g. for loads with high inertia).

This mode can only be used for asynchronous slipring rotor motors and for synchronous induction motors (its use is increasingly rare in industry).

It is particularly used for load starts.

Example of a rotor start in n time

This start up is illustrated in figures 13 and 14. Motor torque varies between two values at each notch. The lower value is taken as being equal to the rated torque. At each notch, rotor resistance changes value and the torque-speed characteristic evolves. In the last stage, rotor resistance is simply equal to the rotor internal resistance.

- first stage
stator supply and starting on full rotor resistance by closing C_L;
- second stage
short-circuiting of the first section of the rotor resistance by closing C_1;
- third stage
short-circuiting of the second section of the rotor resistance by closing C_2;
- Nth stage
short-circuiting of the n-1 section of the rotor resistance by closing C_{n-1}.

The number of stages, or notches, n is always greater by 1 than the number of sections or contactors.

This number n is determined approximately by the formula:

$$n = \frac{\log g_n}{\log \frac{C_n}{C_p}}$$

or by $\frac{C_n}{C_p} = \sqrt[n]{g_n}$

where:
C_p= peak torque,
g_n = rated slippage.

According to each case, n can be deduced from Cp, and vice-versa.

Complete determination of rotor starting equipment calls for knowledge of operation (hourly rate and starting time). Lack of standards for HV motors means this equipment is determined in each individual case by specialists.

Remark

A linear start is sometimes required. This calls for power electronics enabling monitoring of rotor energy: for example using a Graëtz bridge and a chopper to make a continually variable resistance (see fig. 15).

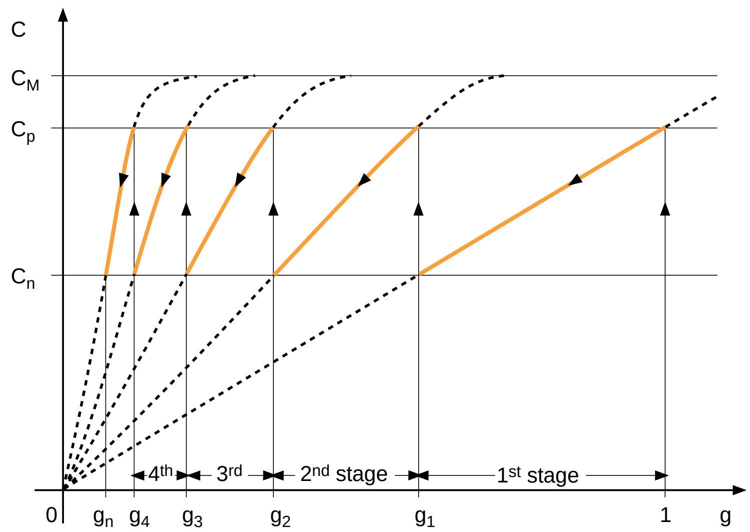


fig. 14: symmetrical rotor starting diagram.

choosing the starting mode

Choice of starting mode is conditioned by ensuring that the motor torque and the load torque of the load are properly matched.

Knowledge of the load torque is required (see fig. 16).

Starting conditions

In view of the required starting characteristics, it is necessary to check that starting can take place in correctly as far as motor torque, current inrush and starting time are concerned, for the starting techniques under consideration:

- motor torque is always greater than load torque (see fig. 17);
- current inrush on the network and the corresponding voltage drop are acceptable to the network;
- starting time is compatible with the equipment used.

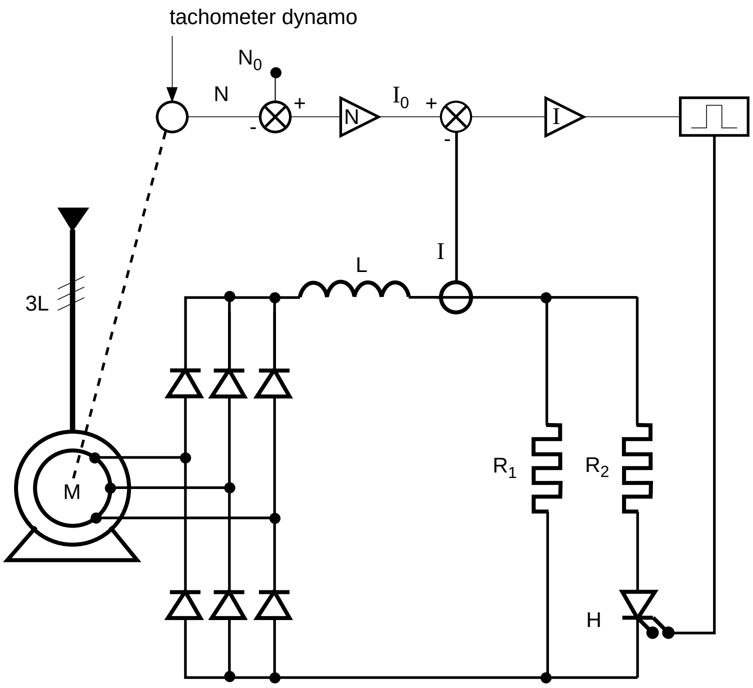


fig. 15: setting speed by rotor chopper.

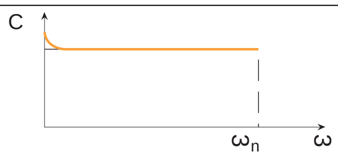
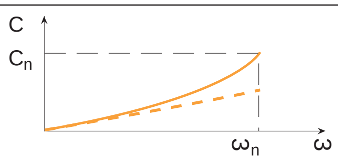
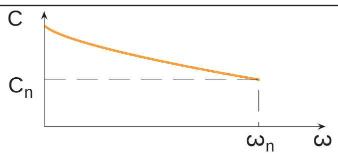
	characteristics	examples
	constant torque	piston compressor
	parabolic torque	pump: valve opened / valve closed
	high breakaway torque	crusher

fig. 16: rreminder of load torque curves of machines to be driven (loads).

Approximative calculation of starting time

Operation of the motor-driven machine assembly is governed by the following mechanical equation:

$$C_m - C_r = J \frac{d\omega}{dt}$$

where:
C_m: motor torque with Un voltage,
C_r: load torque,
J: inertia of rotating frames (motor and machine driven),

$\frac{d\omega}{dt}$: angular acceleration.

Angular velocity varies from 0 to n throughout starting time Δt. Moreover, a mean accelerating torque C_a, equal to the mean difference between C_m and C_r can be defined:

This results in $C_a = (C_m - C_r)$ mean

$$= J \frac{(\omega_n - 0)}{\Delta t}$$

hence:

$$\Delta t = \frac{J \ \omega_n}{C_a}.$$

Bearing in mind that real motor torque varies according to the square of its supply voltage:

$$\frac{C'_m}{C_m} = \left(\frac{U_{real}}{U_n}\right)^2$$ with real voltage.

C'_m = motor torque with real tension.
Reducing this voltage will thus reduce C_a, hence increasing starting time.

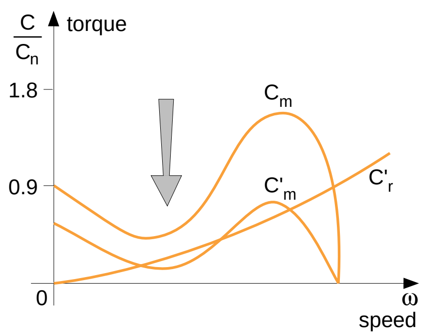


fig. 17: case of non-starting (C'm < Cr).

Starting mode selection table

The table in figure 18 summarises the advantages and disadvantages of the main starting modes for the various applications.

For a given torque, the current absorbed on the network is established in the following increasing order:

■ rotor starting;
■ starting by autotransformer;
■ starting by stator impedance;
■ direct starting.

Choice of starting mode calls for good communication between the electrical energy supplier and the manufacturer of the motor and machine being driven.

The vital characteristics for making this choice are:

■ supply network power and maximum authorised current inrush;
■ motor torque and current at full voltage as a function of rotation speed;
■ load torque of the machine driven (see fig. 16);
■ moment of inertia of the rotating frames.

If the supply network power/motor power ratio is less than 5, particular care must be paid to choice of starting mode and choice of coordination of the protection devices (see appendices 1 and 2).

application needs	**application characteristics**	**starting mode**	**controlled by**		**advantages** ***disadvantages***
permanent or quasi-permanent process ⩽ 1/jour	machines requiring high start torque	direct	1 or	1	simplicity, less investment. *on starting:*
frequent starts > 1/day	motors with low current inrush or low power	direct		1	■ *high torque;* ■ *high current inrush,;* ■ *high mechanical stresses.*
pumps, fans, compressors, frequent starts	machines starting with low torque	stator by reactance		2	reduction of current inrush on starting (possible adjustment).
optimisation of starting characteristics	when starting current must be reduced, but the necessary starting torque maintained	stator by autotransformer		3	optimisation of torque *(reduced)* and of current inrush on starting (possible adjustment).
optimisation of high torque starting characteristics	the most difficult starts	rotor		generally 3	small current inrush and high starting torque.

fig. 18: starting mode selection table for the most common applications.

3. control and monitoring equipment

The function of this equipment is threefold:
■ energising and stopping (control);
■ disconnecting the motor should a fault occur (protection);
■ monitoring the motor (monitoring).

When we talk about monitoring, this implies the equipment is capable (or not) of:
■ initializing the start (starting sequence automation);
■ acting on motor speed;
■ supplying information on motor electrical status and contributing to protection.

The monitoring function chiefly relies on power electronics and low currents (digital technology); it is currently being fully developed. Protection of HV motors will be dealt with in the next chapter.

electromechanical solutions

The choice between the various devices (switch, circuit-breaker or contactor) depends on:
■ operation rate;
■ electrical endurance;
■ motor power.
The main breaking device characteristics are summarised in the table in figure 19.

Fuse-switches
By their very design, the breaking capacity, mechanical and electrical endurance of switches is low. This limits their use to small powers (I_n = approx. 50 A - 5,500 V) and to rates of two to three operations a day.

Moreover, the low breaking capacity of these devices makes choice of protection devices tricky.

Circuit-breakers
Circuit-breakers are generally used for high motor powers of more than 300 A, with a small operation rate, and for operating voltages of more than 6.6 kV.

Their use can naturally be extended to lower powers, operable by switch or contactor.

Fuse-contactors
■ operation rate
Their simple control mechanism combined with the robustness and simplicity of their contacts mean contactors have a high operation rate. This rate cannot be withstood by circuit-breakers, even special ones, and even less so by switches.

Some installations use contactors with mechanical latching to do away with permanent consumption of the closing electromagnet. This may reduce endurance as a result of the greater complexity of the kinematic chain.

■ network short-circuit power
This factor does not really affect contactors thanks to the presence of fuses placed immediately after the isolating switch or next to the disconnecting contacts on the busbar side. These fuses with their high breaking capacity, limit the short-circuit current.

This special feature means that, if network power is increased, the motor feeder cubicles can be maintained. The busbar supports are strengthened if required.

Fuses
Fuse rating is determined according to:
■ rated current I_n;
■ the I_d/I_n ratio (I_d = starting current);
■ starting time determined using the chart in figure 20 page 14.

Finally, it should be pointed out that fuses protect the motor against overcurrents roughly five times greater than motor rated current and that they must be combined with additional protection devices (thermal relays, etc. see "protection device" chapter).

Current transformers
The increasing use of digital protection devices means unconventional current sensors can be used (e.g. Rogowski toroids). These sensors have the advantage of being linear and thus delivering an accurate signal throughout the useful current range.

They present no saturation or thermal problems, as is sometimes the case with classical Current Transformers (see "Cahier Technique" n° 112 "The breaking process with a Fluarc SF6 puffer-type circuit-breaker").

Special features due to use of fuses or circuit-breakers
■ operation in single-phase due to fuse melt, with the striker not working.

Today striker reliability is such that the risk is slight. Their dependability may be increased still further by use of an additional protection device (undervoltage or unbalance relay).

device	mean rate	endurance nb operations	acceptable motor power
fuse-switch	low: 2-3/day	2,000	low ⩽ 50 A
circuit-breaker	low: 10/day	10,000	high ⩾ 7.2 kVA > 300 A
fuse-contactor	high > 10/h	> 100,000	average ⩽ 300 A

fig. 19: breaking device application field.

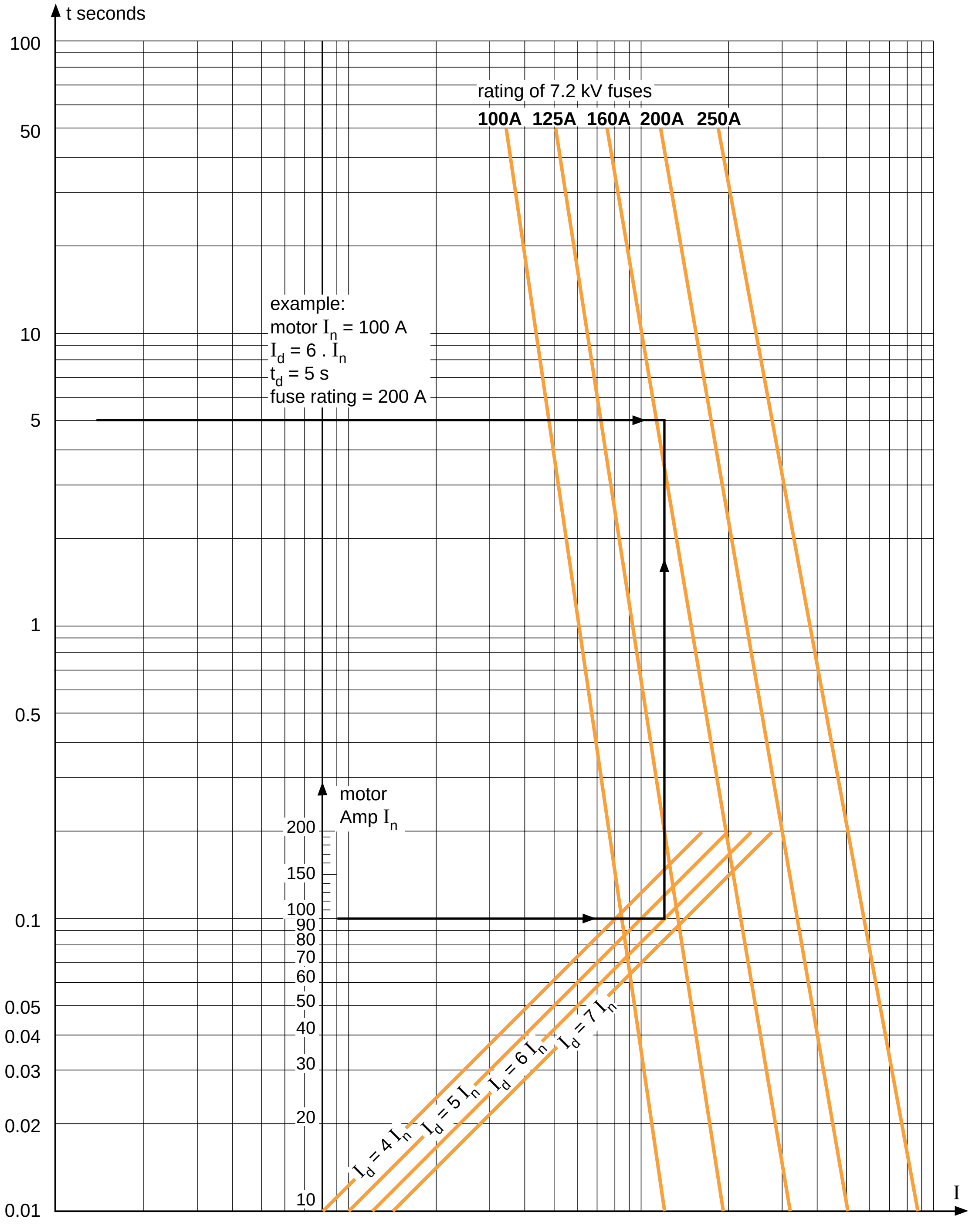


fig. 20: fuse determination chart.

■ discrimination with upstream equipment.
This can be hard to achieve when both:
□ the fuses used have a high rating (200 A or 250 A),
□ and the feeder protected by these fuses accounts for a large fraction of the power supplied by the main circuit-breaker (see fig. 21 and 22).

However, the high breaking capacity of the Rollarc contactors combined with these fuses allows the use of slightly time delayed overcurrent relays, thus ensuring discrimination. Discrimination is easier to achieve if the motor feeder is protected by circuit-breaker but since, for high short-circuit currents the current is not limited, there is an increase in thermal stresses.

■ surge voltages
Some types of device, in particular vacuum breaking devices, generate surge voltages on motor energising and stopping (due to their capacity to break high frequency currents, resulting for example from the current pinch-off phenomenon - see "Cahier Technique" n° 143).
In order to prevent these surge voltages progressively damaging motor insulation, manufacturers place ZnO type surge voltage limiters in the equipment if required.

It can be concluded that today's electromagnetic solutions are reliable, robust, economic and entirely suitable for most applications.

electronic solutions

These provide users with additional possibilities and advantages such as:
■ variable speed;
■ possibility of speed regulation;
■ high operation rate;
■ energy savings.

The electronic solution is rarely used just for starting.

Before dealing with standard cases of electronic devices, it should be pointed out that their use calls for a certain number of constructive precautions at motor level:

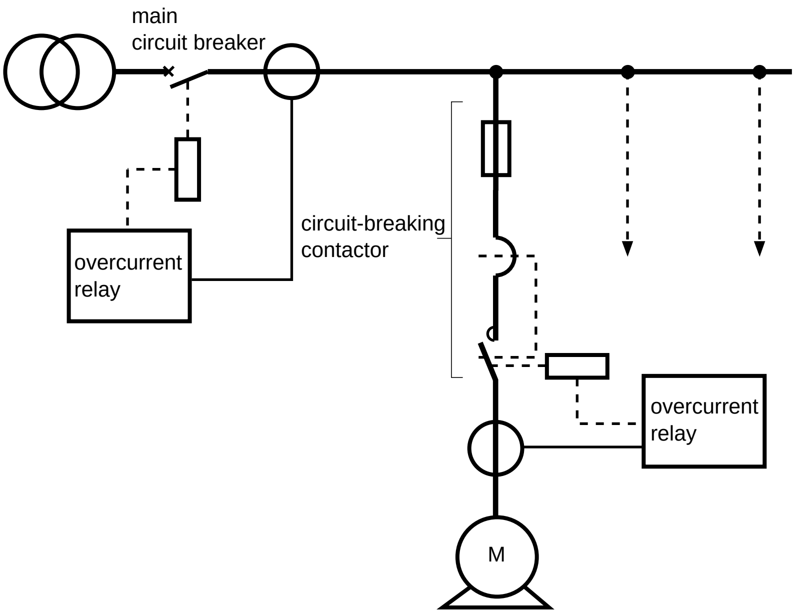


fig. 21: protection diagram showing a high current motor feeder.

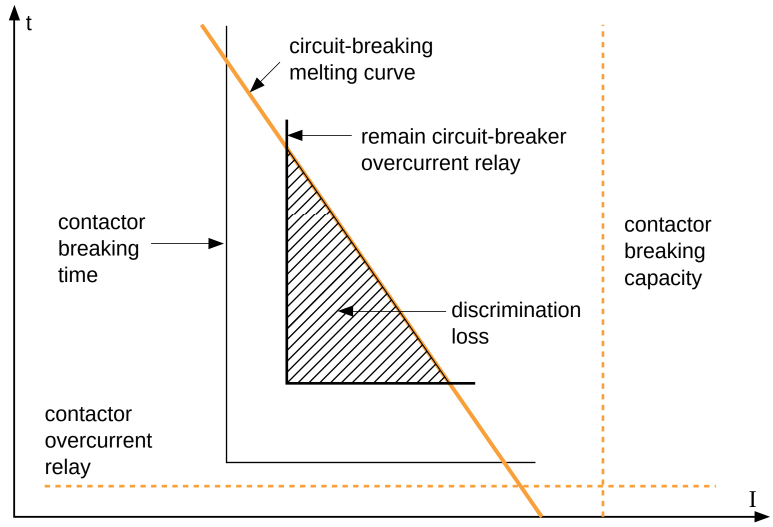


fig. 22: discrimination diagram for a high current motor feeder.

■ safety margin in temperature rise due to harmonics: a 15 % margin on current is generally sufficient;
■ forced ventilation is recommended (motors can run at low speed);
■ reinforced insulation between turns due to the high voltage gradients generated by thyristor switching (which may reach the magnitude of impulse withstand test ones).

motor	loads	speed variations	power	overall efficiency	speed controller type
asynchronous or synchronous	pumps, fans, compressors, extruders	0 % to over 100 %	a few 10 kW to a few 100 kW	0.85 to 0.90	autonomous rectifier/inverter
asynchronous slipring	same	60 % to 100 %*	a few 100 kW to a few MW	0.90 to 0.95	subsynchronous cascade
synchronous	same centrifugal machines TGV bogies (high speed)	0 % to several times 100 %	100 kW to a few 10 MW	0.90 to 0.95	selfcontrolled rectifier/inverter
asynchronous or synchronous	crushers, rolling mills, cement kilns (low speed)	0 % to ± 33 %	100 kW to a few 10 MW	0.85 to 0.90	cyclo converter

*: 100 % corresponds to relative speed at 50 Hz

fig. 23: application areas of electronic speed controllers for AC motors.

The devices described below are the ones most frequently used in medium voltage. Only the general principles are presented.

The table in figure 23 gives an idea of the adequations between the type of speed controller, the type of motor and the type of load driven.

Autonomous rectifiers/inverters

With their capacity to deliver variable voltage and frequency, they guarantee complete control of motor speed and torque.

A reminder for asynchronous motors:

■ torque is proportional to U^2 if f and N are constant;

■ torque is inversely proportional to f for a given voltage and speed.

There are three types of autonomous rectifiers/inverters.

■ voltage rectifier/inverter

□ the thyristor rectifier sets voltage,

□ the thyristor inverter supplies AC current at variable frequency.

This configuration is also used by Uninterruptible Power Supplies (UPS) used in LV to supply computers. The only difference is that frequency and voltage are fixed.

■ rectifier/inverter with Pulse Width Modulation (PWM)

□ the diode rectifier supplies the inverter,

□ the inverter generates voltage pulses enabling reproduction of a sine wave with variable period and amplitude (see fig. 24).

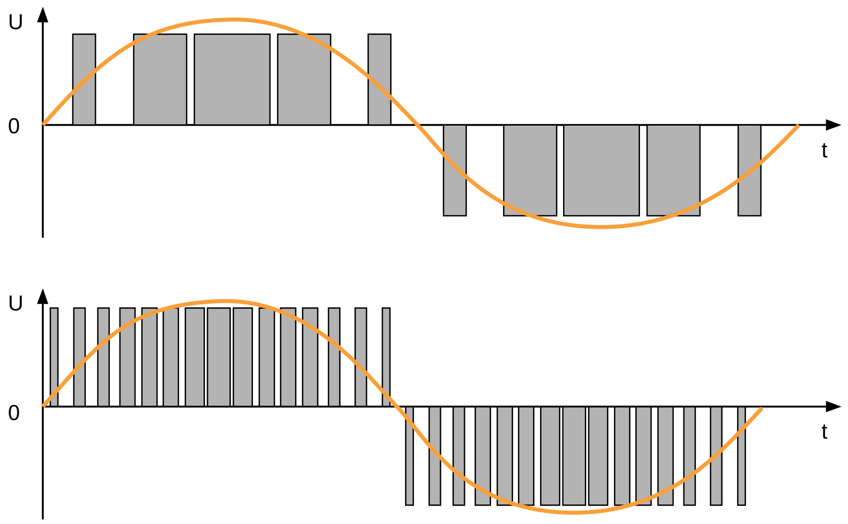


fig. 24: generation of variable voltages and frequency with PWM speed controllers.

■ current rectifier/inverter (switch)

□ the thyristor rectifier combined with a smoothing choke acts like a DC generator,

□ the inverter switches current in turn in the motor windings using capacitors. Motor frequency and thus speed depend on switching speed.

A few elements of comparison between these three types of rectifiers/inverters:

■ voltage inverter

□ suitable for high reactance motors,

□ often requires a filter between inverter and motor,

□ enables regenerative braking if the rectifier is reversible.

■ the PWM inverter

□ allows a wide range of speeds,

□ maximum speed limited by the maximum switching frequency authorised by the inverter thyristors. Use of power transistors (IGBT) makes it possible to work at far higher frequencies but at lower powers,

□ reversible operation possible (two rotation directions).

■ the current switch

□ suitable for low reactance motors,

□ enables operation in the four quadrants.

Subsynchronous cascade
Asynchronous slipring rotor motors are normally supplied by the network.
Speed is adjusted using the rotor current by means of a rectifier/inverter set. The rectifier draws off energy from the rotor circuit, thus increasing slippage. The energy drawn off depends on the conduction setting of the thyristors of the inverter which reinjects energy into the network (see fig. 25). The subsynchronous cascade enables continuous speed variation with a maximum slippage of around 40 %.
Converter set power is low compared with motor power, and the energy regenerated results in outstanding overall efficiency.
Note that the converter is put into operation after starting by rotor resistance.
This assembly can operate at speeds higher than synchronous speed (supersynchronous) in the case of driving loads.

Selfcontrolled rectifier/inverter
The motor stator phases (in this case synchronous) are supplied in turn just as for the current switching autonomous rectifier/inverter.
Switching from one stator phase to the next is selfcontrolled by motor speed by means of a "notched disk" sensor.
There is thus a correspondence between the excitation flux and the armature flux, as for DC machines, and the pull-out risk is zero.
Since switching presents problems both on starting and at low speed, the converter control system must be modified.
This solution is ideal for synchronous motors.

Cyclo converter
Each motor phase is "supplied" by a three-phase double bridge.
The first bridge is used to draw off current throughout the positive cycle on each of the network phases according to the required frequency.
The second bridge is used for reverse current during negative alternation to one of the phases.

The cyclo converter produces a three-phase pseudo mains requiring filtering and with a frequency varying between 0 % and a third of network frequency.

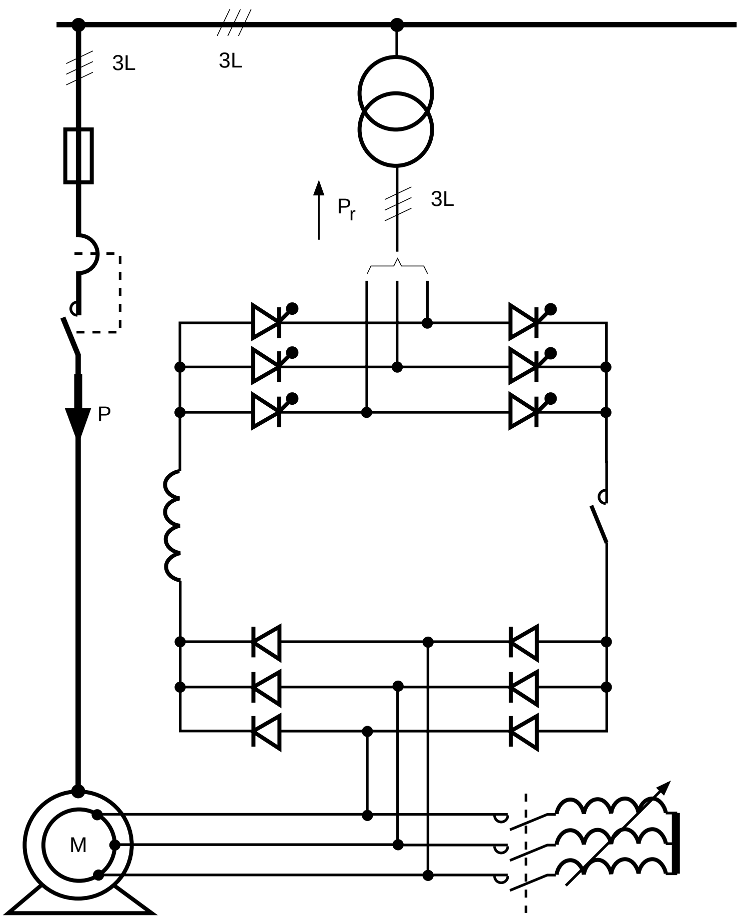


fig. 25: subsynchronous cascade power diagram.

4. protection of HV motors

"Motor protection" groups all the protection devices used to prevent serious damage due to abnormal operating conditions at supply, motor or process level.

The protection devices to be installed are chosen according to the following criteria:

- operating conditions;
- importance of the operation performed by the motor;
- the degree of dependability required;
- the relative cost of the protection device with respect to the motor;
- the likelihood of the faults considered occurring.

As well as:

- the type of load driven;
- disturbances which could occur on the network;
- the type of motor protected.

The faults listed below may therefore require use of a protection device.

main fault types

Asynchronous motors

- overloads;
- short-circuits;
- phase breaking, reversal and unbalance;
- insulation fault between turns;
- stator frame;
- under and overvoltage;
- incomplete starting.

Synchronous motors

All the above faults, plus:

- loss of synchronism;
- loss of excitation;
- rotor frame;
- prolonged operation in asynchronous mode on starting;
- overloads and short-circuits in the exciting winding;
- reverse power (operation on AC generator).

Other faults linked to the process or load

- over frequent starts;
- locked rotor;
- underpower or undercurrent.

The detection/protection processes for the main fault types are studied in the paragraph below.

protection principles

Overloads

Overloads can be detected by reverse time overcurrent relays, thermal image relays or heat sensors.

The relays process the information "current absorbed by the motor" which is generally detected by current transformers.

The heat sensors are inserted in the live parts of the motor.

■ reverse time overcurrent relays

Their use requires:

□ either an operating curve I(t) allowing starting, or a device blocking the relay during starting,

□ an operating threshold I_0 close to the rated current I_n of the motor

$I_0 \approx 1.10\ I_n$.

These relays do not memorise the overloads.

■ thermal image relays

These relays are certainly the most suitable since they ensure the greatest possible advantage is derived from motor overload possibilities without damage.

The operating curve I(t) of the relay must enable the starting current to flow without tripping and be approved by the motor manufacturer.

■ heat sensors

These are resistors, the ohmic value of which varies with temperature.

In theory these devices are not used by themselves, but rather back up the relays using the current absorbed as a measuring means.

Overloads due to temperature rise of a bearing are, in theory, insufficient for detection by the overload relays.

Bearings must therefore be protected by thermostats or heat sensors.

Short-circuits

Short-circuits on circuit-breaker equipment are detected by instantaneous operation overcurrent relays, set above the starting current.

On fuse-contactors, short-circuits are cleared by the fuses.

However, an useful solution is to add slightly time delayed overcurrent relays to the fuses. This means that the contactor can be used right up to its breaking capacity.

Phase breaking, reversal and unbalance

These faults are detected by a filter which highlights the negative phase sequence components.

It is vital to monitor phase breaking and unbalance since these faults give rise to:

- increased current, in the stator,;
- additional temperature rise by Joule effect, due to the fact that all out-of-balance states result in the appearance of reverse currents flowing through the rotor at twice supply frequency in the rotor.

Phase reversal is detected either by currents or voltages:

- by currents: this reversal is detected after contactor closing: the driven machine receives the fault;
- by voltages: this means contactor closing can be prohibited, if necessary, if phase order is not the normal network one.

Insulation fault in winding

Stator windings may have faults between turns on the same phase or between windings of different phases.

As a result of its electrical position, the fault may not be detected quickly enough by the overload protection device, thus causing serious damage. These faults are normally detected by current comparison.

■ longitudinal earth leakage protection

Provides protection against faults between windings of different phases. For this, the ends of the motor windings must be accessible on the neutral side.

Faults are shown up by comparing the input and output currents of the same phase (see fig. 26).
If there are no faults, these currents are identical and the protection relay is not tripped. It trips when the difference between these currents reaches a value set by the relay setting.

■ transverse earth leakage protection
Provides protection against faults between turns of the same phase.
It applies to machines with divided phases, i.e. with two windings per phase.
The operating principle is the same as above, that is the currents of each winding are compared (see fig. 27).

Stator frame

This protection device is vital to comply with the statement of the 14.11.1988 on workers' protection. It is chosen according to the earthing system of the network supplying the motor.

■ motor protection supplied by network with earthed or impedance-earthed neutral.
The fault is detected by measuring the zero sequence current formed between the faulty phase and the network frame. Low threshold overcurrent relays are used for measuring.
The zero sequence current is delivered by three parallel-connected current transformers or, better still, by a toroid (see fig. 28).
Use of a toroid prevents the appearance of a false zero sequence component due to unequal saturation of current transformers on motor starting, and allows a relatively low operating threshold.

These relays must operate for a fault current value such that frame potential compared with earth is never raised to more than 24 V in conductive environments, with frames interconnected, or 50 V in other installation cases.

Knowledge of earth connection value and of the frame interconnection configuration is therefore necessary to determine this setting point.
If the frames are not interconnected, the value of the operating threshold is given by:

$$I_F \leqslant \frac{24 \text{ or } 50\text{ V}}{R_{TM}}.$$

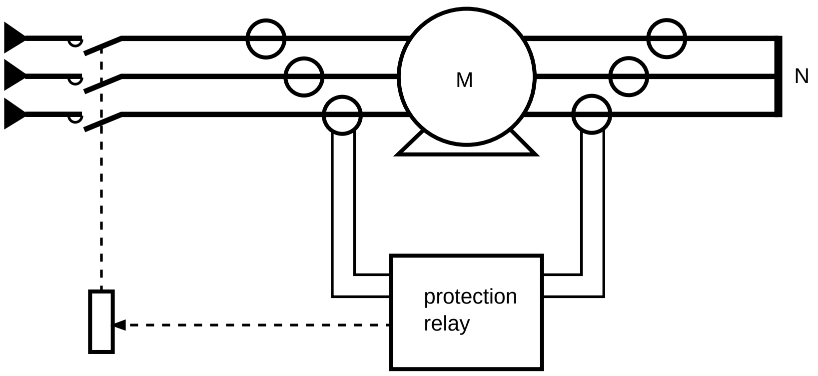


fig. 26: diagram showing a longitudinal earth leakage protection.

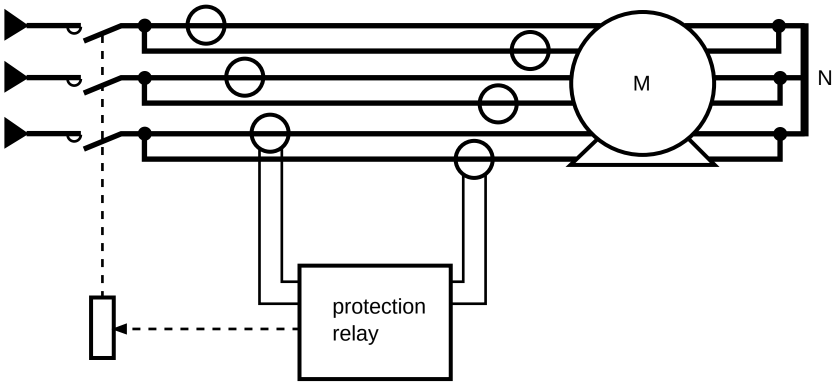


fig. 27: diagram showing a transverse earth leakage protection.

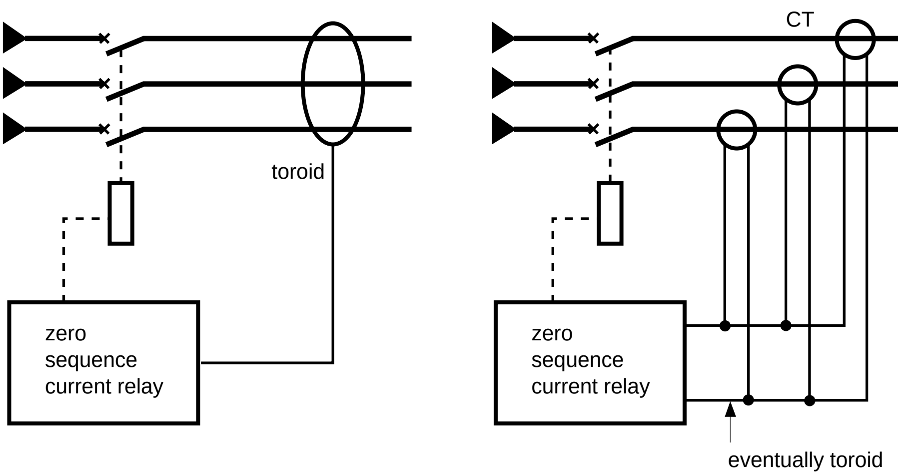


fig. 28: diagram showing a stator frame zero sequence protection with toroid sensor or CT + earthed or impedance-earthed neutral.

R_{TM} is the value of the earth resistance of the frame in question.
Note that the lower the threshold, the earlier the detection, and the smaller the risk of damage to the magnetic circuits.

■ unearthed neutral
The fault is detected by continuous measurement of global network insulation compared to earth by means of DC injection devices such as continuous insulation monitors (see diagram 1 in figure 29) or by zero sequence overvoltage relays where this overvoltage is delivered by three voltage transformers with the secondary winding in open delta (see diagram 2 in figure 29).

Under and overvoltage
(see fig. 30)

■ undervoltage
This relatively common protection prevents the motor from working on overload and waiting for tripping by the overload protection device. Moreover, if the contactor coil is supplied by an auxiliary LV source not from the network, the latch undervoltage protection device is vital to prevent untimely startup on restoration of power.

The "voltage" information is provided by a voltage transformer and processed by a time-delayable threshold device.

■ overvoltage
This protection is necessary if there is a risk of strong fluctuations occurring on the supply network. It means it is no longer necessary to wait for the overload relays to trip, since overvoltage results in motor overcurrent and increased motor torque which could be detrimental for the machine being driven.

The fault is detected by time delayed overvoltage measuring relays.

Incomplete or overlong starting
This protection is justified for starting in several stages.

It is provided by a time delay relay put into operation at the beginning of starting and removed at the end. The value monitored may be speed or current.

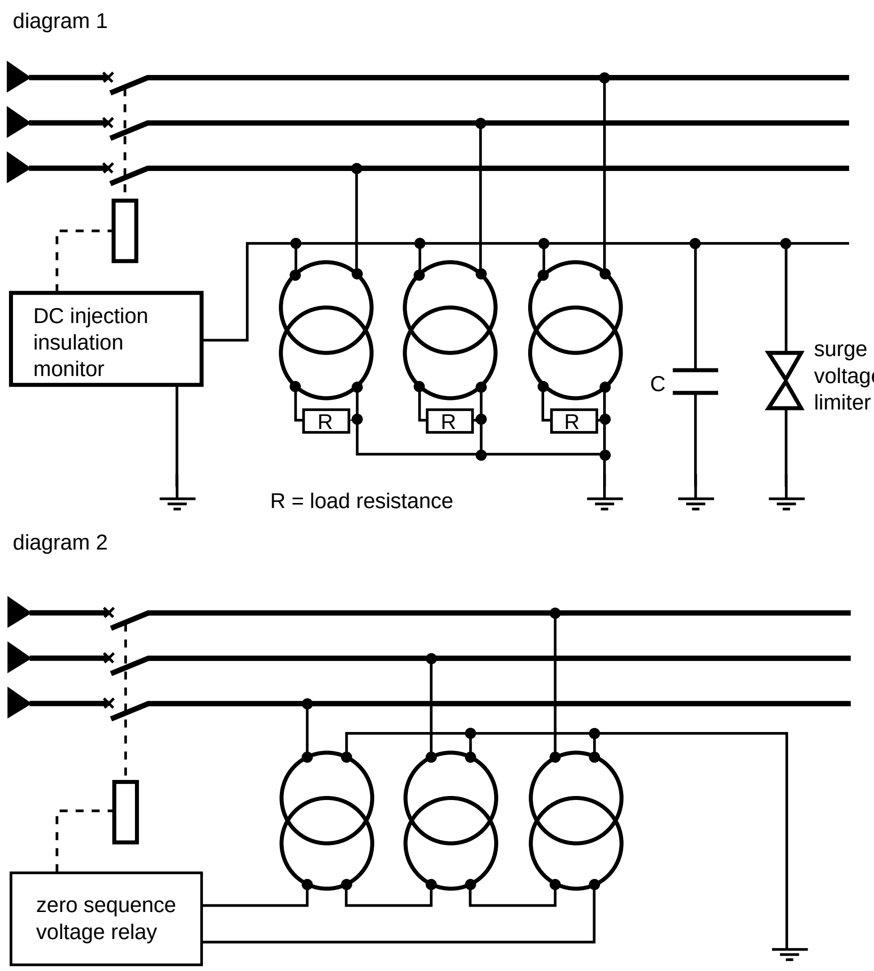


fig. 29: insulation fault monitoring diagram with continuous insulation monitor or zero sequence voltage relay - unearthed neutral

Prolonged use of the starting system, calculated to run for a set time, is thus avoided.

Loss of synchronism
This protection is vital for synchronous motors.
In point of fact, the dampening cage of a synchronous motor is relatively fragile. If the motor jams, induced currents will flow through this cage and could destroy it if the motor is not disconnected.
Jamming may occur following a mechanical overload, undervoltage, a loss of or drop in excitation.

This fault is detected by under impedance or power factor relays supplied by voltage transformers and current transformers (see fig. 31).

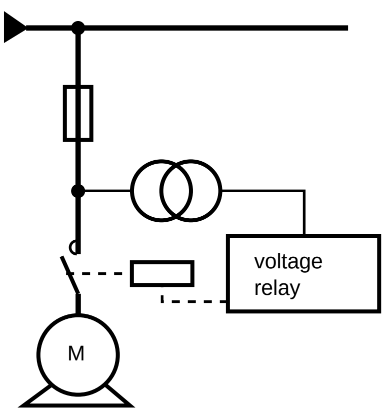


fig. 30: diagram showing under and overvoltage protection. In most cases, two VTs supply the relay phase-to-phase voltages.

Loss of excitation

This loss due, for example, to a break in rotor winding, causes the motor to jam.
It can be detected by:
- the "loss of synchronism" protection described above;
- or an exciting undercurrent or undervoltage relay.

Rotor frame of a synchronous motor

This protection is determined according to the supply configuration and the DC production mode.

If the entire DC exciting circuit is unearthed, an insulation fault will not affect motor operation.
However, should a second fault occur, it may give rise to an overload or short-circuit with all its consequences. The relays used to detect this type of fault are generally devices injecting low frequency 10 Hz or 20 Hz AC current (see fig. 32).

The 50 Hz frequency is also used, which requires that no 50 Hz components must be present in the exciting circuit.

Prolonged operation in the asynchronous mode on starting

Overlong starting on synchronous motors causes excessive temperature rise of the damping cage.

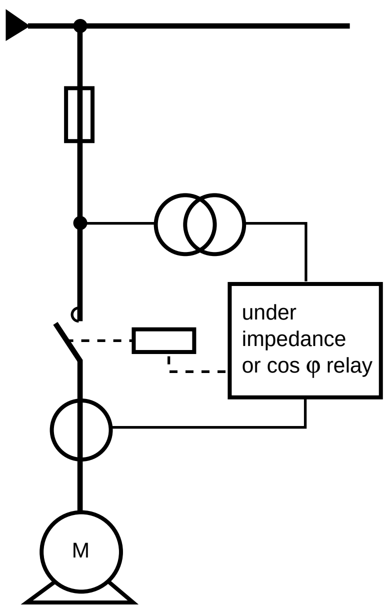
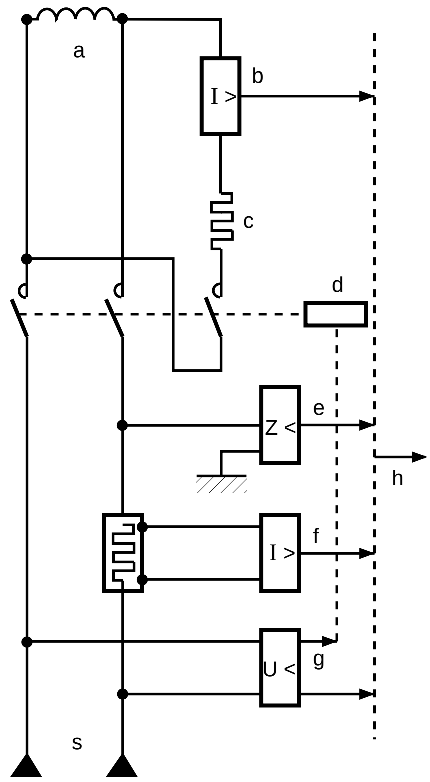


fig. 31: protection against loss of synchronism.

Either the "incomplete starting" protection described above is used or a thermal device adapted to the rotor thermal time constant, placed in series with the inductance during starting (see fig. 32 element b).

Overload and short-circuit in the exciting winding

These protection devices prevent damage due to temperature rise of the exciting winding and its power supply. The fault is detected by an exciting overcurrent relay. Moreover an exciting undervoltage relay is normally used, tripping on voltage drop, caused for example by a short-circuit.



a. exciting winding
b. thermal protection: prolonged operation in asynchronous mode
c. starting resistance
d. exciting contactor
e. rotor frame protection
f. overcurrent protection
g. undervoltage protection
h. to tripping of motor feeder contactor
s. continuous source

fig. 32: rotor protection devices on startup and in operation.

On starting, it is used as an exciting voltage presence relay and authorises closing of the exciting contactor at the end of starting in the asynchronous mode (see fig. 32 element g).

Reverse power

This protection particularly applies to synchronous motors.

When the supply circuit-breaker trips, it prevents energy from being sent back to the loads connected on the same busbar. It also prevents a fault on this busbar from being supplied by the motor.

The protection device has to detect a reversal in current or power direction. Its function is therefore performed by a directional power relay (see fig. 33).

Frequent starts

Too many starts over a given period of time may cause motor damage if the motor is not designed for such an operation.

This protection is provided by a relay performing metering and time delay functions, which automatically limits:
- either the number of starts over a given period of time;
- or the time interval between start ups over a given period of time.

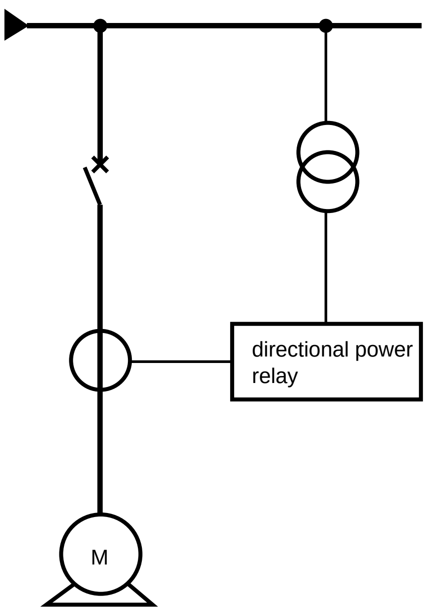


fig. 33: protection against reverse power.

Locked rotor

Jamming of a motor for mechanical reasons causes an overcurrent roughly equivalent to starting current. The resulting temperature rise is considerably greater since rotor losses are maintained at their highest value throughout jamming and ventilation is no longer present if connected to rotor rotation. As a result, when there is a risk of jamming, the "locked rotor" protection is necessary since overload relays sometimes have an excessively long response time.

This fault is detected by an overcurrent relay set at a value less than the starting current. This value is validated after a time delay initiated when the motor is energised. This time delay is set at a value greater than or equal to normal starting time.

Undercurrent or underpower

Pumps may be damaged when unpriming occurs. Unpriming could also result in a drop in the active power absorbed by the motor. Protection against this fault is provided by an undercurrent relay.

technological evolution

The term "relay" is often used in the above description of the various protection devices. This is a the traditionally used term (relay = a type of protection device) which goes back to the time when motor protection required the use of separate "relays" each with a single protection function.

In the seventies, manufacturers brought out RACKS able to house a number of different protection devices in order to meet needs more closely.

In the eighties digital technology increased adaptation possibilities still further. Thus a single programmable device performs the various protection and control/monitoring functions required in each specific case.

appendix 1: determining motor starting mode

The purpose of the example below is not to fully deal with a problem but rather to illustrate, through an example, an approach wich helps to choose the appropriate starting mode for a given application.

calculation hypotheses

Asynchronous motor with:

■ rated power P_n = 1,500 kW;

■ rated voltage U_n = 5,500 V;

■ efficiency x power factor: $\eta \times \cos\varphi = 0.84$;

■ starting torque/rated torque ratio on full voltage:

$$\frac{C_d}{C_n} = 0.8$$

■ starting current/rated current ratio on full voltage:

$$\frac{I_d}{I_n} = 5;$$

■ breakaway torque of the driven machine: 0.2 C_n;

■ main supply transformer power: P_t = 3 MVA;

■ maximum apparent power inrush authorised by the transformer network: S_t = 6 MVA.

Other data necessary for calculation:

■ torque-speed C (N) characteristic of the motor;

■ load torque-speed C_r (N); characteristic of the driven machine

■ transformer delivery on feeders other than the motor one: 1,200 kVA under $\cos\varphi' = 0.87$.

overall approach

The approach chosen by the designer is to look for the best technico-economic choice. For this, first try and validate the easiest and most economical solution. Then, if this does not work, follow the order shown in the table in figure 34.

Direct starting

Motor apparent power at the beginning of starting:

$$S_m = \frac{P_n}{\eta \cos\varphi} \frac{I_d}{I_n}$$

$$S_m = \frac{1{,}500}{0.84}\, 5 = 8{,}925 \text{ kVA}$$

where, with power factor on starting: $\cos\varphi_d = 0.15$, i.e. : $\varphi_d = 81°$.

This power is vectorially added to the power delivered by the transformer on the other feeders (see fig. 35).

The total value of the apparent power required by the transformer is graphically deduced from the following: $S \approx 9{,}580$ kVA.

The maximum inrush authorised is 6,000 kVA: direct starting is thus not possible.

Starting by reactance

Introduction of a reactance reduces the apparent power absorbed by the motor. The available starting power is graphically determined (see fig. 35).

When the motor starts, the presence of the reactance means that the power factor approaches zero. Thus $\varphi_d \approx 90°$.

$\vec{OA} = 1{,}200$ kVA: transformer power used on other feeders.

$\vec{OB} = S_t = 6{,}000$ kVA: maximum apparent power authorised. The apparent power available for starting (motor + reactance) is graphically deduced.

$\vec{AB} = S_d = 5{,}300$ kVA.

Power reduction to be caused by the reactance:

$$\frac{S_d}{S_m} = \frac{5{,}300}{8{,}925} \approx 0.6.$$

starting solutions	main acceptance criteria
direct	power inrush compatible with network
reactance	■ starting torque greater than breakaway torque ■ current peak (for full voltage resumption) acceptable by network
autotransformer	the same

fig. 34: decisive criteria for choosing motor starting mode.

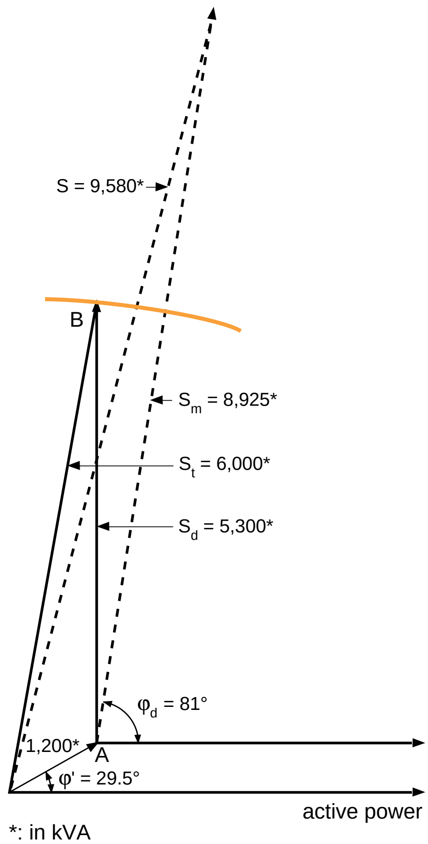


fig. 35: starting power diagram.

I'd is the new starting current value.

$$S_d = U_n \; I'_d \; \sqrt{3}$$

$$S_m = U_n \; I_d \; \sqrt{3}$$

thus: $I'_d = 0.6 \; I_d$.

Moroever: $\dfrac{I'_d}{I_d} = \dfrac{U_d}{U_n} = 0.6$.

The value of voltage at the motor terminals is $U_d = 0.6\ U_n$. Once the electrical problem has been solved, it remains to be seen if this solution is valid from the mechanical standpoint. In the case of direct starting, the starting torque equals : $C_d = 8\ C_n$ (see fig. 36).

In the case of starting by reactance, the starting torque C'_d equals:

$$C'_d = 0.8 \; C_n \left(\frac{U_d}{U_n}\right)^2 = 0.288 \; C_n$$

This value is compatible with the breakaway torque of the machine being driven.

One last point remains to be checked: if the point of mechanical balance $C_m = C_r$ is placed at an excessively low speed, a current peak may occur on the move to full voltage. If this peak is too high for the network, the starting mode will have to be reconsidered and starting by autotransformer, for example, chosen (see fig. 36).

Remark 1

Let us assume that the value of the breakaway torque of the driven machine is 0.35 C_n instead of 0.2 C_n. Starting by reactance is then incompatible with the breakaway torque.
The solution of starting by autotransformer must then be envisaged.

The apparent power available remains S_d = 5,300 kVA. From this value the magnetising force of the auto-transformer S_{mg} must be deduced which, at the initial starting moment, is arithmetically added to motor apparent power. S_{mg} is around 0.2 to 0.4 times motor apparent rated power.

i.e. with the factor 0.4:

$$S_{mg} = 0.4 \left(\frac{P_n}{\eta \; \cos \varphi}\right)$$

$$S_{mg} = 0.4 \; \frac{1{,}500}{0.84} = 720 \text{ kVA}.$$

The power reduction factor is then:

$$\frac{S_d - S_{mg}}{S_m} = \frac{5{,}300 - 720}{8{,}925} = 0.513$$

At constant voltage U_n, the current inrush on the network side is therefore: 0.513 I_d.

Determining the reduced starting voltage U_d.

Equality of primary and secondary autotransformer powers results in the following:

$$0.513 \; I_d \; U_n = I''_d \; U_d$$

I''_d is the reduced voltage starting current on the motor side

$$0.513 \; I_d \; U_n = I_d \; \frac{U_d}{U_n} \; U_d$$

hence: $\left(\dfrac{U_d}{U_n}\right)^2 = 0.513$

i.e. $U_d = 0.718\ U_n$

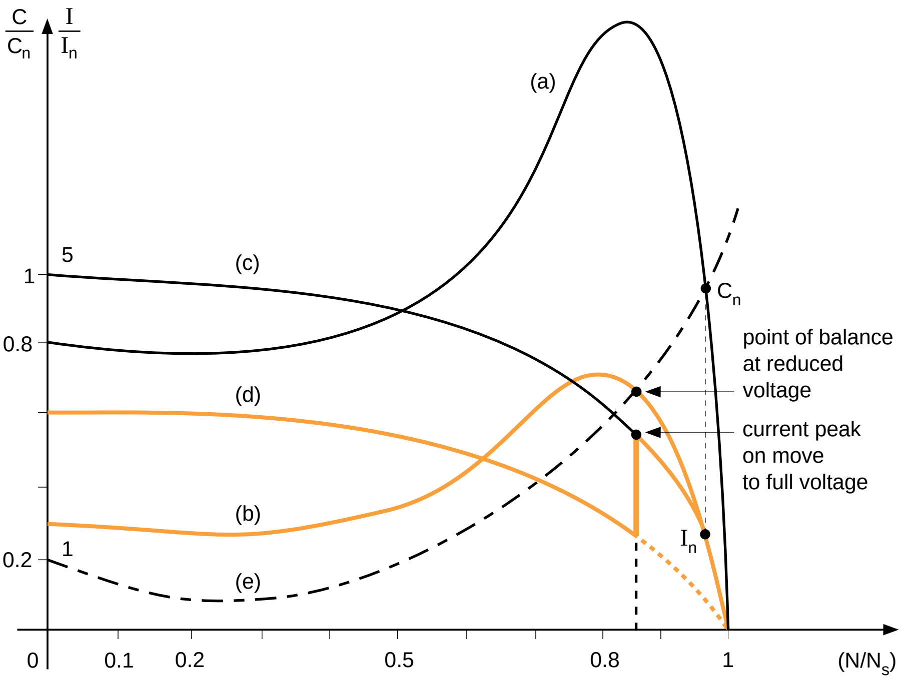
New starting torque:

$$0.8 \; C_n \left(\frac{U_d}{U_n}\right)^2 = 0.41 \; C_n.$$

This value is sufficient for starting to take place.

Remark 2

For a breakaway torque greater than 0.41 C_n, stator starting with this motor is no longer possible.
Either a slipring rotor motor with rotor starting must be used, or a motor with a special cage possessing a high starting torque.



a: curve C (N) on full voltage
b: curve C (N) on reduced voltage (0.6 U_n)
c: curve I (N) on full voltage
d: curve I (N) on reduced voltage (0.6 U_n)
e: curve C_r (N)

fig. 36: torque and current curves for starting by reactance.

appendix 2: coordination of protection devices

Once the protection devices have been chosen according to operating requirements, they must be coordinated to obtain the maximum advantage from their possibilities. A balance must be sought between untimely tripping and delay on fault removal. The problem of protection device coordination is solved by studying the curves t (I) of the relays, of the circuit-breaker and of the breaking capacity of the contactor. The characteristics of the motor shown in the figure are as follows:

- P_n = 550 kW;
- U_n = 3150 V;
- I_n = 130 A;
- $I_d = 5\ I_n$.

The contactor is of the Rollarc fuse type.

Type of protection devices

- thermal relay with indirect tripping, set at I_n = 130 A for overloads;
- positive phase sequence component relay set at 6 I_n, time delayed at 0.05 s for balanced faults;
- negative phase sequence component relay set at 0.3 or 0.4 I_n, time delayed at 0.6 s.

In the case of networks with quasi-permanent unbalances, a two-threshold relay is used:

- a lower time delayed threshold, set just above the permanently accepted negative phase sequence component ratios;
- an upper instantaneous threshold for phase break protection.

Instantaneous tripping by the positive phase sequence component relay enables best use to be made of the contactor's breaking capacity and avoids fuse melting. Analysis of the curves in figure 37 shows that the motor and network are protected against:

- unbalances of approximately 0.3 I_n to 10 I_n,
- balanced faults from 6 I_n to 28 I_n.

The fuses only take action beyond 15 I_n for unbalanced faults and 25 I_n for balanced faults.

The maximum current the contactor may have to break is 28 I_n = 3,640 A. This value is considerably lower than its breaking capacity of 10 kA.

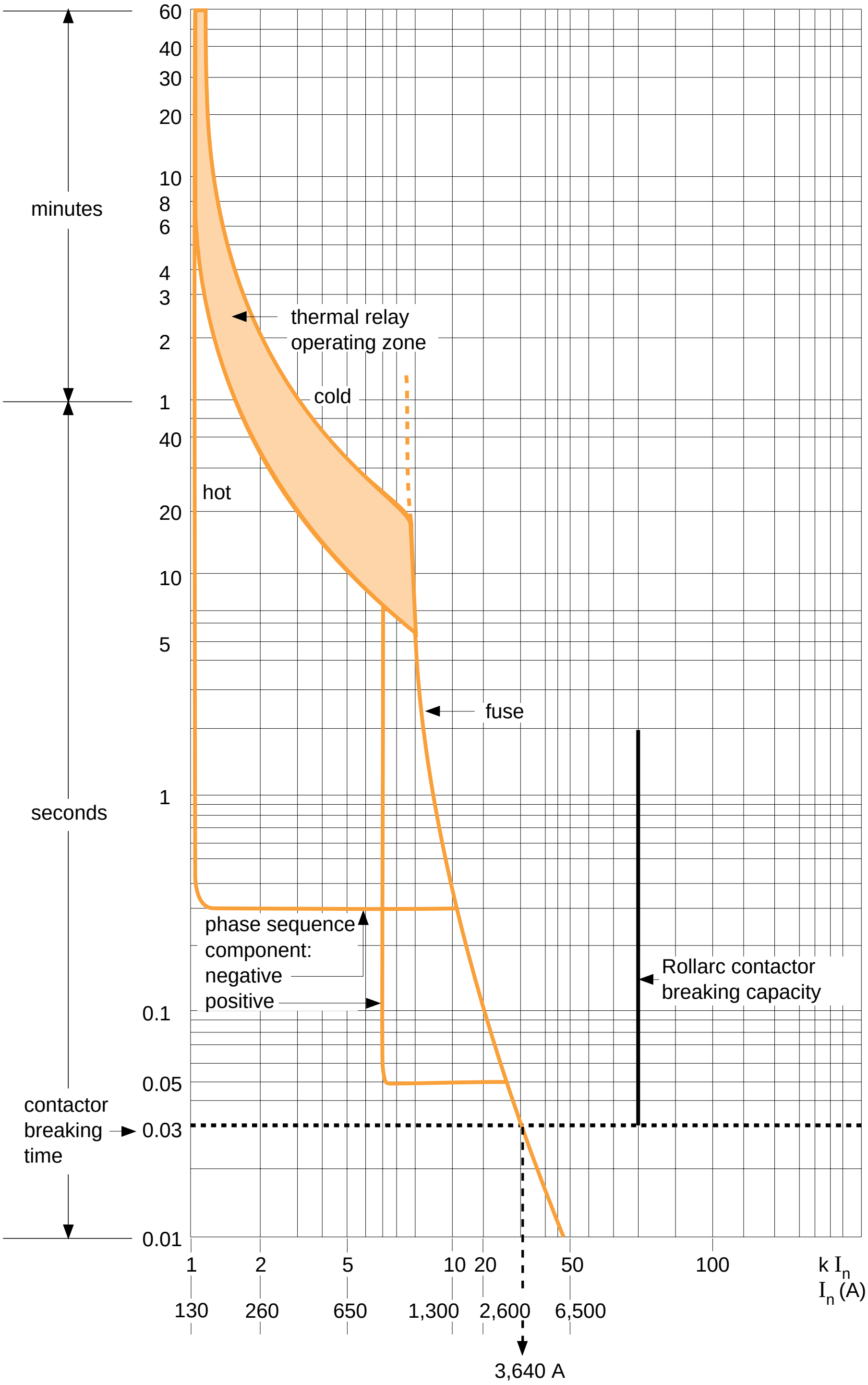


fig. 37: minutes thermal relay operating zone.

appendix 3: bibliography

Standards

- IEC 34-1: Rotating electrical machines.
- IEC 71: Insulation coordination.

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