3. Loads and their power supply constraints
3. LOADS AND THEIR POWER SUPPLY CONSTRAINTS

3.1. Disturbance in industrial networks

The types of disturbance affecting industrial networks may be grouped into four categories: variations in voltage amplitude, modifications in waveform, three-phase system unbalance and frequency fluctuations around 50 Hz.

- frequency variations

The frequency variations that may exist depend on whether or not there is a utility power supply.

- public distribution network

Frequency fluctuations in a public distribution network are rare and are only encountered in exceptional circumstances such as serious faults on the production and transmission network. This type of disturbance notably occurs when there is no longer balance between the production and consumption of electrical energy.

In most public networks, frequency variation does not exceed 1 Hz above or below the nominal frequency (50 or 60 Hz).

- independent network fed by an autonomous production source

High variations in load cause variations in frequency. A load-shedding system allows the frequency to be maintained in the event of an overload. (see § 12.2.3.3.).

Standard 1000-2-4, paragraph 4-4, on compatibility levels in industrial installations states that frequency variations can be as much as ± 4 %.
- **amplitude variations**

- **voltage dips and short supply interruptions**

A voltage dip is a reduction of at least 10% of the voltage for a half period up to several seconds (see fig. 3-1).

![Figure 3-1: voltage dip](image)

A short supply interruption is a dip of 100% for over several seconds and less than one minute.

- **voltage fluctuations** (flicker)

Voltage fluctuations are periodic or random fluctuations in the voltage envelope. Their amplitude is lower than 10% of the nominal voltage (see fig. 3-2).

![Figure 3-2: examples of voltage fluctuation](image)

This type of disturbance is known as “flicker” because of its flickering effect on lighting. Flicker is defined in standard IEV 161-08-13 as the impression of instability in visual sensation due to a lighting stimulus the brightness or colour of which fluctuates in time. It may be a source of annoyance for people in workshops, offices or residential buildings by causing visual and nervous fatigue. Standard IEC 1000-2-2 defines the allowable flicker curve and gives the amplitude of maximum voltage variations in relation to the variation frequency (see fig. 3-3).
Figure 3-3: amplitude of maximum variations in relation to variation frequency
waveform modifications: harmonics

Due to the specific nature of harmonics, they have been dealt with in a separate chapter (§ 8). Any problems concerning harmonics in loads will be referred to this chapter.

three-phase system disymmetry: unbalance

The three-phase network is unbalanced when the three voltages of the three-phase system are not equal in amplitude or are not phased by 120° in relation to each other.

The rate of unbalance is defined as being the ratio of the negative-sequence component module to the positive-sequence component module, \( \tau = \frac{V_2}{V_1} \)

In practice, an approximate unbalance value may be obtained by the ratio:

\[
\frac{\text{Maximum value of the difference between any one of the three voltages }}{\text{Mean value of the three voltages}} \quad \text{where} \\
V_{\text{mean}} = \frac{V_1 + V_2 + V_3}{3}
\]

compatibility level

This is the specified maximum disturbance level expected to be impressed on a device.

Standard IEC 1000-2-4 defines compatibility levels on industrial networks (see table 3-1).

It applies to low and medium voltage networks.
Compatibility levels are given for different classes of environment:

**Class 1**
This class applies to protected networks and has lower compatibility levels than those of public networks. It refers to the use of devices that are very sensitive to power network disturbance, for example technological laboratory instrumentation, some automatic and protection equipment and certain computers, etc.
It normally contains equipment that needs to be fed by an uninterruptible power supply. It only applies to **low voltage** networks.

**Class 2**
This applies to the utility’s point of supply and to the internal network. The compatibility levels are identical to those of public networks.

**Class 3**
This only applies to the internal network. The compatibility levels are higher than those of class 2.

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage variations</td>
<td>± 8 %</td>
<td>± 10 %</td>
<td>+ 10 % to + 15 %</td>
</tr>
<tr>
<td>Voltage dips</td>
<td>10 % to 100 %</td>
<td>10 % to 100 %</td>
<td>10 % to 100 %</td>
</tr>
<tr>
<td>duration at ( f = 50 \text{ Hz} )</td>
<td>10 ms</td>
<td>10 ms to 3s</td>
<td>10 ms to 3 s</td>
</tr>
<tr>
<td>Voltage unbalance</td>
<td>2 %</td>
<td>2 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Frequency variations</td>
<td>± 1 %</td>
<td>± 1 %</td>
<td>± 2 %</td>
</tr>
<tr>
<td>Flicker</td>
<td></td>
<td></td>
<td>See fig. 3-3</td>
</tr>
</tbody>
</table>

*Table 3-1: Compatibility levels on low and medium voltage industrial networks*
3.2. Ways of providing against flicker

There are different ways of limiting the flicker phenomenon.

- **choice of lighting mode**

  There are lighting sources which are more or less sensitive to flicker. The first and most obvious solution is to make the right choice in lighting.

  Fluorescent lamps are two or three times less sensitive to voltage variations than incandescent lamps. They are thus the best choice in relation to flicker.

- **uninterruptible power supply (UPS)**

  In the case where flicker only affects a specific group of users, it may be possible to “clean” the lighting outlet by installing a UPS (see § 1.6.3).

  The investment of such an installation may be relatively low, but it only provides a local solution.

- **modifying the source of disturbance**

  Flicker may be reduced by modifying the operating cycle of the disturbing load: welding rate, furnace filling speed, etc.

  When flicker is caused by a motor being started up directly and frequently, a starting mode which reduces the overvoltage may be adopted.

- **addition of an inertia storage flywheel**

  In some specific cases a motor with a variable load or an a.c. generator whose drive machine power is variable may cause voltage fluctuations. An inertia storage flywheel on the shaft reduces these fluctuations.

- **rotating converter**

  A generating-motor set which supplies power to the fluctuating load is a valid solution if the active power of this load is relatively constant, but it is expensive.
modifying the network

Depending on the structure of the network, there are two methods possible:
- move away (electrically), or even isolate, the disturbing load from the lighting circuits
- increase the network short-circuit power by reducing its impedance.

To do this, there are various solutions:
- connecting the lighting circuits as near as possible to the utility take over point
- increasing the common transformer power (with constant $U_{sc}$)
- decreasing the short-circuit voltage ($U_{sc}$ %) of the common transformer (with constant power)
- connecting extra transformers in parallel
- in LV, reinforcing the cross-section of conductors located upstream of the disturbing load
- connecting the disturbing load to a higher voltage network
- feeding the disturbing load via an independent transformer.

series capacitor (see fig. 3-4-a)

Introducing a series capacitor into the network, upstream of the disturbing load and flicker-sensitive circuit connection point, may halve voltage fluctuations. This solution offers an extra advantage since it also ensures the production of reactive energy. On the other hand, it also has a drawback since the capacitors must be protected against short circuits downstream.

Figure 3-4-a: Series capacitor in the network
**series reactor** (see fig. 3-4-b)

This solution, which is used in arc furnaces, may reduce the flicker rate by 30%. The reactor is inserted in series with the HV power supply of the furnace downstream of the connection point. It may be included in the furnace transformer. It often has an off-circuit setting device (bolted connectors) and a short-circuiting possibility.

The main “positive” effect that it has on voltage variations is that it reduces the current demand from the furnace. Furthermore, it stabilises the furnace arc. Thus, voltage fluctuations are less brusque and random operation of the arc is reduced.

The drawback is that the furnace load current flows through the reactor which thus consumes reactive energy.

![Figure 3-4-b: series reactor](image)

**saturated shunt reactor** (see fig. 3-4-c)

When connected as close as possible to the source of flicker, such a reactor may reduce fluctuations above the nominal voltage by a factor of 10, but does not work for fluctuations below the nominal voltage as the reactor does not saturate.

These reactors have their drawbacks:

- they consume reactive current
- they produce harmonics
- they are rather expensive.

![Figure 3-4-c: Saturated shunt reactor](image)
**Decoupling reactor** (see fig. 3-4-d)

This process is highly efficient since it can reduce fluctuations by a factor of 10. But it requires an appropriate network configuration.

An impedance is introduced into the disturbing load power supply. Through a special autotransformer connected to this impedance, the voltage opposed to the disturbance on the network sensitive to flicker is added. There is no reduction in flicker upstream of the device.

![Decoupling reactor](image)

*Figure 3-4-d: Decoupling reactor*

**Synchronous compensator** (see fig. 3-4-e)

This solution leads to a 2 to 10% reduction in fluctuations and up to 30% with modern electronic control systems.

The compensator is sometimes completed with (linear) damping reactors installed on the power supply.

Synchronous compensators are currently being replaced by static compensators. But they may still serve a purpose if they are already installed and can be restarted.

![Synchronous compensator](image)

*Figure 3-4-e: Synchronous compensator*
Voltage drops caused by single-phase fluctuating loads are greatly reduced by phase converters, rotating machines and transformers with special vector group or Steinmetz bridge (see fig. 3-5). The latter allows a single-phase resistive load to be re-balanced.

Thus, a single-phase load \( S_m = P_m + jQ_m \) may be compensated by a load \( -jQ \) on the same phase. This results in a purely resistive single-phase load \( P_m \) which can be compensated by adding inductive and capacitive admittances on the other two branches.

This set-up is equal to a purely resistive balanced three-phase load with a power of \( \frac{P_m}{3} \) on each phase.

When the single-phase load \( S_m \) is highly fluctuating, an electronic power device may provide dynamic compensation, practically in real time. In this case, the Steinmetz bridge becomes a "static compensator".

**Figure 3-5: Steinmetz bridge arrangement for compensating a single-phase load with a phase-to-phase power supply (block diagram)**
**Static Var Compensator (SVC) (see fig. 3-6)**

This SVC device is designed to provide real time reactive power compensation. It can also be used to reduce flicker by 25% to 50%.

It has compensation reactors, a fixed filter-mounted shunt capacitor bank (tuned to different frequencies, 150 Hz, 250 Hz, etc.) and a thyristor based electronic device. The role of the electronic device is to make the reactive energy consumption of the reactors vary in order to maintain the reactive power absorbed by the flicker generator set, fixed capacitor bank and compensation reactors practically constant.

This phase by phase compensation is obviously useful for arc furnaces whose operating modes are particularly unbalanced.

The performance of such a compensator is very good.

*Figure 3-6: static var compensator installation diagram*
# recapitulative table

Table 3-2 summarises the solutions that may be used and their cost effectiveness in relation to the type of load producing flicker.

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Fluctuating loads</th>
<th>Motor start-up</th>
<th>Motor with fluctuating load</th>
<th>Arc furnace</th>
<th>Welding machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modification of disturbing part</td>
<td>+ c</td>
<td>-</td>
<td>+ b</td>
<td>+ b</td>
<td></td>
</tr>
<tr>
<td>Inertia storage flywheel</td>
<td>-</td>
<td>+ a</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Rotating converter</td>
<td>+ c</td>
<td>+ c</td>
<td>+ b</td>
<td>+ c</td>
<td></td>
</tr>
<tr>
<td>Network modification</td>
<td>+ b</td>
<td>+ b</td>
<td>+ a</td>
<td>+ b</td>
<td></td>
</tr>
<tr>
<td>Series capacitor</td>
<td>+ b</td>
<td>+ b</td>
<td>+ c</td>
<td>+ b</td>
<td></td>
</tr>
<tr>
<td>Series reactor</td>
<td>-</td>
<td>-</td>
<td>+ a</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Saturated shunt reactor</td>
<td>-</td>
<td>-</td>
<td>+ c</td>
<td>+ c</td>
<td></td>
</tr>
<tr>
<td>Decoupling reactor</td>
<td>+ c</td>
<td>+ c</td>
<td>+ c</td>
<td>+ b</td>
<td></td>
</tr>
<tr>
<td>Synchronous compensator</td>
<td>+ c</td>
<td>+ c</td>
<td>+ a</td>
<td>+ b</td>
<td></td>
</tr>
<tr>
<td>Phase converter</td>
<td>-</td>
<td>-</td>
<td>+ c</td>
<td>+ b</td>
<td></td>
</tr>
<tr>
<td>Static var compensator</td>
<td>+ b</td>
<td>+ b</td>
<td>+ a</td>
<td>+ b</td>
<td></td>
</tr>
</tbody>
</table>

- : technically inappropriate
+ : technically possible
a : often economic
b : sometimes cost effective
c : rarely cost effective

*Tableau 3-2: solutions for reducing flicker*
3.3. Electric motors

There are two types of electric three-phase motors:

- asynchronous motors
- synchronous motors.

We shall not deal with direct current motors in this chapter.

3.3.1. Asynchronous motors

**make-up of asynchronous motors**

The stator and rotor separated by the air-gap are made up of a magnetic circuit, which channels most of the magnetic flux, and coils, which are housed in slots spread over the inside diameter for the stator and around the periphery for the rotor.

The stator coils, which are generally three-phase, are connected to the network.

Depending on the type of rotor coils, a distinction is made between two large classes of asynchronous motors:

- slip-ring or wound rotor machines
- "squirrel cage" or short-circuited rotor machines.

**slip-ring or wound rotor machines** (see fig. 3-7)

![Wound rotor diagram](image)

*Figure 3-7: wound rotor*

The rotor windings are always three-phase with a star connection.

The ends of the rotor winding are accessible and are connected to slip-rings mounted on the shaft on which the carbon brushes rub. It is thus possible to connect extra circuit parts in series with the rotor circuit, to allow for adjustments, for example of the starting torque (see fig. 3-37) or speed (see fig. 3-22).
“cage” or short-circuited rotor machine

- **single cage rotor** (see fig. 3-8)

The rotor circuit is made up of conductive bars evenly spread out between two metal rings making up the ends, the complete assembly being shaped like a squirrel cage. Of course, this cage is inserted inside a magnetic circuit similar to that of the wound rotor motor.

This type of motor, which is much easier to build than the wound rotor motor, costs less and is much more robust. It is therefore not surprising that it is far more widely used for asynchronous motors already installed.

Its major drawback is that a rheostat cannot be installed and, on start up, its performance is poor (high current and low torque). It is to solve this problem that two other types of motor have been developed (double cage rotor and deep slot rotor).

![Figure 3-8: single cage rotor](image)

- **double cage rotor**

The rotor has two coaxial cages (see fig. 3-9):

- one (frequently made of brass or bronze), on the outside, with a relatively high resistance, is positioned near the air-gap

- the other (made of copper), on the inside, with a lower resistance, is embedded in the iron and thus has a higher leakage inductance than the first.

![Figure 3-9: double cage rotor](image)
On starting the rotor current, which has a frequency equal to the frequency $f$ of the power supply network, spreads out in an inversely proportional manner to the cage reactances, which are thus high compared with the resistances. In such conditions, the maximum current flows through the external cage; the cage’s relatively high resistance reduces the current inrush and increases the torque.

On the other hand, when the motor reaches its nominal operating mode, normally characterised by a small slip $s$ and a low frequency $sf$, it is the resistance which controls the current distribution and which encourages the current to flow through the low resistance internal cage.

We can thus obtain starting torques approximately two or three times higher than those of the single cage.

Figure 3-10 shows, in relation to the speed, the torque variation of a double cage motor, whose external cage is designed to obtain the maximum starting torque.

![Figure 3-10: torque curve of a double cage motor in relation to its speed](image)

- $T_n$: nominal torque
- $N$: rotor speed
- $N_s$: synchronism speed
• deep slot rotor

It is a lot more difficult to build a double cage rotor than a single cage rotor and it is thus more costly.

This drawback can be overcome, while keeping part of the the advantages of the double cage, by building a single rotor cage with very flat bars which are deeply embedded in the magnetic circuit (see fig. 3-11-a):

![Diagram of deep slots and trapezium conductors](image)

- on **starting**, the reactance is preponderant compared with the resistance as the rotor current frequency is equal to $N_s$ (see § operating principle). The reactance, which increases with the depth, tends to force the current lines to group up near the periphery and it thus provides them with a smaller cross-section and an increased resistance. This then reduces the current inrush and increases the torque.

- on the other hand, during **normal running**, the reactance is weak compared with the resistance as the rotor current frequency is low ($sN_s$). Thus, the effect described on starting disappears and the current lines, by occupying the full cross-section of the bar, have a low resistance circuit.

This type of motor, called a **deep slot** motor, is widely used, notably in the case of high voltage and high starting torque motors. It nevertheless has the drawback of leading to a reduction in the motor power factor, and, of course, it needs a much larger rotor diameter.

To get over the latter problem, conductors with more complicated shapes, **trapezium** shaped (see fig. 3-11-b) or even **L** shaped (with the base of the **L** forming the bottom of the slot) have sometimes been used.
operating principle

Let us consider the case of the wound rotor machine. From an electrical point of view, this machine can be compared to a transformer if the slip-rings are not connected to an external circuit; the voltage collected on the slip-rings may in fact be different from the voltage applied to the stator, taking into account the turns ratio linked to the ratio of the number of rotor/stator turns.

The stator coils are spread out in the space so that a field rotating at a speed of \( N_s \) is created. Being subjected to this variable field, the rotor conductors collect induced voltage. If the rotor coils are also appropriately spread out, even if there is a different number of phases from that of the stator, an a.c. voltage is collected at each end.

If we join these two ends, current is generated (at the network frequency, the rotor being stopped), creating a reaction flux against this phenomenon, as well as forces that make the rotor turn in the direction of the stator field.

With the rotor rotating at a speed \( N \), the induced current frequency decreases and becomes matching the relative speed \( N_s - N = sN_s \) of the rotating field in relation to the rotor. The field created by the induced current rotates in relation to the rotor at a speed of \( sN_s \), in other words in relation to the stator at the speed of:

\[
N + sN_s = N_s
\]

Since the stator and rotor fields rotate at the same constant speed \( N_s \), the relative position of the stator poles and those of the rotor is stationary. These poles can thus constantly attract or repel each other in time which creates a constant torque on the shaft. Thus, as in all electrical rotating machines producing a constant torque, and in particular for synchronous machines, the rotor field is latched to that of the stator; but here the rotor must slip in relation to its own field in order to provide the torque. If the rotor rotates at the same speed as the stator field, no current is induced on the rotor; having become passive, the rotor cannot produce a torque. It should be added that if the rotor rotates at a higher speed than the stator field, the machine operates as an asynchronous generator (see § 4.3).
rotor slip in relation to the stator's rotating field

As illustrated in the introduction, the rotor speed $N$ of an asynchronous motor is necessarily lower than the speed of the rotating field $N_s$ (synchronous speed reached during no-load operation only). The relative difference of speeds is called the "slip" $s$:

$$s = \frac{N_s - N}{N_s}$$

where:

$$N_s = 60 \frac{f}{p} \text{ (tr/min)}$$

$f$ : network frequency (Hz)

$p$ : number of pairs of poles

In practice, the nominal slip remains small (several percent for small motors, less than 1% for large).

asynchronous motor power layout

On the stator and rotor of the asynchronous motor there are conductors through which current flows: the stator and rotor are thus the seat of Joule loss. Similarly, each of their iron parts is subjected to variable inductions which cause eddy current loss. Figure 3-12 illustrates the power transfer loss.

The relation defining rotor Joule loss illustrates the comparison that is often made between an asynchronous machine rotor and a friction clutch; in the latter, the friction loss is equal to the product of the torque transmitted by the speed difference between the primary and secondary.

In the breakdown of the overall efficiency $\eta = P_u / P_o$, the rotor Joule loss part, characterised by the term $(1 - s)$ (called "rotor efficiency"), can be noted. With the overall efficiency being necessarily lower than $(1 - s)$, good efficiency can only be obtained if the slip value is relatively low.
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Figure 3-12: asynchronous motor power arrangement

\[ \Omega_s = \frac{N_s}{60} \cdot 2\pi \] : angle frequency corresponding to the synchronism speed

\[ \Omega = \frac{N}{60} \cdot 2\pi \] : angle frequency corresponding to the rotor speed

\[ T_t \] : electromagnetic torque supplied to the rotor

\[ T \] : mechanical torque supplied to the shaft
simplified equivalent electrical arrangement of an asynchronous motor

During constant heating, frequency and voltage, the stator windings present a constant resistance $R_1$ and reactance $X_1$. In values converted to the primary, the rotor has a resistance $R_2$ and an inductance $L_2$ such that:

$$L_2 \omega_{\text{rotor}} = L_2 s \omega_{\text{stator}} = s X_2$$

The voltage induced on the rotor, which is also proportional to the rotor frequency, can be noted as follows: $sE_2$, where $E_2$ represents the induced voltage in the open rotor, when stopped ($s = 1$).

The induced current in the rotor is thus:

$$I_2 = \frac{s E_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$= \frac{E_2}{\sqrt{s^2 R_2^2 + X_2^2}}$$

Figure 3-13 represents the equivalent single-phase diagram of the asynchronous motor, without taking into account eddy current loss.

The middle branch corresponds to the magnetizing reactive current needed to maintain the magnetic flux in the machine.

During no-load operation: $s \rightarrow 0$ and $R_2 / s \rightarrow \infty$; the no-load current is practically reduced to the magnetizing current.

For this current to be weak, in particular because it determines the machine's $\cos \varphi$, the manufacturer tries to reduce the magnetic circuit reluctance (small air gap, half-closed slots).
On starting, \( X_2 >> \frac{2}{s} \), and we can thus write the algebraic relation: \( I_1 = I_\mu + I_2 \). Limited by the motor's total impedance, this inrush current is high and reaches four to ten times the nominal current.

![Diagram of an equivalent asynchronous motor electrical arrangement](image)

**Figure 3-13: equivalent asynchronous motor electrical arrangement**

The reactance of the motor on starting \( X_m = X_1 + \left( \frac{X_2}{\mu} \right) \) can be calculated using the data supplied by the manufacturers:

\[
X_m = \frac{U_n^2}{P} \frac{I_n}{I_{st}} \eta \cos \varphi
\]

- \( \eta \) : motor efficiency at nominal power
- \( \cos \varphi \) : motor power factor at nominal power
- \( \frac{I_n}{I_{st}} \) : ratio of the nominal current to the motor starting current
- \( P \) : mechanical power supplied by the motor

### analysis of the asynchronous motor torque

If we neglect the rotor eddy current loss and mechanical loss, we can describe the motor torque as follows (cf. fig. 3-12 and 3-13):

\[
T = T_l = \frac{P_{je}}{\Omega_s s} = \frac{3 R_2 I_\mu^2}{\Omega_s s}
\]

\[
= \frac{3 R_2 \frac{E_2^2}{R_2^2 + (s X_2)^2}}{\Omega_s}
\]

- At a constant rotor resistance and equal slip, the torque is proportional to the square of the voltage (\( E_2 \) is proportional to \( V \)).
- On synchronism \((s = 0)\), the torque is zero.

- At the moment of start-up \((s = 1)\), the torque is proportional to the rotor resistance \(R_2\):

\[
T_{st} = \frac{3 R_2 E_2^2}{\Omega_s X_2^2}
\]

- When synchronism is almost reached, i.e. in the stable operating zone of the motor, \(s X_2 \ll R_2\), the torque is proportional to the slip:

\[
T \equiv \frac{3 E_2^2}{\Omega_s R_2} s
\]

We also see that at constant \(V\) (or \(E_2\)) and \(T\), the slip is proportional to the rotor resistance, and that at constant \(R_2\) and \(T\), the slip varies in inverse proportion to the square of the voltage.

- When there is a lot of slip, i.e. during the starting phase, \(s X_2 \gg R_2\), the torque is inversely proportional to the slip:

\[
T = \frac{3 R_2 E_2^2}{s \Omega_s X_2^2}
\]

- Between these two extreme areas, the torque goes via a maximum which is equal to \(\frac{dT}{ds} = 0\), i.e. to \(R_2 = s X_2\).

This last condition, reintroduced in the previous relation linking the torque \(T\) and the current \(I_2\), can be used to write:

\[
T_{\text{max}} = \frac{3 E_2^2}{2 X_2 \Omega_s}
\]

At a constant voltage, the torque is maximum when the rotor reactance is equal to its resistance \(X_2 = \frac{R_2}{s}\), this maximum torque value is independent of the rotor resistance \(R_2\).

The slip at \(T_{\text{max}}\) is proportional to \(R_2 \left( s = \frac{R_2}{X_2} \right)\). Thus, by increasing the rotor resistance, the torque curve is moved towards large slip without modifying \(T_{\text{max}}\), and, furthermore, the start-up torque is increased.
characteristics in relation to speed (see fig. 3-14)

The characteristic values of the motor torque are:

- \( T_{st} \): starting torque (measured by "locked rotor" test)
- \( T_{min} \): minimum torque (torque dip especially sensitive for double cage machines)
- \( T_{max} \): maximum torque (or pull-out torque)
- \( I_{st} \): starting current

![Graph showing characteristics of a cage asynchronous motor in relation to speed](image)

Figure 3-14: characteristics of a cage asynchronous motor in relation to speed
asynchronous motor stability

On figure 3-14 showing the characteristics of a cage asynchronous motor in relation to speed, the operating point $M$ is located at the intersection of the motor torque curve and the load torque curve. The motor only runs in a stable manner between no-load and maximum torque conditions. In this operating zone there is an increase in torque when the motor slows down.

$T_{\text{max}}$ also determines:

- the maximum instantaneous overload (or load torque) allowable
- the maximum instantaneous voltage drop allowable or the pull-out voltage $V_{\text{pull-out}}$, which defines the minimum voltage needed for the motor not to pull out when there is a load torque equal to its nominal value:

$$\frac{T_{\text{max}}}{T_n} = \left( \frac{V_n}{V_{\text{pull-out}}} \right)^2$$

**Example**

To avoid pull-out at a voltage of 0.7 $V_n$, the following must be respected:

$$\frac{T_{\text{max}}}{T_n} > \left( \frac{1}{0.7} \right)^2$$

whence $\frac{T_{\text{max}}}{T_n} > 2.04$
- **voltage influence** (see fig. 3-15)

  The asynchronous motor is particularly sensitive to voltage variations.

  For constant $f$ and $N$, the motor torque is proportional to $V^2$, the current inrush is proportional to $V$:

  \[
  \frac{T_n}{T_l} \quad \frac{I}{I_n}\%
  \]

  ![Figure 3-15: voltage influence on motor torque and current](image)

- **rotor resistance influence**

  According to the previous equations, the increase of $R_2$ mainly causes an increase in starting torque.

  This property can be exploited to solve starting problems (starting problems mainly condition the size of asynchronous motors).
**wound rotor motor** (or slip-ring motor)

In a ring motor, the use of an external rheostat in the rotor circuit allows the torque curve to be changed (see fig. 3-16). The motor torque curve and load torque curve intersection points determine the operating points at different speeds.

\[
R_c > R_b > R_a : \text{additional resistance in rotor circuit}
\]

*Figure 3-16: wound rotor asynchronous motor*
**cage motor**

In a cage motor it is possible to act:

- on the resistivity of the rotor conductors (for example, by using bronze or brass instead of copper)

- on the increase in large slip apparent resistance, via the **skin effect** (see § “double cage and deep slot motor”).

Figure 3-17 shows the comparative development of the motor curve for four types of standard rotors.

*Figure 3-17: torque characteristics for different types of cage*
- **characteristics in relation to load** (see fig. 3-18)

An asynchronous motor has the drawback of absorbing reactive power.

Its power factor and efficiency are quickly degraded when the load decreases. In no-load operating conditions, the current input remains non negligible and the corresponding power input is almost exclusively reactive. It is therefore not advisable for the user to operate motors underload.

![Characteristics of an asynchronous cage motor in relation to load](image)

*Figure 3-18: characteristics of an asynchronous cage motor in relation to load*

- **using the wound rotor motor** (or slip-ring motor)

Slip-ring motors are more expensive than cage motors (between 20 and 30 % for P > 150 kW and between 30 and 100 % for P < 150 kW).

In practice, they are used in special cases which cannot be solved with the cage motor.

They should be chosen, together with the appropriate switchgear in the rotor circuit, when:

- the current or power inrush on starting is not permitted by the supply source
- the motor must be used with a temporary or permanent speed setting
- the motor must ensure:
  - intensive duty, with a high starting and braking frequency
  - driving fo high inertia or high starting torque device.
3.3.2. **synchronous motors**

The analysis of synchronous motors is only one specific part of the analysis of synchronous machines (see § 4.4.2, synchronous motor operation).

3.3.3. **Variable speed drive via electrical motors**

The variable speed drive of a machine can be made according to two types of procedures which are basically different:

- the first consists in acting on the transmission between the fixed speed rotating motor and the part which is driven at a variable speed: this is the case of mechanical, hydraulic and electromagnetic systems

- the second is obtained by making the varying speed motor operate using electrical or electronic solutions.

■ **reasons for variable speed**

■ **different types of machines driven**

Variable speed drives are well known in a certain number of industries and are an integral part of the production system or process (rolling mills, mixers, coating machines, extruders, wire makers, scrapers, tool-machines, traction, etc.). In this area, the development of electronic control systems has meant that the loss of mechanical energy which is transformed into heat can be avoided.

But the most interesting field of application is without a doubt that formed by machine drives such as pumps, ventilators, blowers or compressors, as it is necessary to adapt their inherent characteristics (speed, torque, power) to variations in external parameters (flow, pressure, pitch, temperature). Table 3-3 classifies the main types of machines in relation to their load torque.
Table: 3-3: power and torque required for driving rotating machines

<table>
<thead>
<tr>
<th>Power $P$ proportional to</th>
<th>Load torque $T_r$ proportional to</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N^3$</td>
<td>$N^2$</td>
<td>Pumps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compressors</td>
</tr>
<tr>
<td>$N$</td>
<td>constant</td>
<td>Compressors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pumps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gear pumps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rolling mills</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lifting machines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conveyor belts</td>
</tr>
<tr>
<td>constant</td>
<td>$1/N$</td>
<td>Coilers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wooden delivery spools</td>
</tr>
</tbody>
</table>

$N$ : speed in tr / min

**relation between flow and power consumption of a centrifugal pump or ventilator**

The flow of a centrifugal pump or ventilator is proportional to the machine rotation speed, the torque increases with the square of the speed and the power increases as the cube of the speed (see fig. 3-19).

The table in figure 3-19 eloquently shows just how far the power is reduced when the flow decreases.

Thus, a reduction in flow of 20 % can be obtained either at constant speed by dissipating 50 % of the power (energy loss) by acting directly on the fluid flow, or by reducing the speed by 20% with a reduction of 50% in the power consumed. We can thus understand why energy is saved by varying the speed.
- mechanical, hydraulic and electromagnetic solutions

It should be noted that the efficiency of these devices quickly decreases with the speed.

- belt or chain variators

These are simple and inexpensive devices which are able to transmit power up to 200 kW. Loss is relatively high in particular at low speed.

- gearboxes

These are costly devices which have a high efficiency and which can be used with a high level of transmitted power. But they do not allow a continued speed variation.
**friction clutches**

These devices are characterised by a part $\alpha P$ of the power being dissipated by slip on the clutch (see fig. 3-20). The efficiency is thus degraded by a coefficient $(1 - \alpha)$.

- friction systems are based on the principle of a metal to metal transmission in oil. The power transmitted is limited to about 100 kW and loss is quite high, especially at low speed.

- hydraulic variators, especially devices which operate via the circulation of oil between two rotating parts acting as pump and turbine respectively, can transmit power well above 1 MW. These variators are not suitable for low speeds.

- magnetic particle couplings are generally used for power below 100 kW. The transmission between motor and driven part is carried out by friction, via a magnetic powder, the fluidity of which depends on the magnetic field to which it is subjected.

- eddy current electromagnetic couplings can be used to reach 1 MW.

\[ \alpha P : \text{dissipated power} \]
\[ (1 - \alpha) : \text{speed reduction factor} \]

*Figure 3-20: Friction clutch*
electrical solutions

Only the most widely used solutions have been mentioned:

- setting the speed of a wound rotor asynchronous motor using a rheostat is incompatible with high efficiency and, because of this, it is a process that is only used in specific cases where the setting requirements are considered to be of top priority and must be carried out even at the cost of a heavy decrease in efficiency.

- setting cage asynchronous motors by changing polarity consists in connecting the stator coils differently. This process can only be used to obtain small speeds the number of which depends on that of the pairs of poles possible (generally two speeds).

- installing two different speed motors on the same shaft.

electronic solutions

Before briefly describing the main procedures used, it seems useful to have a quick look at the advantages which make electronic speed variation an attractive solution for a large number of industrial processes, both from a technical and economic point of view.

advantages of electronic speed variation

The main advantages, which are moreover often closely linked, are as follows:

- setting flexibility and optimum running
  - easy starting with a programmable motor torque. Starting is independent of climatic conditions and requires no preparation time.
  - operating flexibility allowing the driven part to be adapted to variable conditions of use and even, in some cases, to increase its useful service range.
  - easy to adapt to modern automation processes and, because of this, it helps improve productivity and product quality.
  - possible to use motors with speeds higher than those applied by the network.
  - simplified shaft lines.
• energy saving
  - capable of making significant energy savings in comparison to friction clutch type drives due to intrinsically higher electromechanical conversion efficiencies.
  - possible for a piece of equipment to operate permanently at the best rates of efficiency and using the whole range of speeds and not only at the maximum rating.
  - see paragraph 3.3.3.6., example of speed variator choice.

• availability and maintainability
  - equipment that is widely available, resulting on the one hand from its high reliability and, on the other hand, from the short time needed for necessary repairs and maintenance.
  - breakdown repairs are facilitated by the modularity of the electronic sub-assemblies and the possibility of implementing automatic fault detection and rapid replacement procedures.

• stress on equipment and certain sources of annoyance reduced
  - reduction of stress applied to mechanical parts (temporary starting torque, pulling out of synchronism, ramming, etc.) through permanent control of acceleration
  - no more current inrush on the network when motors are started up.
  - possible to do without slip-rings and sliding contacts thus facilitating use in explosive or aggressive atmospheres.

• precautions for use
The electronic devices used to vary motor speeds generate harmonic currents which may disturb the electrical installation or utility (see § 8).
## Recapitulative Table of the Characteristics of Different Speed Variators

<table>
<thead>
<tr>
<th>Type</th>
<th>Approximate Maximum Power (kW)</th>
<th>Speed Variation</th>
<th>Speed Stability (%)</th>
<th>Overall Efficiency</th>
<th>Reliability</th>
<th>Maintenance</th>
<th>Simplicity</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belts</td>
<td>100</td>
<td>20 to 200 %</td>
<td>1 to 3</td>
<td>70 to 90 %</td>
<td>*</td>
<td>**</td>
<td>****</td>
<td>Zero speed impossible. Heavy maintenance. Low price.</td>
</tr>
<tr>
<td>Friction</td>
<td>50</td>
<td>30 to 95 %</td>
<td>0.1</td>
<td>50 to 90 %</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>Zero speed possible. Limited to low power.</td>
</tr>
<tr>
<td><strong>Hydraulic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrokinetic</td>
<td>&gt; 1000</td>
<td>25 to 98 %</td>
<td>1 to 2</td>
<td>60 to 95 %</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>Highly suitable for centrifugal pumps and ventilators. Not suitable for low speeds.</td>
</tr>
<tr>
<td>Hydrostatic</td>
<td>&gt; 1000</td>
<td>5 to 98 %</td>
<td>2 to 3</td>
<td>60 to 90 %</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>Control flexibility but zero speed impossible.</td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic powder</td>
<td>50</td>
<td>25 to 98 %</td>
<td>3 to 5</td>
<td>50 to 90 %</td>
<td>**</td>
<td>**</td>
<td>****</td>
<td>Efficiency rapidly decreases when the speed decreases.</td>
</tr>
<tr>
<td>Eddy current</td>
<td>1000</td>
<td>50 to 98 %</td>
<td>3 to 5</td>
<td>50 to 95 %</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td><strong>Electronic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For asynchronous motor</td>
<td>25 000 (1)</td>
<td>0 to &gt; 100 %</td>
<td>0.5 to 4 (open loop)</td>
<td>85 to 90 %</td>
<td>****</td>
<td>***</td>
<td>*</td>
<td>All types of applications.</td>
</tr>
<tr>
<td>For synchronous motor</td>
<td>80 000 (1)</td>
<td>0 to &gt; 100 %</td>
<td>1</td>
<td>90 to 95 %</td>
<td>****</td>
<td>***</td>
<td>**</td>
<td>All types of applications.</td>
</tr>
</tbody>
</table>

**** = excellent  *** = very good  ** = OK  * = average  
(1) Economic threshold between asynchronous motor and synchronous motor: 500 to 1000 kW.

*Table 3-4: Main Characteristics of Speed Variators*
3.3.3.1. **Cage asynchronous motor fed by a soft start device** (see fig. 3-21)

The soft start device allows an asynchronous motor to be started with a progressive voltage. Thus, current inrush on the network is limited and the speed pick-up of the motor is controlled.

This process can be used to vary the stator voltage, and thus the speed, by acting on the delay angle of the parallel-mounted thyristors placed in each of the motor power supply phases.

This type of setting is better suited to low speed weak load torque drives than those with a constant load torque whatever the speed. Furthermore, the decrease in speed results in an increase in slip loss which reduces the speed variation range and restricts the application to low power resistive cage or intermittent service motors.

![Figure 3-21: cage asynchronous motor fed by a soft start device](image)

3.3.3.2. **Wound rotor (or slip-ring) asynchronous motor with hyposynchronous cascade** (see fig. 3-22)

With a wound rotor motor it is possible to vary the slip by modifying the rotor resistance (see fig. 3-16). If a rheostat is used to do this, active energy is dissipated at a pure loss and the efficiency is reduced to an unacceptable level. For the process to be cost-effective, a circuit allowing the corresponding energy to be recovered by reinjecting it into the network must be used. The rotor current is rectified via a diode bridge and, after filtering, it is sent back into the network via an inverter and a voltage adapting transformer. The slip is set using the delay angle of the thyristors. The efficiency obtained is of the order of 0.9 to 0.95.

In theory, it is possible to adjust the speed from its maximum value upto around the stop point. In fact, it is not useful to plan such a variation range. On the one hand, it is rare that such a large speed variation will be needed and, on the other hand, the cascade power rating is shown to be proportional to the slip. From the point of view of cost, the variation must be set for the only slip margin necessary, which implies using a rheostat for starting.
Thus made up, the indirect converter can often be advantageously replaced by a cycloconverter.

By replacing the diode bridge by a thyristor bridge and injecting, from the network, energy into the rotor, we have the means of exceeding the synchronism speed, by thus making a hypersynchronous (and hyposynchronous) cascade.
3.3.3.3. Cage asynchronous motor fed by an autonomous rectifier-inverter

When the motor is a cage asynchronous motor, a rectifier-inverter type converter can be used. For small and medium power ratings (< 400 kW), commutation is currently carried out by Insulated Gate Bipolar Transistors (IGBT). They allow a commutation speed above that of thyristors and thus authorise high speeds. For high power ratings, only thyristors are used. Thyristor commutation must be carried out by auxiliary circuits made up of thyristors and capacitors (forced commutation). This type of variator is often called a "commutator".

Different types of power supply are possible:

- voltage rectifiers-commutators
- pulse width modulation rectifiers-inverters
- current rectifiers-commutators.

**voltage rectifier-commutator** (see fig. 3-23)

This includes a controlled rectifier which allows a three-phase inverter to be fed with a variable voltage. The required output frequency is obtained by modifying the inverter thyristor delay angle.

This is the simplest type of frequency converter but it requires a filtering capacitor and reactor.

Braking via energy recovery is possible as long as the head thyristor rectifier is itself reversible. Speed reversibility is obtained by reversing the order of phases in the inverter thyristor control.

This type of power supply is highly suitable for high reactance motors.

![Figure 3-23: cage asynchronous motor with voltage rectifier-commutator](image-url)
pulsed width modulation (PWM) rectifier-inverter (see fig. 3-24)

The rectifier used in this case is a constant voltage rectifier (diodes instead of thyristors). The inverter supplies both a variable voltage and frequency. By making the width of the output pulses as well as their frequency vary, an output voltage and load current close to that of a sinusoidal curve are obtained.

This solution can be used to create high performing variable speed drives. It allows for a large speed variation range. On the other hand, for high speeds, the commutation frequency is high. Transistors must therefore be used, which limits the maximum power \( P \leq 400 \, kW \).

![Diagram of a cage asynchronous motor with PWM rectifier-inverter.](image)

*Figure 3-24: cage asynchronous motor with PWM rectifier-inverter.*
current rectifier-commutator

The diagram in figure 3-25 shows an example of a current rectifier-commutator. This solution includes an input converter (thyristor controlled rectifier) using natural commutation (thyristor commutation is carried out without an auxiliary circuit) which, associated with a smoothing inductor, behaves like a direct current source. An output converter (commutator) commutes this current in the machine phases with the help of capacitors. This commutation, which is carried out at a variable frequency, allows the motor to operate with great flexibility over a large speed range.

The device operates in the four quadrants of the torque-speed plane without the addition of any extra element. When operating as a generator, the network side converter operates in inverter mode and the machine side commutator in rectifier mode.

![Diagram of a current rectifier-commutator](image)

*Figure 3-25: cage asynchronous motor with current rectifier-commutator*
3.3.3.4. **Synchronous motor fed by auto-controlled rectifier-inverter**

This solution uses a first converter fed by the network and a second controlled by the machine. The link between the two converters is made via a decoupling reactor.

During motor operation, the network side converter operates in rectifier mode and regulates the direct current in the intermediary stage; the second converter works in non-autonomous inverter mode and commutes this variable frequency current in the machine phases.

The commutation from one stator phase to the next is determined either by measuring the rotor position or by measuring stator voltage, with the reactive energy needed for this commutation being supplied by the machine excited. This setting mode avoids any risk of pulling out of synchronism with the frequency always remaining in perfect synchronism with the speed.

On starting and at low speed, the machine voltage is insufficient to carry out inverter commutation. In this case, it is the input converter which, temporarily used as an inverter, carries out this function.

This solution is in principle used for unit powers above several hundreds of kilowatts and upto several tens of megawatts.

![Diagram of synchronous motor fed by auto-controlled rectifier-inverter](image-url)

*Figure 3-26: synchronous motor fed by auto-controlled rectifier-inverter*
3.3.3.5. **Asynchronous or synchronous motor fed by cycloconverter**

This is the only variable frequency generating system able to carry out a direct frequency conversion from the alternative network.

The alternative motor power supply requires one converter per phase as shown in figure 3-27 which gives an example of the possible layout. The three converters are controlled by three references phase shifted by 120°. When one of the bridges is conductive, it acts as a rectifier if the current and the voltage have the same sign and as an inverter if the current and voltage have opposite signs. In practice, the cycloconverter limits the excursion of the output frequency between 0 and f/3 (f being the network frequency). This type of solution is thus particularly suited to low rotation speed motor drives.

![Figure 3-27: alternating current motor with cycloconverter](image-url)
### 3.3.3.6. Characteristics and fields of application of electronic speed variators

<table>
<thead>
<tr>
<th>Speed variation principle</th>
<th>Power</th>
<th>Variation range</th>
<th>Overall efficiency</th>
<th>Fields of application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asynchronous motor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed frequency Soft start device</td>
<td>Action on stator voltage Fixed frequency</td>
<td>sev 10 kW</td>
<td>20 to 90 % of $N_s$ (1)</td>
<td>0.2 to 0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wound rotor asynchronous motor</strong></td>
<td>Rectifier-inverter system. Action on slip via rotor current variation. Energy recovery on rotor <strong>Hyposynchronous cascade</strong></td>
<td>sev 100 kW to sev 1 000 kW</td>
<td>60 to 100 % of $N_s$</td>
<td>0.90 to 0.95</td>
</tr>
<tr>
<td>Fixed frequency with energy recovery</td>
<td></td>
<td></td>
<td>100 to 140 % of $N_s$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Asynchronous or synchronous motor</strong></td>
<td>Action on stator voltage and frequency. Frequency converter via thyristor bridge: 0 to 16 Hz for a 50 Hz network. Generally using natural commutation via the network (synchronous and asynchronous motors) or via the load (overexcited synchronous motor). <strong>Cyclo-converter</strong></td>
<td>sev 100 kW to sev 10 000 kW</td>
<td>0 to 120 % de $N_s$ (if not several times $N_s$)</td>
<td>0.85 à 0.90</td>
</tr>
<tr>
<td>Cyclo-converter Variable frequency Direct conversion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Asynchronous motor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable frequency Indirect conversion</td>
<td>Action on stator voltage and frequency. Autonomous rectifier-inverter system: voltage commutator (2) - PWM inverter. - current commutator <strong>Autonomous rectifier-inverter</strong></td>
<td>sev 10 kW to sev 100 kW</td>
<td></td>
<td>0.85 à 0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Synchronous motor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auto-controlled Variable frequency</td>
<td>Action on voltage and frequency. Autosynchronous rectifier-inverter system. <strong>Auto-controlled rectifier-inverter</strong></td>
<td>sev 100 kW to sev 10 000 kW</td>
<td>0 to several $N_s$</td>
<td>0.90 to 0.95</td>
</tr>
</tbody>
</table>

(1) $N_s$: synchronism speed (in tr/min.)
(2) More particularly suited to multi-motor control.

**Table 3-5: characteristics of electronic speed variators**
**Example of speed variator choice**

The most useful area of application for variable speed drives is undoubtedly that of machine drives such as pumps, ventilators, blowers or compressors. In most industrial processes these machines in fact require their operating point to be adjusted so that their ratings are adapted to the parameters of use (e.g. flow, pressure, temperature).

This adjustment can be carried out by modifying the rating of the initial network: by introducing an extra load loss (power loss), the means used (flow resistance, by-pass, adjustable blades, etc.) result in the machine consuming an active power which is higher than the power required by the process.

Another adjustment technique consists in moving the machine’s rating so that it matches the operating point required by the network rating. This can be done by making its rotation speed vary. In this case, the power consumed is identical to the power actually required which thus leads to energy saving.

This very quickly becomes a considerable energy saving in the case of centrifugal machines. This can be illustrated very simply using the example of a water pump (point $A$ de la figure 3-28):

- flow: $Q = 1,000 \text{ m}^3/\text{h}$
- equivalent water pressure in height: $H_A = 27 \text{ m}$
- efficiency: $\eta = 0.73$
- volumic mass of water: $\rho = 1,000 \text{ kg/m}^3$

The power of this pump is given (with the units above) in the expression:

$$P = \frac{Q H \rho \times 9.81}{3,600 \eta}$$

whence $P = 100 \text{ kW}$
The service conditions often require a flow of 500 m$^3$/h, and thus frequent adjustment of the operating point.

![Diagram showing flow resistance and variable speed solutions for driving a centrifugal pump.]

**Figure 3-28:** Comparison of «flow resistance» and «variable speed» solutions for driving a centrifugal pump

**Note:** The difference $H_B - H_C$ shows the extra loss given by flow resistance.

- **first solution**

Flow resistance is established at the pump outlet (the valve performs "a brake in flow"). The new operating point $B$ ($H_B = 29$ m, $Q = 500$ m$^3$/h, $\eta = 0.5$) requires a drive power of:

$$P = \frac{500 \times 29 \times 1000 \times 9.81}{3600 \times 0.6} = 79 \text{ kW}$$

- **second solution**

The speed is modified so that the required flow is reached without moving the network rating. The new operating point $C$ ($H_C = 15$ m, $Q = 500$ m$^3$/h, $\eta = 0.6$) allows the pump to work at a reduced pressure. The drive power required is thus:

$$P = \frac{500 \times 15 \times 1000 \times 9.81}{3600 \times 0.6} = 34 \text{ kW}$$

Compared with the flow resistance technique, using speed variation results in a reduction of the drive power of 45 kW. Great savings can thus be made on the energy bill.
3.3.4. Starting electric motors

Starting is a delicate part of using electric motors. The starting devices described in this paragraph should be able to solve most of the cases with which the installation designer is confronted:

- high load torque
- limited current inrush
- frequent starts.

On power-up, the impedance of the motor is very low. A violent current inrush (4 to 10 times the nominal current) may follow if no specific device is provided to limit it.

Since the power supply network is never of infinite power, this current inrush may cause a drop in voltage on the network which is likely to disturb other users. This voltage drop may also cause the motor to operate in operating zones which are not recommended, due to the resulting excessive temperature-rise, or a speed build up of the machine which is too slow, or even a slowing down or stopping of the energized motor.

**network short-circuit power**

This is a very important parameter. A motor starts more quickly, heats less and causes a smaller voltage drop if the short-circuit power at the connection point of the motor is high. We may consider that it is high if it is above 100 times the motor power.

**motor starting torque**

**load torques**

There are two types of load torque (see fig. 3-29):

- constant torque whatever the speed: piston pumps and compressors, displacement compressors, gear pumps, ore or cement crushers, lifting and conveying machines (curve 1)

- torque parabolic with speed: ventilators, centrifugal compressors, agitators (curve 2 for starting a machine on-load and curve 2 b for starting a machine off-load, i.e. valves or sliding lock panels closed).

Of course, the motor breakaway torque must be higher than the load breakaway torque and, in the case of a synchronous motor, the motor torque on pull-in must be higher than at least 10% of the load torque.
Moment of Inertia

Generally expressed as \( J = MR^2 \)

where:
- \( M \): mass in kg
- \( R \): equivalent radius in metres

But, the following term is also used: \( PD^2 \), where \( PD^2 = 4J \).

When the moment of inertia is great, a lot of energy is needed to bring the motor to its stabilised operating speed. It must not therefore be too great so that the starting time is not too long and the rotor temperature-rise is not too high.

Some machines are only overrated due to a great moment of inertia so that the temperature-rise at the surface of the rotor or the squirrel cage is limited.

If the speed \( N_1 \) of the machine driven differs from that of the motor \( N_n \) (by a gear system), the moment of inertia of the driven machine is given by the ratio: \( \left( \frac{N_1}{N_n} \right)^2 \).

Thus, the expression of the motor’s moment of inertia with the machine driven is:

\[
J = J_m + \left( \frac{N_1}{N_n} \right)^2 J_e
\]

\( J_m \): moment of inertia of the motor
\( J_e \): moment of inertia of the machine driven.

---

Figure 3-29: load torque curves of driven machines

Curve 1: constant torque
Curve 2 and 2 b: parabolic torque
**starting time**

The machine builds up speed in a time that can be calculated using the following simplified formula:

\[ t_{st} = \frac{2 \pi}{60} \times \frac{J N}{T_m} \]

- \( t_{st} \) : starting time in seconds
- \( J \) : moment of inertia of the assembly (motor + machine driven), converted to the motor shaft, in kg x m\(^2\)
- \( N \) : rotation speed after starting, in tr/min
- \( T_m \) : mean acceleration torque in N.m.

\( T_m \) is the mean torque developed by the motor during starting from which the mean load torque during the same period has been deducted.

Generally, for centrifugal machines, a fairly approximate mean torque value can be calculated as follows:

\[ T_m = \frac{T_{st} + 2 T_{\text{run-up}} + 2 T_{\text{max}} + T_n}{6} - T_l \]  (see fig. 3-30)

\( T_{st} \) : starting torque
\( T_{\text{run-up}} \) : run-up torque
\( T_{\text{max}} \) : maximum torque
\( T_l \) : mean load torque

*Figure 3-30: torque in relation to the speed*
3.3.4.1. Starting three-phase asynchronous motors

On power-up, the asynchronous motor behaves like a transformer whose secondary (rotor) is short-circuited. The starting current \( I_{st} \) in the stator can thus reach 4 to 10 times the nominal current value \( I_n \).

The solution chosen must provide the best compromise between the three requirements:

- torque required on motor starting
- allowable temperature on starting
- limited power supply network short-circuit power.

**torque required during motor starting**

To limit the voltage drop resulting from the motor current inrush, it is natural to reduce the current; but this technique is limited by the ensuing reduction in motor torque. For starting to be possible, the motor torque curve must be situated, at every instant and for all speeds, above the load torque curve; the safety margin must be sufficient to ensure a sufficiently fast rise in speed. This motor torque is proportional to the square of the voltage and thus to the square of the current. The secondary effect of saturation is neglected, even if in some machines this phenomenon may increase the starting current by over 20% under full voltage, and the torque by over 40%. However, given that the saturation effect very quickly decreases with the voltage, and that all starting is generally accompanied by a more or less heavy drop in voltage, it is advisable only to consider the torque value without the saturation effect in order to determine starting possibilities. A mean value between torques with or without saturation may be taken into account when the latter value is given by the manufacturer.
allowable temperature rise on starting

During on-load starting of an asynchronous motor, the thermal energy supplied to the rotor greatly depends on the kinetic energy which must be supplied to the rotating masses:

\[ \frac{1}{2} I \omega^2 \].

In the case of cage motors, all this thermal energy must be absorbed by the rotor cage; this is why manufacturers provide the maximum allowable driven moments of inertia (converted to the motor speed) in their catalogues, based on hypotheses which are generally as follows:

- direct-on-line starting under full voltage (stable and at nominal frequency)
- parabolic-type load torque up to nominal torque
- number of successive cold starts (2 or 3 starts), and warm starts (1 or 2 starts).

The problem of the cages overheating is all the more difficult to solve as the rated power and speed increase. The maximum temperature allowable, which is different depending on the metal used for the cage, must also be taken into account; in practice, the following is chosen:

- aluminium up to 2 000 kW for a four-pole motor
- copper up to 3 000 kW for a two-pole motor, and 7 000 kW for a four-pole motor
- brass for higher power ratings.

If we want to start a machine with a moment of inertia exceeding the recommended limit, or increase the rate of starts, the machine must be overrated and the maximum thermal capacity of the cage must be increased. With this in mind, it should be noted that the use of a double cage is rarely the best solution since the heat cannot quickly spread itself evenly from one cage to another.

In the same start conditions, any current loss to be dissipated in the rotor windings of a slip-ring motor is much lower than in a cage motor. Indeed, the start rheostat absorbs most of the loss, in proportion to the ratio of the external resistances and the total resistance (rotor resistance + external resistances).

**Note:** a speed variator operating on the principle of frequency variation allows the start current to be decreased while maintaining a high torque. It thus eliminates the necessity to use a motor with a high cage thermal capacity.
**supply network short-circuit power**

In the case of a motor being **directly energized**, throughout the speed build-up we notice (see fig. 3-14):

- a very strong current,
  \[4 I_n < I_{st} < 10 I_n\]
- a low power factor,
  \[0.1 < \cos \varphi < 0.6\]

It is necessary to make sure that the motor supply network can withstand such a current; the induced drop in voltage must not disturb other users (see § 6.1.7).

The relative voltage drop created by the motor at a point \( A \) of the electrical path supplying the motor is approximately:

\[
\Delta U = \frac{S_{st}}{S_{sc_A} + S_{st}}
\]

\( S_{st} \) : apparent motor starting power
\( S_{sc_A} \) : network short-circuit power at point \( A \)

\[
S_{st} = \frac{P_n}{\eta_n \cos \varphi_n} \cdot \frac{1}{I_n} \cdot I_{st}
\]

where:

\( P_n \) : nominal mechanical power of the motor
\( \eta_n \) : nominal efficiency of the motor
\( \cos \varphi_n \) : nominal power factor
\( I_{st} \) : starting current
\( I_n \) : nominal current
3.3.4.1.1. Cage motor starting

- star-delta starting of a cage motor (see fig. 3-31)

This is the simplest starting procedure at a reduced voltage. It may be recommended for maximum motor power ratings of 500 kW. It requires the six winding ends of the motor to be connected to the terminals and the motor to be delta-connected at its nominal voltage.

First of all, upon energizing, the windings are star-connected. If we neglect the saturation effect, the current is thus three times less than the direct-on-line starting current; and the starting torque is divided by three. In the case where the saturation effect is non negligible, the division factor may reach over 3.5.

Secondly (at approximately 80% of the nominal speed for small motors), when the motor torque comes close to the load torque (use of a pre-set time delay), the delta-connection commutation of the windings brings the torque and current back to their normal curve, with a temporary peak in current accompanied by an occasionally heavy mechanical jolt.

\[ I_{st} = \frac{1}{3} I_{stY} \]

\[ T_{st} = \frac{1}{3} T_{stY} \]

\[ T_Y = \frac{1}{3} T_Y \]

\[ N_n \]

---

**Successive contactor switching**

<table>
<thead>
<tr>
<th>Successive orders</th>
<th>Contactor states</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 0 1</td>
</tr>
<tr>
<td>2</td>
<td>1 0 1</td>
</tr>
<tr>
<td>3</td>
<td>1 0 0</td>
</tr>
<tr>
<td>4</td>
<td>1 1 0</td>
</tr>
</tbody>
</table>

(1 = closed) (0 = open)

\[ \Delta \]: delta supply  
\[ Y \]: star supply  
\[ s \]: on breakaway start

---

*Figure 3-31: star-delta starting of a cage motor*
stator resistor starting of a cage motor

This system consists in introducing a series resistor onto each motor phase. The voltage drop in the resistor, when the starting current flows through it, limits the voltage at the motor terminals and, consequently, the starting current. The current is reduced in proportion to the voltage. The motor torque is reduced in proportion to the square of the voltage. This technique is essentially used in low voltage.

Two types of resistors are used:

- metal resistors with one or more notches
- electrolytic resistors.

metal resistors with one or more notches (see fig. 3-32)

When the reduced motor torque is not high enough to continue the machine speed build-up, it is either possible to switch to a weaker resistance value (change in notch), or the resistor can be short-circuited in order to come back to the normal torque and current curves, with a slight mechanical jolt (less than the star-delta starting jolt).

$R_S$: stator resistor

$X_m$: motor starting reactance (see § 3.3.1.)

$D$: direct power supply

Successive contactor switching

<table>
<thead>
<tr>
<th>Successive orders</th>
<th>Contactor states</th>
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<tbody>
<tr>
<td></td>
<td>$C_1$</td>
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<tr>
<td>1</td>
<td>0</td>
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<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 3-32: stator resistor starting of a cage motor (case of a single notch)
**electrolitic resistor** (see fig. 3-33)

The resistance is continually variable during motor starting and allows the nominal speed to be reached without any jolts, right up to the short-circuiting of the resistor.

The resistance may be varied either by varying the level of electrolyte between the electrodes, or by natural variation of the resistivity due to the electrolyte heating up.

In the case of a varying level electrolytic resistance, the resistor is inserted downstream of the motor in order to reconstitute the motor’s neutral point; this must be star-connected under its nominal voltage with the ends of the windings connected to the terminals. The initial resistance value is fixed by the concentration of the electrolyte bath, the maximum current by the level of electrolyte and the starting time by the level variation speed.

![Successive contactor switching](image)

<table>
<thead>
<tr>
<th>Successive orders</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

\[ R_E : \text{electrolytic resistance} \]
\[ D : \text{direct power supply} \]
\[ X_m : \text{motor starting reactance (see § 3.3.1.)} \]

**Figure 3-33: electrolytic resistor starting of a cage motor with motor neutral point reconstitution**

In the case of a **thermo-variable** electrolytic resistor, the initial value of the resistance is also fixed by the concentration of electrolyte. The starter is inserted between the electrical power supply and the motor. Once the motor has been energized, the high resistance of the cold electrolyte progressively decreases owing to the Joule losses caused by the passage of the starting current, which leads to a voltage increase at the motor terminals and thus an increase in motor torque.
stator resistor star-delta starting of a cage motor (see fig. 3-34)

Using both of the previous techniques constitutes a good compromise between a strong reduction in breakaway starting current and a strong reduction of the current peak at the end of starting. Starting is carried out in three stages:

- star power supply

\[ I_{stY} = \frac{1}{3} I_{st\Delta} \quad \text{and} \quad T_{stY} = \frac{1}{3} T_{st\Delta} \]

- delta power supply with stator resistors; at the instant of commutation, the ratio \( \alpha \) is defined such that:

\[ I_{st\Delta RS} = \alpha I_{st\Delta} \quad \text{where} \quad \alpha > \frac{1}{\sqrt{3}} \]

we thus have

\[ T_{st\Delta RS} = \alpha^2 T_{st\Delta} \quad \text{where} \quad \alpha^2 > \frac{1}{3} \]

- delta power supply (short-circuited stator resistors).

---

**Successive contactor switching**

<table>
<thead>
<tr>
<th>Successive orders</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
<th>( C_4 )</th>
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<tbody>
<tr>
<td>1</td>
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<td>0</td>
<td>1</td>
<td>0</td>
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<td>3</td>
<td>1</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 3-34: stator resistor star-delta starting of a cage motor**
**Stator reactor starting of a cage motor** (see fig. 3-35)

Similar in principle to stator resistance starting, connecting reactors in series with the motor can be used for starting at a reduced voltage, with a drop in the power factor. Here again the current is reduced in proportion to the voltage, while the torque is reduced in proportion to the square of the voltage.

It has the advantage of not dissipating active energy and thus replaces the use of stator resistors for medium voltage motors (ratings above roughly 400 kW).

We may also cite the use of a saturable reactor starting device connected in series with the motor. A d.c. fed winding saturates the flux and modifies the inductance value.

![Successive Contactor Switching](image)

<table>
<thead>
<tr>
<th>Successive orders</th>
<th>Contactor states</th>
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<tbody>
<tr>
<td>1</td>
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<td>2</td>
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<tr>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

$L$ : inductance  
$X_m$ : motor start reactance (see § 3.3.1.)

**Figure 3-35: Stator reactor starting of a cage motor**
"Block-transformer" starting of a cage motor

In the case where a motor must be fed by a specific transformer, the transformer may be rated with a high short-circuit voltage (e.g. twice the usual voltage). During the starting phase the high transformer inductance acts in exactly the same way as the starter with series-connected stator reactors.

During normal running, a slight drop in the power factor may be seen.

A further advantage of this starting principle is that it is possible to choose the nominal supply voltage of the motor (MV or LV).

The name « block-transformer » means that the manufacturer has designed and supplied the motor together with its associated transformer for determined starting and operating ratings.

Auto-transformer starting of a cage motor (see fig. 3-36)

The presence, upstream of the motor, of an auto-transformer with a pre-determined ratio $k$ allows the voltage to be reduced at the motor terminals, by decreasing the currents by a ratio of $k^2$.

Starting is carried out in three stages:

- **motor energizing at a voltage reduced by a factor** $k$; the torque is thus reduced by a factor $k^2$.

- **auto-transformer neutral point opening**; a fraction of the winding is thus connected in series with the motor and is crossed by the starting current; the voltage and current surges of the third stage are thus limited. On the other hand, the neutral point is subjected to an overvoltage practically equal to twice the single-phase voltage. The transformer neutral point insulation must therefore be sized accordingly.

- **device short-circuiting and charging under nominal voltage**.

The second stage is in principle short as it has a slowing down effect. It corresponds to the natural contactor commutation time. This operation may require the reactance value presented by the auto-transformer operating with open neutral point to be precisely determined, so that the reduction in motor torque during the second stage and the voltage drop at the beginning of the third stage are not too great.

It is necessary to make sure that the contactors are correctly and automatically locked and fitted with time delays. During commutation it is necessary to avoid any risk of short-circuiting on the auto-transformer secondary.
This starting system is recommended for high power motors in low and medium voltage. It has the advantage of not dissipating energy (unlike the stator resistor starter). It can be used to obtain, for the same decrease in current, a lesser reduction in torque than in the case of a reactor starter.

![Diagram showing auto-transformer starting of a cage motor](image)

**Successive contactor switching**

<table>
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<tbody>
<tr>
<td>1</td>
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<td>1 0 1</td>
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<td>3</td>
<td>1 0 0</td>
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<tr>
<td>4</td>
<td>1 1 0</td>
</tr>
</tbody>
</table>

$k$ : reciprocal value of the turns ratio \( (k < 1) \)

$at$ : auto-transformer

**Figure 3-36: auto-transformer starting of a cage motor**

- **capacitor starting of a cage motor**

Connecting capacitors in parallel with the motor would ensure direct-on-line starting of the motor at the nominal voltage by limiting the starting current on the upstream network. The reactive power required by the motor would be supplied by the capacitors. The global power factor would be converted to an acceptable value.

This system is, however, very difficult to implement and requires a specific analysis in order to avoid resonance and overvoltage due to auto-excitation (see § 7.9).
starting a double cage motor (see § 3.3.1., fig. 3-10)

Table 3-6 shows the start properties of double cage motors.

<table>
<thead>
<tr>
<th>( \frac{T_{st}}{T_n} )</th>
<th>2.0</th>
<th>1.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{I_{st}}{I_n} )</td>
<td>5 to 4.5</td>
<td>3.8 to 3.5</td>
<td>3.5 to 3.2</td>
</tr>
</tbody>
</table>

Table 3-6: double cage motor start properties

starting a deep slot cage motor

See paragraph 3.3.1.

electronic systems for starting cage motors

- **soft start device** (see § 3.3.3.1.)

The soft start device can be used to reduce the voltage at the cage motor terminals and it thus limits the current. It is generally short-circuited once the motor has been started. Use of the controller is especially recommended to start large motors fed by a.c. generators.

electronic frequency variation

The power supply of a cage asynchronous motor using a variable frequency rectifier-inverter system allows starting with a maximum torque and minimum current.

Besides the necessity for speed variation or a drive speed that is greater than the motor synchronism speed, the electronic frequency variator can be used to solve many problems connected with starting:

- possibility of maintaining the starting current close to the nominal value \( I_n \), which prevents any overheating and allows high inertia and/or high load torque loads to be frequently started

- possibility of limiting the torque throughout the starting time (with no surge) to a value compatible with the mechanical parts driven

- possibility of maintaining a non zero torque when the motor has stopped.
3.3.4.1.2. Starting asynchronous wound rotor (or slip-ring) motors

The starting torque, current and time requirements may necessitate the use of a slip-ring motor (or wound rotor motor) as it allows the maximum torque to be obtained the moment the motor is started for a current close to the nominal value.

The presence of slip-rings, and thus of rotating contacts, requires greater precaution when using these motors (dust, explosive environment, etc.) than for cage motors.

- **rotor resistance starting** (see fig. 3-37)

Inserting resistors in the rotor circuit moves the torque curve in the right direction while limiting the current.

The resistors used have one or several discrete value notches (metal resistors) or are continually variable (electrolytic resistors), which means that the starting time and current can be chosen.

In the case of a *level variation* or *electrode displacement* electrolytic resistor the variation in resistance is obtained by gradually submerging the electrodes in a tank using a suitable electrolyte.

The rotor is short-circuited once the tank is full (the flow setting regulates the filling time) or once the electrodes have all been submerged (pre-set time). The resistance is then almost zero and the corresponding current peak is low.

The composition of the electrolyte can be chosen in order to suit the resistance value and to obtain the desired breakaway torque. The **thermo-variable** electrolytic resistance decreases due to the Joule losses caused by the passage of the starting current, through overheating or partial vaporization and liquid-vapour mixing of the electrolyte.
Successive contactor switching

<table>
<thead>
<tr>
<th>Successive orders</th>
<th>Contactor states</th>
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<tbody>
<tr>
<td>1</td>
<td>1 0 0 0</td>
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<td>2</td>
<td>1 1 0 0</td>
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<tr>
<td>3</td>
<td>1 1 1 0</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1 1</td>
</tr>
</tbody>
</table>

234 : contactors \(C_2\), \(C_3\) and \(C_4\) are closed
34 : contactors \(C_3\) and \(C_4\) are closed, \(C_2\) is open
4 : contactor \(C_4\) is closed, \(C_2\) and \(C_3\) are open

Variant (see above):

This has the advantage of using contactors with a weaker nominal current.

Figure 3-37: rotor resistor starting of a wound rotor (or slip-ring) motor
"induced resistance" starting

A set of coils surrounding a solid iron core is inserted into the rotor's external circuit. The rotor currents generate eddy currents in the iron core which then acts as an induced rotor resistance, continually decreasing with the frequency of these currents during the rise in motor speed.

At the end of starting, the device is short-circuited with a slight mechanical jolt.

The torque and current curves can be compared with those of electrolytic resistance starting.

This system has the advantage of being entirely static and fluidless, but is less able to adapt to the motor rating than the electrolytic starting system.

3.3.4.2. Three-phase synchronous motor starting

Table 3-7 shows the four main ways of starting fixed speed synchronous motors.

With a variable speed motor fitted with a rectifier-inverter assembly, it is possible to make the frequency vary from zero to the nominal frequency while the ratio $U_n / f$ remains constant.

This starting method in synchronous mode enables the nominal torque to be kept throughout the starting period.

Fixed speed synchronous motors all start in asynchronous mode, on the damping cage for laminated pole motors and on the pole shoes for solid pole motors.

For laminated pole and complete cage motors:

$$ I_{st} = \frac{U_n}{X_{st}} \frac{1}{\sqrt{3}} $$

$X_{st}$ : subtransient reactance

For solid pole motors:

$$ I_{st} = (1.1 \text{ to } 1.2) \frac{U_n}{X_d} \frac{1}{\sqrt{3}} $$

For fixed speed motors it is possible to use a rectifier-inverter system sized for this phase only for starting.

Note: using a generator starting motor is also possible.
- **Direct-on-line starting**
  This is the simplest, least expensive and fastest starting procedure. It does not cause overvoltage unlike reactor or auto-transformer starting during different commutations. Its use is limited by the network short-circuit power. It must be remembered that the higher the motor’s maximum torque (case of motors having large air-gaps), the weaker the subtransient reactance, and the higher the starting current is.

- **Reactor starting**
  This is the most widely used and most economic mode after direct-on-line starting. It gives the best cost-effective compromise. It only requires a set of three reactors and an extra short-circuiting contactor for them. It is not as easy to adapt the starting rating to the load and network as in the case where an auto-transformer is used.

- **Auto-transformer starting**
  This is the most flexible mode for use, as it has the advantage of adapting the current and torque to the load and network. However, it requires an auto-transformer and extensive controlgear to be installed and is thus relatively costly.

- **Block-transformer starting**
  When the motor has a high unit power (= 10 MW), it may be useful to connect it to the HV network via an HV/MV transformer with the same apparent power as that of the motor. Inrush currents and voltage drops are reflected on the HV network and no longer on the MV network.

  This is a relatively costly solution as it requires a transformer and extra HV switchgear; this solution nevertheless helps to solve the problem of voltage drops on the network.

---

Table 3-7: main fixed speed synchronous motor starting modes
synchronous motor starting torque (in asynchronous mode)

The shape of the starting torque, depending on whether the pole is solid or laminated, is given in figure 3-38.

The torque curve of the laminated pole rotor, fitted with damping windings and a complete cage, looks like the usual asynchronous motor torque curve.

The solid pole rotor torque curve has a clearly different run. It is practically constant up to three-quarters of the speed and then quickly drops. The slope of the curve is smaller which means that, for the same load torque, the slip is higher for a solid rotor than for a laminated rotor. When the motor speed is stable and close to the synchronism speed, the continuous excitation voltage is applied to the rotor so that the motor operates as a synchronous machine.

![Figure 3-38: asynchronous starting torque of a synchronous motor](image)

Figure 3-38: asynchronous starting torque of a synchronous motor
3.3.5. **Asynchronous motor braking**

The braking torque of the motor and driven machine assembly is equal to the torque developed by the motor to which is added the load torque of the machine driven:

\[ T_b = T_m + T_l \]

- \( T_b \): braking torque
- \( T_m \): motor torque
- \( T_l \): load torque

The braking time, or time necessary for the asynchronous motor to go from a speed \( N \) to a stop position, is:

\[ t_b = \frac{2 \pi J N}{60 T_b} \]

- \( t_b \): braking time in seconds
- \( J \): moment of inertia in kg x m²
- \( N \): rotation speed in tr/min.
- \( T_b \): mean braking torque in the interval \( N \to 0 \) in Newton x m

### reverse-current braking

This braking mode is obtained by reversing two phases.

The phase reversing contactor is time delayed in order to wait for the remanent voltage to be low enough. This voltage is due to the flux stored by the rotor which is exponentially extinguished and lasts for about one second. The time delay also prevents phase inversion coupling which would damage the motor.

Generally, an electrical breaking device finally disconnects the motor from the network when the speed reaches \( N = 0 \).

The mean braking torque is generally higher than the starting torque for cage asynchronous motors.

This braking mode involves a high current input which is approximately constant and slightly higher than the starting current.

During braking, thermal stress is 3 times higher than for a speed build-up.

**Note:** to reverse the rotation direction of a machine, it must be regeneratively braked and then started. From a thermal point of view, a reversal is thus equivalent to 4 starts.
**d.c. voltage braking**

Operating stability during reverse current braking can pose problems in some cases.

D.c. voltage braking does not have this drawback. It applies to cage motors and slip-ring motors.

The machine is braked by cutting the a.c. voltage and applying a d.c. voltage to the stator once the remanent voltage is sufficiently low.

There are four ways in which the windings can be coupled to the d.c. voltage (see fig. 3-39).

The d.c. voltage applied to the stator is generally supplied by a rectifier connected to the network. A controller used for starting the motor can perform this function.

Thermal stress is approximately 3 times lower than for the reverse-current braking mode, but the braking time is longer.

The braking torque run in the speed interval \((0, N_s)\) is similar to that of the curve \(T_m = f(N)\) (see fig. 3-40)

\[ V_{dc} : \text{d.c. voltage} \]

*Figure 3-39: motor winding d.c. voltage connecting modes*

*Figure 3-40: braking torque run*
asynchronous generator braking

This braking mode applies to motors with several speeds (e.g. 2 and 4 poles, 1 500 and 3 000 tr/min) when the speed reaches the lowest value. It is impossible to make the motor stop using this procedure.

Thermal stress is approximately identical as that obtained when the speed goes from the lowest to the highest level.

The braking torque developed by the asynchronous machine, at the lowest speed, operating as an asynchronous generator in the speed interval \( \left( 2 N_s, N_s \right) \) is very high.

The maximum braking torque is slightly higher than the motor starting torque at the lower speed.

braking of a motor fed by an electronic speed variator

This braking mode is possible when the speed variator is controlled.

When the variator inverter supplies a frequency that is lower than the motor speed then this brakes and redirects its energy:

- to the network when the rectifier is reversible (thyristor rectifier)
- to a thermal dissipation resistor controlled by a transistor connected in parallel on the d.c. circuit.

An energy recovery system is essential to prevent the inverter from being deteriorated as in the case of voltage dips on the network (see § 3.4.7).

3.3.6. Choice of motor type

The choice of motor type essentially depends on the load torque of the machine driven, the duty (intermittent, continuous) and the power rating.

cage asynchronous motor

The cage asynchronous motor is generally suitable:

- for all applications in small and medium power ratings
- for driving machines with a parabolic load torque (pumps, ventilators, centrifugal compressors, etc.) for continuous duty or a reduced number of starts in high power ratings.
asynchronous slip-ring motor

For medium and high power ratings, the asynchronous slip-ring motor is suitable for problems related to:

- starting a load with a very long moment of inertia
- frequent starts (lifting machines with over 150 starts per hour, etc.)
- high load torque on starting (grinders, crushers, etc.)
- supply network unable to withstand the inrush current of a cage motor.

The drawbacks of the slip-ring motor in relation to the cage motor are essentially:

- higher purchase price
- maintenance of slip-rings and brushes
- fragility of slip-ring rotors at high speeds (3 000 tr/min)
- unsuitability in certain environments (notably explosive).

synchronous motor

The synchronous motor is mainly used in the following cases:

- need for a fixed speed
- high power ratings at low speed (the asynchronous motor has a lower power factor at low speed)
- high power ratings with variable speeds (notably high speeds)
- need to improve the network’s power factor (the synchronous motor can supply reactive power)

The drawbacks of the synchronous motor in relation to the cage motor are essentially:

- its purchase price
- a more complex rotor.

On the other hand, the more and more widespread manufacture of rotating rectifier synchronous machines cancels the drawback of the slip-rings and brushes, a drawback which still applies to asynchronous slip-ring machines.
### advantages and drawbacks of different types of motors (see table 3-8)

<table>
<thead>
<tr>
<th>Synchronous motor (SM)</th>
<th>Asynchronous motor (ASM)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power supply</strong></td>
<td>A.C. supply.</td>
</tr>
<tr>
<td></td>
<td>D.C. supply (converter) for excitation.</td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td>Complex.</td>
</tr>
<tr>
<td></td>
<td>Relatively large air-gap.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Starting</strong></td>
<td>Laminated pole motor:</td>
</tr>
<tr>
<td></td>
<td>- torque analogous to ASM.</td>
</tr>
<tr>
<td></td>
<td>Solid salient pole motor:</td>
</tr>
<tr>
<td></td>
<td>- high starting torque</td>
</tr>
<tr>
<td></td>
<td>- able to start high inertia loads due to large thermal capacity of poles.</td>
</tr>
<tr>
<td></td>
<td>Generally lower inrush current than the ASM.</td>
</tr>
<tr>
<td></td>
<td>High transient torques on starting.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Overloads</strong></td>
<td>Smaller overloads than ASM.</td>
</tr>
<tr>
<td><strong>Power factor</strong></td>
<td>Pre-determined power factor.</td>
</tr>
<tr>
<td><strong>Reactive energy</strong></td>
<td>Can be high and close to 1.</td>
</tr>
<tr>
<td></td>
<td>The motor can supply reactive power.</td>
</tr>
<tr>
<td><strong>Stability when confronted with voltage dips</strong></td>
<td>Better stability than ASM since overexcitation is possible (depending on the rotor power supply capacity) which restores stability.</td>
</tr>
<tr>
<td></td>
<td>Risk of pull-out and need to restart if too big a voltage drop.</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>Fixed speed for a given frequency.</td>
</tr>
<tr>
<td></td>
<td>Variable speed (see tab. 3-5).</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>High, especially due to the cost of d.c. excitation.</td>
</tr>
</tbody>
</table>

*Table 3-8: advantages and drawbacks of different types of motors*
3.3.7. Effects of disturbance on motors

asynchronous motors

At the moment, over half the energy consumed in industry is used by asynchronous motors which explains the importance of their behaviour when confronted with disturbance.

voltage dips

When a voltage dip occurs, the motor torque proportional to the square of the voltage (see § 3.13.1.), undergoes a sudden decrease which causes the motor to slow down. This slowing down, which is a function of the dip time and amplitude, essentially depends on the moment of inertia of the rotating masses and the load torque.

When the network voltage is restored, each motor consumes a current which is all the closer to its starting current at full voltage as the slip reached at the end of disturbance is high. This reacceleration phase does not, a priori, lead to serious consequences except if the motors represent a major part of a busbar’s or the installation’s power rating. In this case, the sum of inrush currents of all the motors upon restarting may cause the protections to trip.

These overcurrents may also lead to voltage drops in the upstream impedances (especially those of the transformers) so much so that the return to normal running is difficult and restrictive (little difference between the motor and load torques causing a re-acceleration with overheating) if not impossible (the motor torque having greatly decreased thus dropping below the load torque).
☐ short supply interruptions

Completely cancelling the supply voltage does not immediately eliminate the voltage at the motor’s terminals. In fact, the flux stored in the rotor cannot be extinguished instantaneously. The rotating field created by the rotor induces a « remanent » voltage in the stator, the amplitude of which decreases exponentially (time constant equal to several tenths of a second). The frequency of this voltage decreases with the rotation speed. If, when the voltage is restored on the network, it is in phase inversion with the remanent voltage, the amplitude of which has only slightly decreased, a high overcurrent is produced which may reach twice the motor starting peak, i.e. 12 to 15 times its nominal current.

This may have serious consequences for the motor:

- extra rise in temperature and electrodynamic stress in the windings able to cause a breakdown in insulation
- dangerous torque jolts which may lead to abnormal mechanical stress (especially on the couplings).

The way to provide against this risk is to install a remanent undervoltage protection (see § 7.13. of Protection guide).

☐ voltage unbalance

Unbalanced single-phase loads on three phases and three-phase loads which do not operate symmetrically (resistance furnaces, welding machines, boilers, etc.) create voltage unbalance (§ 3.4.2 and 3.4.6).

Three-phase supply voltage unbalance can be seen by the existence of three positive-sequence, negative-sequence and zero-sequence voltage systems (see § 4.2.2. of Protection guide). The negative-sequence system creates a rotating field which rotates in the opposite direction to that of the rotor. When there is a negative-sequence voltage system, the stator then induces current with a frequency that is equal to double that of the network frequency. This current causes an extra rise in temperature and impulse torques which may lead to mechanical stress and abnormal noise.

It can be added that the presence of induced current in the rotor has the effect of reducing the network voltage unbalance; the machine acts as an unbalance compensator.

The zero-sequence system has no influence as the zero-sequence impedance of the motor is infinite (delta or star connection with unearthed neutral).

IEC standard 892 indicates the derating factor of three-phase cage asynchronous motors in relation to the voltage unbalance rate (see fig. 3.40-b).
The voltage unbalance rate is defined by the following relation:

\[ \tau = \frac{\text{maximum value of the difference between any one of the three voltages and the mean value of the three voltages}}{\text{mean value of the three voltages}} \]

![Diagram showing the relationship between derating factor and voltage unbalance rate.](image)

*Fig. 3.40-b: three-phase cage motor derating factor in relation to the voltage unbalance rate*

- **voltage harmonics**

  The influence of voltage harmonics on motors is discussed in paragraph 8.2.

- **synchronous motors**

- **voltage dips and short supply interruptions**

  The effects are more or less the same as those described in the case of asynchronous motors.

  It must be pointed out, however, that synchronous motors can withstand higher voltage dips as:
  - the torque is proportional to the voltage (and not to the square of the voltage)
  - the possibility of overexciting the machine helps the return to normal running (depending on the rotor power supply capacity)
  - the moment of inertia is great since the rotor has a higher mass.

  On the other hand, in the event of pulling out of synchronism, the overcurrent is high and the protections put the motor out of service. The motor must therefore be started again.

- **voltage harmonics and unbalance**

  This type of disturbance has the same consequences as for asynchronous motors; it leads, in particular, to overheating, mainly in the damper windings.

  Furthermore, the current induced in the rotor causes a disturbance in the rotor current measurement, thus leading to faulty operation of the varmeter regulator.
3.4. **Other loads**

We shall study the operation of loads (other than motors) which are usually encountered in electrical installations and the power supply constraints which they engender.

3.4.1. **Arc furnaces**

- **Operating principle**

The electric arc allows very high ratings to be implemented and high temperatures to be reached (roughly 3000 °C). Alternating current arc furnaces generally have a three-phase supply and consequently have three graphite vertical electrodes from which the arcs are generated (see fig. 3-41).

![Diagram of an arc furnace installation](image)

*Figure 3-41: diagram of an arc furnace installation*

There are also a.c. single-phase arc furnaces used for small production capacities, and d.c. arc furnaces, the use of which has become more and more widespread over the last few years.

The ratings of furnaces stretch from several MVA to over 100 MVA.

The highest voltage currently used at the location of the furnace never goes above 950 Volts. As for the current used, this goes from roughly ten thousand Amps up to a hundred thousand Amps; the current densities in the electrodes can reach 25 A/cm².

With the main field of application for arc furnaces being melting metal in steelworks, the rest of this section will be limited to this sector which nevertheless covers practically all existing arc furnaces.
Traditional electric steelworks are fitted with two types of arc furnaces:

- an a.c. or d.c. fed melting furnace
- an aluminium refining cell with a lower power rating and which is generally a.c. supplied for the steel bath rise in temperature.

The main parts making up each furnace are:

- the electrical power supply
- the furnace tank (the diameter of which may vary from 4 to 10 m) which has a heat-resisting inside coating (bricks storing the heat and which therefore have a high thermal inertia)
- annexe systems (evacuation, smoke treatment and electrical connection cooling systems).

---

### power supply constraints, disturbances and solutions

In this part, the two types of arc furnaces, a.c. and d.c., will be dealt with and compared as each has its own specific characteristics and power supply constraints.

The electric circuit of an a.c. arc furnace has (see figure 3-42):

- a step-down transformer
- a switching operation circuit-breaker
- a protection circuit-breaker
- a furnace transformer
- if necessary, a reactive energy compensation, anti-harmonic filtering and overvoltage protection system

- electrical cables.
A d.c. arc furnace electric circuit differs from the previous type due to its rectified electrical power supply and the presence of one or several electrodes for the current to be returned (see fig. 3-43).
The furnace power is regulated by adjusting the power supply voltage and the position of the electrodes, and thus the length of the arc. The power consumed varies, in fact, depending on the furnace operating phases (see fig. 3-44).

*Figure 3-43: d.c. furnace power supply*
Arc furnaces have three phases of operation:

1. **Arcing**: this is the period during which the electrodes dig their wells through the cold metal. The arc voltage and power are not maximum so that the stability of the highly disturbed arc is held by the movement of the metal mass and the non homogenous mixture.

2. **Melting**: in this phase, the charge is melted through direct radiation or electrical conduction of the bath. The furnace power is then at maximum level.

3. **Refining**: during this last phase the temperature of the steel is raised at a lower power in order to avoid wear on the side wall refractories, before casting in the refining furnace where the temperature will continue to rise.

Throughout these stages the power consumed by the furnace greatly fluctuates which creates voltage variations on the network.
**Voltage drop from busbar to furnace connection point**

The voltage drop from the busbar to the furnace connection point (see fig. 3-45) is given by the usual formula:

\[
\frac{\Delta U}{U_n} = \frac{RP + XQ}{U_n^2}
\]

where:

- \( P \): active power consumed by the furnace
- \( Q \): reactive power consumed by the furnace
- \( Z = R + jX \): sum of impedances from the furnace connection point upto the busbar (cables, series reactor and step-down transformer)

![Figure 3-45: voltage drop from busbar to furnace connection point](image)

**Flicker**

The flicker phenomenon is the main type of disturbance generated by arc furnaces, notably a.c. furnaces.

This is due to the instability of the electrical arc during the melting phase. The alternating voltage leads to extinction and re-lighting phenomena when the current reaches zero. The metal charge also disturbs the operation of the arc by its movements and leads to variations in current able to cause short circuits or interruptions in operation.

This results in the flicker phenomenon or voltage fluctuations.
"flicker dose" created by an alternating current arc furnace

Let us consider the diagram in figure 3-46.

\[ X_{up} : \text{equivalent reactance of the upstream network at the calculation point} \]
\[ X_f : \text{sum of reactances of all electrical connections from the calculation point upto the furnace (cables, step-down transformer and furnace electrode connections)} \]

**Figure 3-46: equivalent wiring diagram of an arc furnace power supply**

The flicker dose created by an a.c. arc furnace is defined in the following equation:

\[ G = k^2 \left( \frac{X_{up}}{X_{up} + X_f} \right)^2 \]

The coefficient \( k \) is statistically estimated by the analysis of the test results carried out on fifty or so furnaces. The mean value obtained is equal to 11.25 with a standard deviation of 2.

Experience shows that an allowable flicker dose value is:

\[ G = 0.09 \]

i.e.

\[ k^2 \left( \frac{X_{up}}{X_{up} + X_f} \right)^2 = 0.09 \]
It is thus possible to deduce from this a condition for connecting an arc furnace on an industrial network:

\[ \frac{X_f}{X_{up}} \geq 36 \]

Moreover, it is possible to quickly determine the minimum short-circuit power required to supply the furnace:

\[ S_{sc \, min} = \frac{36 \, U_n^2}{X_f} \]

Solutions for providing against flicker are explained in paragraph 3.2.

The strong dose of flicker due to the operation of arc furnaces only occurs with a.c. furnaces. Using a d.c. furnace in fact enables the flicker phenomenon to be considerably reduced. On the other hand, supplying d.c. furnaces generates numerous harmonics on the power supply network (see § 8.1.3).

- harmonics

Due to the instability of the electric arc, arc furnaces have a continuous spectrum of harmonics superposed at individual rates of high values (see § 8.1.3).

In the specific case of direct current furnaces, integral number harmonics are created by rectifier bridges.
furnace circuit-breaker and transformer

An arc furnace transformer is completely different from a conventional distribution transformer. Its turns ratio is high as the secondary voltage is only several hundred volts for a primary in medium or high voltages from 20 kV to 63 kV. It has multiple taps on the primary to adjust the secondary voltage. It undergoes high electrodynamic stress which is why the shell-type transformer is often preferred for its geometry (see fig. 3-47).

The furnace circuit-breaker must, on the one hand, ensure the system's protection and must therefore have a breaking capacity which is at least equal to the supply short-circuit power, and, on the other hand, withstand numerous daily openings and closings (as many as 5000 per year) required by the operation of the furnace.

These two functions are often disassociated and carried out by two different circuit-breakers (see fig. 3.4.2 and 3.4.3):

- a switching operation circuit-breaker
- a protection circuit-breaker.
## Calculation Example of the Flicker Supplied by an Arc Furnace

The installation characteristics are given in figure 3-48.

<table>
<thead>
<tr>
<th>Calculations</th>
<th>X ( )</th>
<th>R ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{sc}$</td>
<td>$\frac{(63 \times 10^3)^2}{800 \times 10^6}$</td>
<td>4.96</td>
</tr>
<tr>
<td>$R_1$</td>
<td>$\frac{36}{238} \times 20$</td>
<td>8</td>
</tr>
<tr>
<td>$X_1$</td>
<td>$0.4 \times 20$</td>
<td></td>
</tr>
<tr>
<td>$X_{t1}$</td>
<td>$\frac{12}{100} \times \frac{(63 \times 10^3)^2}{20 \times 10^6}$</td>
<td>23.8</td>
</tr>
<tr>
<td>$X_S$</td>
<td>$L = 97 \times 10^{-3} \times 100 \times$</td>
<td>30.5</td>
</tr>
<tr>
<td>$X_{t2}$</td>
<td>$\frac{11}{100} \times \frac{(22 \times 10^3)^2}{2.5 \times 10^6}$</td>
<td>21.3</td>
</tr>
<tr>
<td>$X_e$</td>
<td>$2.5 \times 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3-48: Arc Furnace Power Supply Characteristics**
■ determining the flicker dose at the utility take over point (point A)

This is the dose of flicker that other users on the 63 kV line (all users downstream of this line) will be subjected to.

The upstream impedance at point A is:

\[ X_{up} = 4.96 \Omega \]

The downstream impedance at point A (based on 63 kV) is:

\[ X_f = 8 + 23.8 + 30.5 \times \left( \frac{63}{22} \right)^2 + 21.3 \times \left( \frac{63}{22} \right)^2 + 2.5 \times 10^{-3} \times \left( \frac{63}{0.210} \right)^2 = 681.6 \Omega \]

whence

\[ \frac{X_f}{X_{up}} = 137 \]

\[ \frac{X_f}{X_{up}} > 36 \], the other users on the 63 kV line will therefore not be disturbed.

■ determining the flicker dose on the 22 kV busbar (point B)

This is the dose of flicker that the factory's internal network will undergo.

The upstream impedance at point B (based on 22 kV) is:

\[ X_{up} = (4.96 + 8 + 23.8) \times \left( \frac{22}{63} \right)^2 = 4.48 \Omega \]

The downstream impedance at point B (based on 22 kV) is:

\[ X_f = 30.5 + 21.3 + 2.5 \times 10^{-3} \times \left( \frac{22}{0.21} \right)^2 = 79.2 \Omega \]

whence

\[ \frac{X_f}{X_{up}} = 17.7 \]

\[ \frac{X_f}{X_{up}} < 36 \], the factory lighting will thus be subjected to an unacceptable dose of flicker.

With the furnace being already fitted with a high series reactance which cannot therefore be increased, the solutions are, for example:

- connecting the furnace to the 63 kV busbar via a specific transformer for which the connection requirement has been met.

- installing a static var compensator on the 20 kV busbar (see § 3.2, fig. 3-6).

The other solutions possible are explained in paragraph 3.2.
3.4.2. Resistance welding machines

■ operating principle

Resistance welding uses the Joule effect resulting from the passage of a high current through the parts to be assembled. The energy is stored in the material itself and the melting takes place in the plane of contact of the two parts to be assembled.

There are different resistance welding processes:

- spot welding for assembling superposed sheet metal (see fig. 3-49)

![Figure 3-49: spot welding](image)

- projection welding for the overall assembly of superposed parts. The parts to be assembled have projections at the welding points (see fig. 3-50).

![Figure 3-50: projection welding](image)

- seam welding for making sealed links between two pieces of sheet metal (see fig. 3-51)

![Figure 3-51: seam welding](image)
- butt welding for welding the ends of two bars together (see fig. 3-52)

Figure 3-52: butt welding

The resistance welding system is nevertheless the same whatever the type of machine (see fig. 3-53). It includes:

- an electrical circuit through which high current passes (welding circuit) and which ends in electrodes

- a transformer with a variable ratio and which thus acts as a current generator \( I = \frac{V_{\text{variable}}}{Z_{\text{transfo}}} \) as the load impedance is negligible).

- a clamping device to create the welding force

- a time delay device.

Figure 3-53: resistance welding system
- *power supply constraints, disturbance and solutions*

The intermittent operation of resistance welding machines means that precautions must be taken when fixing their power supply rating.

Two standard ratings of a welding machine can be defined:

\[ S_{\text{max}} \]: machine welding power  
\[ S_{100\%} \]: nominal power or equivalent power to continuous operation

\[ S_{\text{max}} \] is the power supplied when the machine is welding, taking the impedance at the welding point to be zero.

The welding machine operates intermittently and thus has a welding period \( t_w \) and a rest period \( t_r \) (see fig. 3-54). The machine operating factor can thus be defined as:

\[ f = \frac{t_w}{t_w + t_r} \]

\[ R I_m^2 \]

\[ R I_{100\%}^2 \]

real current

equivalent permanent current for operation at limit factor

\[ t_w \] \hspace{1cm} \[ t_r \]

*Figure 3-54: resistance welding machine operation*

The machine applies a limit operating factor \( f_{\ell} \) of the order of 0.3 to 0.8.
For $f_\ell$, we shall determine the equivalent power of the machine as if it operated continuously; i.e. with a fictive operating factor equal to 100%.

This will allow us to fix the thermal rating of the equipment (transformer, cables, etc.).

The thermal power consumed by the equipment at the limit factor is: $R I_m^2 f_\ell$.

$R$: resistance of the equipment to be rated (transformer, cables, etc.)

$I_m$: current during the welding period

The thermal power equivalent to continuous operation is:

$$R I_{100\%}^2$$

$I_{100\%}$: permanent current which would supply the same thermal power

By writing the balance of these two powers, we obtain

$$R I_{100\%}^2 = R I_m^2 f_\ell$$

whence

$$I_{100\%} = I_m \sqrt{f_\ell}$$

The machine power during the welding period is:

$$S_{\text{max}} = V_n I_m$$

$V_n$: nominal off-load voltage at the machine terminals

The machine power equivalent to continuous operation is:

$$S_{100\%} = V_n I_{100\%}$$

whence

$$S_{100\%} = S_{\text{max}} \frac{I_{100\%}}{I_m} = S_{\text{max}} \sqrt{f_\ell}$$

$$S_{100\%} = S_{\text{max}} \sqrt{f_\ell}$$
If the actual use of the machine is reduced to a use factor of $f_u < f_\ell$, then the equivalent power of the machine is:

$$S_u = S_{\text{max}} \sqrt{f_u}$$

$S_u$ thus gives the equipment thermal power rating.

In any case, $S_{\text{max}}$ gives the rating of equipment with regard to voltage drops.

**Voltage drops and flicker**

Voltage drops caused by the welding machine depend on the machine’s connection mode.

For three-phase welding machines, the charge is balanced by the machine generator.

The voltage drop caused is thus given by the conventional formula:

$$\frac{\Delta U \%}{U_n} = \frac{\Delta V \%}{V_n} = 100 \times \frac{RP + XQ}{U_n^2}$$

where:

$\Delta U$: voltage drop  
$U$: phase-to-phase voltage  
$V$: single-phase voltage  
$U_n$: nominal phase-to-phase network voltage  
$R + jX$: network upstream impedance  
$P$: active power consumed by the machine  
$Q$: reactive power consumed by the machine

Single-phase machines are nevertheless the most widespread given that the welding circuit is always single-phase.

For these machines, voltage drops depend on the connection mode (phase-to-phase or phase-to-neutral) and the supply transformer vector group. Disymmetrical current consumed by the machine causes an unbalance on the single-phase and phase-to-phase voltages in MV. Because of the power levels used and the level of flicker caused, welding machines are always connected to the MV network via a specific MV/LV transformer.

For every vector group, the single-phase and phase-to-phase voltage drops at the transformer primary can be determined.
Let us define the following values:

\[
\begin{align*}
    a &= \sqrt{3} \times \frac{\sqrt{3} (RP + XQ) - (XP - RQ)}{2 U_n^2} \times 100 \\
    b &= \sqrt{3} \times \frac{\sqrt{3} (RP + XQ) - (XP - RQ)}{2 U_n^2} \times 100 \\
    c &= 0 \\
    d &= 2 \times \frac{RP + XQ}{U_n^2} \times 100 \\
    e &= \frac{(RP + XQ) + \sqrt{3} (XP - RQ)}{2 U_n^2} \times 100 \\
    f &= \frac{(RP + XQ) - \sqrt{3} (XP - RQ)}{2 U_n^2} \times 100
\end{align*}
\]

where:

- \( U_n \) : nominal network phase-to-phase voltage
- \( R + jX \) : network upstream impedance
- \( P \) : active power consumed by the machine
- \( Q \) : reactive power consumed by the machine

Tables 3-9, 3-10, 3-11, 3-12, 3-13 et 3-14 give the different voltage drops at the transformer primary depending on the vector group.
phase-to-phase connection

\[
\begin{align*}
\Delta V_1 &= a \\
\Delta V_2 &= b \\
\Delta V_3 &= c \\
\Delta U_{12} &= d \\
\Delta U_{23} &= e \\
\Delta U_{31} &= f \\
\end{align*}
\]

phase-to-neutral connection

\[
\begin{align*}
\Delta V_1 &= R_P + X_Q 	imes 100 \\
\Delta V_2 &= 0 \\
\Delta V_3 &= 0 \\
\Delta U_{12} &= b \\
\Delta U_{23} &= c \\
\Delta U_{31} &= a \\
\end{align*}
\]

Table 3-9: Yy0 vector group

phase-to-phase connection

\[
\begin{align*}
\Delta V_1 &= c \\
\Delta V_2 &= a \\
\Delta V_3 &= b \\
\Delta U_{12} &= f \\
\Delta U_{23} &= d \\
\Delta U_{31} &= e \\
\end{align*}
\]

Table 3-10: Dd10 vector group
### phase-to-phase connection

<table>
<thead>
<tr>
<th>$I_s$</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
</table>

\[ \begin{align*}
\Delta V_1 &= f \\
\Delta V_2 &= d \\
\Delta V_3 &= e
\end{align*} \]

\[ \begin{align*}
\Delta U_{12} &= a \\
\Delta U_{23} &= b \\
\Delta U_{31} &= c
\end{align*} \]

### phase-to-neutral connection

<table>
<thead>
<tr>
<th>$I_s$</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
</table>

\[ \begin{align*}
\Delta V_1 &= a \\
\Delta V_2 &= b \\
\Delta V_3 &= c
\end{align*} \]

\[ \begin{align*}
\Delta U_1 &= d \\
\Delta U_2 &= e \\
\Delta U_3 &= f
\end{align*} \]

*Table 3-11: Dy11 vector group*

### phase-to-phase connection

<table>
<thead>
<tr>
<th>$I_s/3$</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
</table>

\[ \begin{align*}
\Delta V_1 &= f \\
\Delta V_2 &= d \\
\Delta V_3 &= e
\end{align*} \]

\[ \begin{align*}
\Delta U_{12} &= a \\
\Delta U_{23} &= b \\
\Delta U_{31} &= c
\end{align*} \]

*Table 3-12: Yd11 vector group*
phase-to-phase connection

\[
\begin{align*}
\Delta V_1 &= a \\
\Delta V_2 &= b \\
\Delta V_3 &= c \\
\end{align*}
\]

\[
\begin{align*}
\Delta U_{12} &= d \\
\Delta U_{23} &= e \\
\Delta U_{31} &= f \\
\end{align*}
\]

phase-to-neutral connection

\[
\begin{align*}
\Delta V_1 &= f \\
\Delta V_2 &= d \\
\Delta V_3 &= e \\
\end{align*}
\]

\[
\begin{align*}
\Delta U_{12} &= b \\
\Delta U_{23} &= c \\
\Delta U_{31} &= a \\
\end{align*}
\]

Table 3-13: Dz6 vector group

phase-to-phase connection

\[
\begin{align*}
\Delta V_1 &= e \\
\Delta V_2 &= d \\
\Delta V_3 &= f \\
\end{align*}
\]

\[
\begin{align*}
\Delta U_{12} &= a \\
\Delta U_{23} &= b \\
\Delta U_{31} &= c \\
\end{align*}
\]

phase-to-neutral connection

\[
\begin{align*}
\Delta V_1 &= a \\
\Delta V_2 &= b \\
\Delta V_3 &= c \\
\end{align*}
\]

\[
\begin{align*}
\Delta U_{12} &= d \\
\Delta U_{23} &= e \\
\Delta U_{31} &= f \\
\end{align*}
\]

Table 3-14: Yz11 vector group
Along with arc furnaces, welding machines are the main causes of flicker on electrical networks. Resistance welding machines are characterised by their operating cycle. This cycle can be used to calculate the number of variations created per minute, in order to define the maximum amplitude of the voltage variation allowable.

As a first approximation, it is possible to consider that a weld generates two fronts, one rising and the other descending; but in some cases the form of the inrush current, which can present more than two fronts, will have to be taken into account in order to determine the number of variations per weld and thus the allowable limit.

To limit the influence of voltage drops caused by resistance welding machines, it is essential to separate the machine power supply from the rest of the low voltage power supply by connecting the welding machine to the medium voltage network via a specific MV/LV transformer. Of course, it is recommended to connect the machine to a network with the highest possible voltage in order to limit the flicker effect. The ways to solve flicker are described in 3.2.

- reactive power compensation

Resistance welding machines consume a lot of reactive energy and consequently have a low power factor (of the order of 0.3 to 0.8). It is very often essential to compensate this reactive energy using capacitors.

It is dangerous to connect the capacitors close to the welding machine. Indeed, because of its intermittent operation, there is a continuous spectrum of frequencies which may consequently lead to low frequency resonance and cause overvoltages likely to affect the switchgear.

It is, however, possible to connect the capacitors further upstream at the utility take-over point or main medium voltage busbar.

The compensation power can be calculated using the usual formula:

\[ Q_c = P \left( \tan \phi_1 - \tan \phi_2 \right) \]

- \( P \): welding machine active power
- \( \cos \phi_2 \): required power factor
- \( \cos \phi_1 \): machine power factor

\[ \cos \phi_1 = \frac{P}{S_{\text{max}}} \]

- \( S_{\text{max}} \): maximum apparent power of the resistance welding machine
connection calculations

Given that resistance welding machines operate intermittently, it is necessary to distinguish between the connection of a single welding machine from that of several machines.

- case of a single machine

Two elements should be taken into account for the connection of a resistance welding machine: the LV supply cables and the transformer (voltage drops in the MV cables are negligible).

- cables

For cable size-up, two criteria must be met: a thermal criterion and a voltage drop criterion. Indeed, the cable cross-section must be chosen to withstand a permanent current corresponding to the 100 % operating factor, obtained using the apparent power of the machine (in kVA) given by the manufacturer.

It is also necessary to limit the voltage drop in the cable to 4 %. Knowing what the current is in each phase (for the machine welding power factor $S_{\text{max}}$) as well as the cable length we can determine the minimum cable cross-section.

The voltage drop is written as $\Delta V = R I_m \cos \varphi + X I_m \sin \varphi$ (see § 6.1.7).

whence $R = \frac{\Delta V - X I_m \sin \varphi}{I_m \cos \varphi}$

The minimum cable cross-section is thus $S = \frac{\cos \varphi \cdot \rho \cdot \ell}{T_m - X \sin \varphi}$ .

$\rho$ : LV cable resistivity
$\ell$ : LV cable length
$I_m$ : current flowing through the LV cable during the welding period

The most restrictive of the two criteria must be chosen.
- transformer

As for cables, the transformer rating must take into account a thermal criterion and a voltage drop criterion.

The first criterion depends on the type of machine connection (see table 3-15):

<table>
<thead>
<tr>
<th>Machine</th>
<th>Transformer</th>
<th>Transformer rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>three-phase</td>
<td>three-phase</td>
<td>$S_{100%}$</td>
</tr>
<tr>
<td>single-phase</td>
<td>Dy11 or Yz5 three-phase</td>
<td>$\sqrt{3} S_{100%}$</td>
</tr>
<tr>
<td>single-phase</td>
<td>single-phase</td>
<td>$S_{100%}$</td>
</tr>
</tbody>
</table>

$S_{100\%}$: welding machine power at the 100% operating factor

Table 3-15: transformer thermal rating

In order to remain within the allowable voltage drop limit, it is necessary to limit the total drop to 10%, and thus the voltage drop in the transformer to 6% (4% in the LV cable).

This then gives the results shown in table 3-16 for the transformer power rating ($U_{sc\%}$ corresponds to the voltage drop in the transformer at the nominal power).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Transformer</th>
<th>Transformer power</th>
</tr>
</thead>
<tbody>
<tr>
<td>three-phase</td>
<td>three-phase</td>
<td>$S_{max} \cdot \frac{U_{sc%}}{6}$</td>
</tr>
<tr>
<td>single-phase</td>
<td>Dy11 or Yz5 three-phase</td>
<td>$\sqrt{3} S_{max} \cdot \frac{U_{sc}}{6}$</td>
</tr>
<tr>
<td>single-phase</td>
<td>single-phase</td>
<td>$S \cdot \frac{U_{sc%}}{6}$</td>
</tr>
</tbody>
</table>

$S_{max}$: machine welding power  
$U_{sc\%}$: transformer short-circuit voltage

Table 3-16: transformer rating for voltage drop criterion
• case of several machines

The calculation principle for an installation with several resistance welding machines is the same as the connection of a single machine but, in this case, the machine simultaneity factor must be taken into account.

In some cases (few machines or low operating factors), it may be possible to interlock the machines to avoid them welding at the same time.

When this is not possible, the maximum power to be considered is the result of a probability calculation.

The equivalent power of \( n \) identical single-phase machines connected to the same phase is:

\[
S_{\text{equ}} = S_{\text{max}} \sqrt{n \cdot f(1 + (n-1) \times f)}
\]

\( S_{\text{max}} \): maximum power of each machine

\( f \): operating factor of each machine

\( n \): number of connected machines

In the case of different machines, then:

\[
S_{\text{equ}} = S_{\text{max, mean}} \sqrt{n \cdot f_{\text{mean}}(1 + (n-1) \times f_{\text{mean}})}
\]

where

\[
S_{\text{max, mean}} = \sqrt{\frac{\sum S_{\text{max}}^2}{n}}
\]

\[
f_{\text{mean}} = \frac{S_{100\% \text{mean}}^2}{S_{\text{max, mean}}^2}
\]

and

\[
S_{100\% \text{mean}} = \sqrt{\frac{\sum S_{100\%}^2}{n}}
\]

\( S_{\text{max}} \): maximum power of each machine

\( S_{100\%} \): power of each machine for an operating factor of 100 %
**resistance welding machine connection example**

Let us consider a single-phase type spot welding machine connected between two phases with the power ratings $P = 78 \text{ kW}$ and $Q = 104 \text{ kVAR}$ ($\cos \varphi = 0.6$), and with an operating cycle of 30/min. The limit operating factor is $f_l = 0.3$.

$P$ and $Q$ are the equivalent thermal power ratings for a running factor of 100 %, and thus:

$$S_{100\%} = \sqrt{P^2 + Q^2}$$

$$S_{100\%} = 130 \text{ kVA}$$

The machine is fed by a three-phase Dy11 transformer (see table 3-11), connected to the factory's 5.5 kV network (see fig. 3-55).

### Calculations

<table>
<thead>
<tr>
<th>Transformer</th>
<th>$U_{in}$</th>
<th>$S_{sc}$</th>
<th>Voltage basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 km overhead line</td>
<td>$20 \text{ kV}$</td>
<td>140 MVA</td>
<td>20 kV</td>
</tr>
<tr>
<td>5 MVA transformer</td>
<td>$7.5 %$</td>
<td>$20kV / 5.5kV$</td>
<td>5.5 kV</td>
</tr>
<tr>
<td>Cable : 500 m Copper : 70 mm$^2$</td>
<td>$147 \text{ mm}^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 kV / 400 V transformer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LV cable : 10 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance welding machine</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculations</th>
<th>$X(\ )$</th>
<th>$R(\ )$</th>
<th>Voltage basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X \frac{(20 \cdot 10^3)^2}{140 \cdot 10^6}$</td>
<td>2.85</td>
<td>0</td>
<td>20 kV</td>
</tr>
<tr>
<td>$R \frac{29}{147} \times 1.5$</td>
<td>0.17</td>
<td>0.29</td>
<td>20 kV</td>
</tr>
<tr>
<td>$X \frac{0.362 \times 10^3 \times 100}{1.5}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X \frac{7.5}{100} \times \frac{(5.5)^2}{5}$</td>
<td>0.45</td>
<td>0</td>
<td>5.5 kV</td>
</tr>
<tr>
<td>$R \frac{18}{70} \times 0.5$</td>
<td>0.175</td>
<td>0.13</td>
<td>5.5 kV</td>
</tr>
<tr>
<td>$X \frac{0.35 \times 0.5}{0.5}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 3-55: resistance welding machine power supply arrangement*
• unbalance

The upstream network impedance at the 5.5 kV / 400 V transformer connection point is thus:

\[ Z_A = (2.85 + 0.17) \left( \frac{5.5}{20} \right)^2 + 0.45 + 0.175 + j \left[ 0.13 + 0.29 \left( \frac{5.5}{20} \right)^2 \right] \]

\[ Z_A = (0.15 + j 0.85) \Omega \]

(basis)

□ calculation of the voltage drop and unbalance on the 5.5 kV busbar (point A)

\[
\left\{ \begin{array}{l}
\frac{\Delta V_1}{V_n} = f = \frac{(R_A + X_A Q) - \sqrt[3]{(X_A P - R_A Q)}}{2 U_n^2} \times 100 \\
\frac{\Delta V_2}{V_n} = d = 2 \times \frac{R_A + X_A Q}{U_n^2} \times 100 \\
\frac{\Delta V_3}{V_n} = e = \frac{(R_A + X_A Q) + \sqrt[3]{(X_A P - R_A Q)}}{2 U_n^2} \times 100 \\
\end{array} \right.
\]

where: \( R_A = 0.15 \Omega \); \( X_A = 0.85 \Omega \); \( P = 78 \, kW \); \( Q = 104 \, kvar \); \( U_n = 5.5 \, kV \)

\[
\left\{ \begin{array}{l}
\frac{\Delta V_1}{V_n} = 0.02 \% \\
\frac{\Delta V_2}{V_n} = 0.66 \% \\
\frac{\Delta V_3}{V_n} = 0.31 \% \\
\end{array} \right.
\]

whence

• the voltage drop is small and not at all restrictive
• **unbalance**

\[
V_{\text{max}} = V_1 - \Delta V_1 = V_n \left(1 - 0.02 \times 10^{-2}\right)
\]

\[
V_{\text{mean}} = \frac{V_1 - \Delta V_1 + V_2 - \Delta V_2 + V_3 - \Delta V_3}{3} = V_n \times \frac{3 - (0.02 + 0.66 + 0.31) \times 10^{-2}}{3}
\]

This is used to deduce the unbalance value:

\[
\frac{V_{\text{max}} - V_{\text{mean}}}{V_{\text{mean}}} = 0.31\%
\]

The compatibility limit given in standard IEC 1000-2-4 is 2 % unbalance (see tab. 3-1), the installation considered thus meets this requirement.

• **flicker**

The operating cycle is 30 / min. Now, each time the machine operates there is a rising front and a descending front, and thus two voltage variations. Thus, the voltage variation frequency is 60 / min. Figure 3-3 (standard IEC 1000-2-2) shows that for this frequency the maximum voltage variation amplitude is 0.8 %. The voltage variation of 0.66 % is therefore acceptable.
reactive power compensation

The welding machine has a power factor of \( \cos \varphi_1 = 0.6 \) (\( \tan \varphi_1 = 1.33 \)); we want to obtain a power factor of \( \cos \varphi_2 = 0.8 \) (\( \tan \varphi_2 = 0.48 \)), and therefore:

\[
Q_c = P (\tan \varphi_1 - \tan \varphi_2) = 78 \cdot 10^3 \times (1.33 - 0.48)
\]

The compensation power to be installed is:

\[
Q_c = 659 \text{ kvar}.
\]

transformer rating

The MV/LV (5.5 kV / 400 V) transformer vector group is Dy11.

The two criteria are therefore (see tables 3-15 and 3-16):

- \( S_{\text{transfo}} \geq \sqrt{3} \cdot S_{100 \%} \)
  \[
  S_{\text{transfo}} \geq \sqrt{3} \cdot 130 \cdot 10^3
  \]
  whence \( S_{\text{transfo}} \geq 225 \text{ kVA} \)

- \( S_{\text{transfo}} \geq \sqrt{3} \cdot S_{\text{max}} \frac{U_{sc} \%}{6} \)

The machine limit operating factor is:

\( f \ell = 0.3 \)

whence: \( S_{\text{max}} = \frac{S_{100 \%}}{\sqrt{0.3}} \)

\( S_{\text{max}} = 237 \text{ kVA} \)
Furthermore, for the range of transformers being considered (200 to 630 kVA), we should have $U_{sc} \% = 4\%$.

Which gives the criterion: $S_{transfo} \geq \sqrt{3} \cdot 237 \cdot 10^3 \times \frac{4}{6}$

$$S_{transfo} \geq 274 \text{ kVA}$$

In the range of standardised liquid-insulation transformers, a 315 kVA transformer will thus be chosen.

**cable size-up**

Here we wish to determine the LV cable cross-section linking the MV/LV transformer to the welding machine (see fig. 3-56). It is made up of two XLPE insulated copper single-pole conductors placed on punched boards; it is installed in standard installation conditions.

![Figure 3-56: welding machine LV connection](image-url)
The thermal criterion gives the current that is to flow through the cable:

\[ I_C = \frac{S_{100\%}}{U_n} \]  

(\text{phase-to-phase connected single-phase machine})

\[ I_C = \frac{130 \times 10^3}{400} = 325 \, A \]

Table 6-3 gives the selection letter E, and table 6-16 (selection letter E, XLPE2, copper), gives a minimum cross-section of:

\[ S = 95 \, mm^2 \]

The voltage drop criterion gives a minimum cross-section of:

\[ S_{\text{min}} = \frac{\cos \phi \cdot \rho \cdot \ell}{\Delta U} \left( \frac{U_n}{I_m} - X \cdot \ell \cdot \sin \phi \right) \]

\[ \frac{\Delta U}{U_n} = 4 \% \]

whence

\[ \Delta U = 400 \times 0.04 = 16 \, V \]

\[ \cos \phi = 0.6 \]

\[ \sin \phi = 0.8 \]

\[ \ell = 10 \, m \]

\[ \rho = 0.0225 \, \Omega \, mm^2 / m \quad \text{for copper} \]

\[ I_m = I_C = 325 \, A \]

\[ X = 0.09 \, \Omega / km \quad \text{for single-pole cable bundles (see § 6.1.5.)} \]

We can calculate:

\[ S_{\text{min}} = 2.8 \, mm^2 \]

It is obvious that in this case the thermal criterion is more restrictive than the voltage drop as the cable length is small enough (10 m).

A cable with a cross-section of 95 mm$^2$ will thus be chosen.
calculation of the voltage drop, unbalance and flicker on the specific transformer secondary (point B)

The specific transformer power rating previously determined is:

\[ S_{\text{transfo}} = 315 \text{ kVA} \]

Let us take a liquid-insulated transformer. Its impedance (based on 400 V) is:

\[ Z_T = 6.61 \times 10^{-3} + j 20.3 \times 10^{-3} \] (see Protection guide, § 4.2.1.4)

The upstream network impedance at the transformer secondary (based on 400 V) is thus:

\[ Z_B = Z_T + Z_A \times \left( \frac{400}{5500} \right)^2 \]

where \( Z_A = 0.15 + j 0.85 \)

whence \( Z_B = 7.40 \times 10^{-3} + j 24.8 \times 10^{-3} \)

Assuming that the machine is connected between phases 1 and 2, we have:

\[
\begin{align*}
\frac{\Delta V_1}{V_n} &= \frac{R_B P + X_B Q}{V_n^2} \times 100 \\
\frac{\Delta V_2}{V_n} &= \frac{R_B P + X_B Q}{V_n^2} \times 100 \\
\frac{\Delta V_3}{V_n} &= 0
\end{align*}
\]

where \( R_B = 7.40 \times 10^{-3} \ \Omega \); \( X_B = 24.8 \times 10^{-3} \ \Omega \); \( P = 78 \ kW \); \( Q = 104 \ kvar \); \( V_n = 230 \ V \)

whence \( \frac{\Delta V_1}{V_n} = 6.0 \% \)

\( \frac{\Delta V_2}{V_n} = 6.0 \% \)

\( \frac{\Delta V_3}{V_n} = 0 \)
\section*{Conclusion}

The flicker and unbalance levels forbid the use of any lighting load and most other loads. Installing a specific transformer to feed the welding machine is thus essential.
3.4.3. Arc welding machine

- **operating principle**

Arc welding consists in creating an electric arc supplying the necessary energy for welding between an electrode and a part to be welded.

The system operates at a voltage of several Volts to fifty or so volts and with currents able to reach several tens of thousands of Amps.

- **power supply constraints, disturbance and solutions**

The machine operates intermittently and two power ratings can be defined for fixing the power supply rating of the welding machine:

- $S_{100\%}$: equivalent power to continuous operation or nominal power
- $S_{\text{max}}$: maximum power consumed by the machine during arcing

$S_{100\%}$ is defined for the arc welding machine in the same way as for the resistance welding machine (see § 3.3).

$S_{\text{max}}$ corresponds to the power consumed by the arc welding machine during arcing, i.e. when the power input is maximum.

Using these two power ratings, the machine power supply rating and the calculation of the levels of disturbance caused is carried out according to the method used for resistance welding machines (see § 3.3).

Let us note that for arc welding machines, only voltage variations caused during arcing must be taken into account when the flicker is calculated, as they cause the most disturbance. The solutions for providing against flicker are described in paragraph 3.2.
3.4.4. High frequency or microwave equipment

**operating principle**

The operating principle of high frequency or microwave equipment is based on the transformation of electrical energy into heat inside the dielectric products. This energy is supplied by electromagnetic radiation.

High frequency or microwave equipment is made up of (see fig. 3-57):

- a high frequency generator
- an energy transmission system
- an applicator containing the charge to be heated.

![High frequency installation diagram](image)

**Figure 3-57: principle of a high frequency installation**

High frequency systems generally have a three-phase 400 V supply at 50 Hz.

**disturbance caused**

Besides the harmonic disturbance created by the rectifier (see tab. 8-1), two types of high frequency disturbance are emitted.

- **conducted disturbance**
  
  The high frequency current of the oscillating circuit flows through the rectifier and moves up the network. To eliminate this disturbance, a filter must be installed upstream of the rectifier and/or a transformer with screen which cancels the capacitive coupling.

- **radiated disturbance**
  
  This is supplied by the installation's HF equipment and associated wiring. To prevent it, the HF equipment shielding must be reinforced and the devices disturbed must be shielded or moved away.

The ultimate solution consists in placing the high frequency system in a Faraday cage.
3.4.5. Induction furnaces

- operating principle

The induction furnace operates according to the principle of a transformer with a secondary made up of the charge to be heated. Induced current in the metal charge causes it to rise in temperature via the Joule effect.

There are three usual types of induction furnaces:

- reheating furnace
- crucible melting furnace
- tunnel melting furnace.

- reheating furnace

This is made up of an inductive winding in which the part to be reheated is placed. The current circulating in the primary winding induces eddy current in the load which then heats the metal. (see fig. 3-58).

There is no magnetic circuit in this type of induction furnace.

Using induction technology for reheating allows the metal to be heated quickly, a uniform temperature to be maintained and great operating flexibility.
**crucible melting furnace**

The crucible furnace operates according to the same principles as the reheating furnace but has a different inductive winding arrangement (see fig. 3-59).

The turns are wound around a crucible made of a refractory ramming mixture. The magnetic flux is channelled via a laminated sheet metal circuit wrapped around the primary winding.

![Figure 3-59: crucible furnace principle](image)

**tunnel melting furnace**

The tunnel furnace has a similar make-up to the conventional transformer. The liquid metal circulating in the tunnel makes up the secondary of a transformer with a magnetic circuit (see figure 3-60).

![Figure 3-60: tunnel furnace principle](image)
**power ratings**

For reheating furnaces, the most frequently used power ratings vary from 100 W to 50 kW for 230 or 400 V single-phase fed furnaces. Furnaces with power ratings able to reach 2000 kW are also found; these furnaces have a three-phase power supply and, generally, a specific LV/MV transformer.

As for melting furnace power ratings, these may reach 100 kW in single-phase and 1000 kW in three-phase for crucible furnaces, and 150 kW in single-phase and 1200 kW in three-phase for tunnel furnaces.

**power supply constraints and disturbance**

**reactive power**

Due to their design, induction furnaces consume a lot of reactive power. Reheating furnaces do not have a magnetic circuit and melting furnaces require a lot of space between the primary winding and the charge; the resulting leakage flux is thus very high.

Consequently, the equivalent inductance is very high; this is why the power factor rarely exceeds 0.2. It is therefore always essential to compensate for this consumption of reactive power by connecting a capacitor bank to the terminals of the inductor (see fig. 3-61).

Some induction furnaces operate at frequencies higher than 50 Hz and therefore require a frequency converter.

![Diagram](image)

*Figure 3-61: induction furnace installation principle*
□ current inrush on energization of an induction furnace operating at the network frequency

The induction furnace has a small power factor which requires considerable reactive power compensation by the installation of a capacitor bank at the inductor terminals. There is a very strong high frequency (several kHz) transient current when the furnace is energized due to the capacitor bank. The calculation of the value of this inrush current is given in the Protection guide - § 10.6.1.

The peak value of the inrush current is:

\[
\dot{i} = \frac{2QS_{sc}}{3U_n^2}
\]

\(S_{sc}\) : network short-circuit power at the connection point  
\(Q\) : power compensated by the capacitors  
\(U_n\) : nominal network phase-to-phase voltage

Given the large daily number of openings and closings on the furnace power supply circuit, it is generally essential to use a contactor for the energization of the furnace.

A contactor with a sufficient making capacity must therefore be chosen in order for it to withstand the inrush current.

□ medium frequency furnace connection

The use of induction furnaces at frequencies above 50 Hz is more and more widespread as heating is much faster and temperature regulation much more precise.

The inductor is fed by a frequency converter which may generate extra disturbance. The power electronic based power supply injects harmonics onto the network and creates electromagnetic radiation which may disturb sensitive systems.
induction furnace connection example

Let us consider a three-phase induction furnace with a power of \( P = 60 \text{ kW} \) operating at \( \cos \phi_1 = 0.3 \) \( (\tan \phi_1 = 3.18) \) and with a 400 V supply. The network short-circuit power at the connection point is \( S_{sc} = 2500 \text{ kVA} \).

We want to compensate the reactive power consumed by the furnace so as to obtain \( \cos \phi_2 = 0.95 \) \( (\tan \phi_2 = 0.33) \).

The capacitors must therefore compensate:

\[
Q = P \left( \tan \phi_1 - \tan \phi_2 \right) = 60 \times (3.18 - 0.33) \\
Q = 171 \text{ kvar}
\]

The inrush current is thus:

\[
I = \frac{2 \times 171 \times 10^3 \times 2500 \times 10^3}{3 \times (400)^2} \\
I = 1.3 \text{ kA}
\]

The apparent power of the furnace + capacitor bank is \( S = \frac{P}{\cos \phi_2} = 63 \text{ kVA} \)

The nominal current of the assembly is \( I_n = \frac{S}{\sqrt{3} \times 400} = 91 \text{ A} \)

We shall take as an example an LC1-F115 type Telemecanique contactor which has a making capacity of 1300 A and a nominal current of 200 A. We can see that the constraint on the making capacity is much greater than that on the nominal current.
3.4.6. Resistance furnaces

- operating principle

Numerous industries use resistance furnaces in extremely varied applications and highly varying temperature ranges. The operating principle is identical for all resistance furnaces which essentially differ by their operating temperature and the way the charge is arranged or handled.

We can thus distinguish between the furnace operating with charge cycles and a continuous furnace permanently fed by a system of conveyors or conveyor belts.

A resistance furnace is made up of (see fig. 3-62):

- a heating chamber with walls made of refractor to resist the temperature and having insulating qualities for the best possible thermal efficiency.

- heating elements that radiate over a thermal load.

- a temperature regulation system.

There is a switching device on the heating element supply circuit which may be a power contactor or thyristor voltage controller which allows the furnace temperature to be adjusted to the level required by the user.

*Figure 3-62: elements making up a resistance furnace*
**power supply constraints, disturbance and solutions**

**furnace power supply**

A resistance furnace is always fed at a voltage below 400 V and thus via a step-down transformer. For power ratings above 100 kW, the power supply is three-phase while for lower ratings it may sometimes be single-phase.

The furnace temperature is regulated in relation to:

- the controlled temperature.
- the temperature rise speed limit required by the load.
- the limit temperature of the heating resistors.

These parameters can be used to define the maximum power for the resistance furnace. This power depends on the operating cycles of the furnace as the temperature regulation sometimes leads to discontinuous operation (see fig. 3-63).

![Figure 3-63: example of a resistance furnace operating cycle](image-url)
disturbance generated by a resistance furnace

In some three-phase furnaces having several heating zones, each zone is fed by one of the network's three phases. These zones are regulated separately and, consequently, the power consumed on each phase differs at any given time and thus causes voltage unbalance.

- neutral conductor size-up

In the case where a single furnace zone is fed, the current circulating in the neutral conductor is equal to the phase current. The conductor cross-section must therefore be equal to that of the phases.

- voltage unbalance

Two types of unbalance exist depending on whether the furnace operates on one or two zones.

- unbalance for two zone operation

The equivalent wiring diagram of the furnace operating on two zones is shown in figure 3-64.

![Equivalent wiring diagram for two-zone operation](image)

Figure 3-64: equivalent wiring diagram for two-zone operation

where:

- \( Z \) : network impedance upstream of the transformer
- \( Z_T \) : transformer impedance based on the secondary
- \( R \) : resistance of one furnace phase
- \( k \) : transformer turns ratio
With the furnace having a two-phase power supply (the third being in open circuit) the current distribution is similar to the case of the two-phase short circuit (see Protection guide - § 10.3.2.).

We thus have:

\[
I = \frac{\sqrt{3}}{2} \frac{V_S}{R}, \quad V_S \text{ being the secondary single-phase voltage}
\]

\[
\begin{align*}
I_1 &= \frac{2k}{\sqrt{3}} I \\
I_2 &= -\frac{k}{\sqrt{3}} I \\
I_3 &= -\frac{k}{\sqrt{3}} I
\end{align*}
\]

Voltage drops upstream of the transformer are thus:

\[
\Delta V_1 = |Z I_1| = \frac{2Zk}{\sqrt{3}} I
\]

\[
\Delta V_2 = |Z I_2| = \frac{Zk}{\sqrt{3}} I
\]

\[
\Delta V_3 = |Z I_3| = \frac{Zk}{\sqrt{3}} I
\]

The voltage unbalance is defined by:

\[
\max_i |V_i - V_{\text{mean}}| \leq \frac{V_{\text{mean}}}{V_{\text{mean}}}
\]

where \( V_i = V_1, V_2 \) or \( V_3 \)

We have:

\[
V_{\text{mean}} = \frac{3V_n - (\Delta V_1 + \Delta V_2 + \Delta V_3)}{3} = \frac{1}{3} \left( \frac{2}{\sqrt{3}} + \frac{1}{\sqrt{3}} + \frac{1}{\sqrt{3}} \right) Z k I
\]

\[
V_{\text{mean}} = V_n - \frac{4}{3\sqrt{3}} Z k I
\]

\[
\max_i |V_i - V_{\text{mean}}| = \left| V_n - \frac{2ZkI}{\sqrt{3}} - V_{\text{mean}} \right|
\]

\[
= \left| V_n - \frac{2ZkI}{\sqrt{3}} - V_n + \frac{4}{3\sqrt{3}} Z k I \right|
\]

\[
= \frac{2ZkI}{3\sqrt{3}}
\]
which gives the unbalance:

$$\max_i \left| V_i - V_{\text{mean}} \right| = \frac{2 Z k I}{3 \sqrt{3} V_n} = \frac{2}{3} \frac{Z I}{\sqrt{3} V_S} = \frac{2}{3} \frac{Z}{\sqrt{3}} R = \frac{1}{3} \frac{Z}{R}$$

By writing

$$S_{sc} = \frac{U_n^2}{Z}$$

and

$$P = \frac{U_n^2}{R}$$

$P$: furnace power

$S_{sc}$: short-circuit power upstream of the transformer

we obtain:

$$\max_i \left| V_i - V_{\text{mean}} \right| = \frac{1}{3} \frac{P}{S_{sc}}$$

The ratio $\frac{Z}{R}$ represents the voltage drop at the nominal current. We thus find an unbalance equal to $\frac{1}{3}$ of the voltage drop for the nominal current. Thus, when the voltage drop for the nominal current is below 6 %, the unbalance created by the resistance furnace operating on two zones is lower than 2 % (compatibility level of industrial networks, see table 3-1).
- unbalance for one-zone operation

In the case where only one furnace zone is fed, the equivalent wiring diagram is shown in figure 3-65.

![Equivalent Wiring Diagram for One-Zone Operation](image)

Figure 3-65: equivalent wiring diagram for one-zone operation

With the furnace having a single-phase power supply (the other two being in open circuit) the current distribution is similar to the case of the single-phase short circuit (see § 10.3.2. of the Protection guide).

We thus have \( I = \frac{V_S}{R} \), \( V_S \) being the secondary single-phase voltage

\[
\begin{align*}
I_1 &= \frac{k}{\sqrt{3}} I \\
I_2 &= 0 \\
I_3 &= -\frac{k}{\sqrt{3}} I
\end{align*}
\]

Voltage drops upstream of the transformer are thus:

\[
\begin{align*}
\Delta V_1 &= |Z I_1| = \frac{Z k I}{\sqrt{3}} \\
\Delta V_2 &= |Z I_2| = 0 \\
\Delta V_3 &= |Z I_3| = \frac{Z k I}{\sqrt{3}}
\end{align*}
\]

We have:

\[
V_{mean} = \frac{3 V_n - (\Delta V_1 + \Delta V_2 + \Delta V_3)}{3} = V_n - \frac{2}{3 \sqrt{3}} Z k I
\]

\[
\max_i |V_i - V_{mean}| = \left| V_n - \frac{Z k I}{\sqrt{3}} - V_n + \frac{2}{3 \sqrt{3}} Z k I \right| = \frac{Z k I}{3 \sqrt{3}}
\]
The resulting unbalance is:

$$\max_i \left| V_i - V_{\text{mean}} \right| = \frac{Z k I}{3 \sqrt[3]{V_n}}$$

$$= \frac{Z k V_S}{3 \sqrt[3]{V_n} R}$$

$$= \frac{1}{3 \sqrt[3]{R}}$$

$$= \frac{1}{3 \sqrt[3]{S_{sc}} P}$$

We find an unbalance equal to $\frac{1}{3 \sqrt[3]{5}} \equiv \frac{1}{5}$ times the voltage drop at the nominal current.

There is thus less unbalance for single-zone operation than for two.

- **flicker and harmonics**

This type of disturbance may be generated by certain resistance furnaces regulated by a control system with power electronic components. It is the regulation and power electronics that, in this case, cause flicker and harmonics and not the furnace itself (see § 3.4.7). The ways to solve flicker problems are explained in paragraph 3.2.

- **resistance furnace sensitivity to disturbance**

- **long supply interruptions**

Owing to their thermal inertia, resistance furnaces are only slightly sensitive to short supply interruptions. On the other hand, long supply interruptions may, in some cases, have a prejudicial effect on the furnace and its load. For a melting furnace, for example, it is absolutely essential to avoid the liquid setting. There should therefore be a back-up power supply (the generator set type) to maintain the furnace above a certain temperature threshold.
• rapid voltage fluctuations

Furnace regulation systems and measuring equipment may be highly disturbed by rapid supply voltage fluctuations. The modification of their reference voltage may, in fact, cause zero resetting and restarts from a new operating point. In an environment where the voltage is likely to be disturbed, it is necessary to use an uninterruptible power supply.

• harmonics
The measuring and control devices of a furnace are extremely sensitive to harmonics. Moreover, in order to avoid this type of disturbance, it is important to fit the power supply of such devices with anti-harmonic filters on the one hand and, on the other hand, take precautions with the measuring cable shielding.

Any eventual Steinmetz bridges used to eliminate the unbalance of single-phase furnaces are especially sensitive to harmonics.

☐ resistance earth faults

When a resistance furnace is being used, loss of electrical insulation causing the furnace to trip (TT earthing system) or an insulation fault alarm to go off (IT earthing system) is frequently observed.

The risk of insulation loss can be reduced by regular maintenance of the resistor supports.
3.4.7. Power electronic assemblies

- Use and types of converters

Power electronic assemblies allow electrical energy to be converted using static means. They are more and more widely used owing to their considerable performance.

As well as passive components such as capacitors and inductors, these systems use semi-conductive devices such as diodes, thyristors, triacs, etc.

- a.c. - d.c. conversion

This is the oldest type of conversion. Single-phase or three-phase rectifiers may be used (see fig. 3-66).

![Figure 3-66: three-phase rectifier](image)

This type of device is widely used, especially in the chemical and electro-metallurgical industries.
**d.c. - d.c. conversion**

These devices are usually called "choppers" (see fig. 3-67).

They are widely used in the field of electric traction. One of the most popular applications is speed variation for d.c. motors.

![Chopper operating principle](image)

**d.c. - a.c. conversion**

Inverters are used for this. The main applications are:

- the production of alternating current at a different frequency from that of the network
- uninterruptible power supplies (see § 1.6.3.).

**a.c. - a.c. conversion**

There are two types of conversion in this case:

- direct conversion by cycloconverter
- indirect d.c. or intermediary d.c. voltage conversion; a rectifier connected to an inverter is used in this case.
- power supply constraints

- converter sensitivity to disturbance

Power electronic converters may be sensitive to different types of disturbance encountered on industrial networks.

- voltage dips

Electronic speed variators supplying motors are disturbed.

Indeed, when a voltage dip occurs, the network behaves like a short circuit. The motor thus supplies a very high current which flows through the static converter. This current causes the protection fuses of the semi-conductors to melt.

To get over this drawback it is possible to:

- install a capacitor or a storage battery on the d.c. circuit which recovers the motor energy

- install a bypass static contactor which allows the motor energy to be directly sent back onto the network when a voltage dip occurs.

- voltage unbalance

IEC standard 146-1-1 § 2.5.3. gives the operating limits without loss of converter performance. They are given in relation to the device's immunity class (see table 3-17):

- **class A**: the limit is valid for converters designed for highly disturbed networks

- **class B**: the limit is valid for converters designed for an average network

- **class C**: the limit is valid for converters designed for a slightly disturbed network.
If the immunity class is not specified, class B is assumed to apply.

<table>
<thead>
<tr>
<th>Immunity class</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage unbalance (in %)</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table 3-17: voltage unbalance*

- harmonics

The operating limits without converter loss of performance are given in paragraph 8.2.

- disturbance generated by converters
- harmonic currents

The values of harmonic currents created by converters are given in paragraph 8.1.3.
3.4.8. Electric steam generators

■ operating principle

There are different types of electric steam generators which correspond to two heating modes.

□ indirect heating

Thermal energy is transmitted to the water by conduction via an exchange surface.

The most usual examples of indirect heating steam generators are the immersion heater steam generator (see fig. 3-68) and the induction steam generator (see fig. 3-69).

The principle of the induction steam generator is similar to that of a transformer. The secondary is made up of a short-circuited pipe in which the liquid to be heated circulates.
### Direct heating

The water is used like an electric resistor and heats up as the current flows through it. The immersed electrode steam generator and the multiple jet steam generator are based on this principle.

- **Immersed electrode steam generator** (see fig. 3-70)

  The three electrodes are immersed in the water through which the current flows between the electrodes or between the electrodes and the neutral which is most often made up of the body of the steam generator.

  In the example in figure 3-70, the power is regulated by displacement of an insulating screen. It may also be regulated by varying the level of immersion of the electrodes.

![Figure 3-70: immersed electrode steam generator](image)
• **multiple jet steam generator** (see fig. 3-71)

The multiple jet steam generator pumps the water and sprays the electrodes through the nozzles.

The water jet created between an electrode raised to a high potential and the corresponding counter-electrode makes up a resistor, part of which is vaporized by the passage of the current.

![Figure 3-71: multiple jet steam generator](image)


- power supply constraints

- supply voltage

Depending on the type of steam generator to be connected, the most suitable public distribution network connection voltage will be chosen (see table 3-18).

<table>
<thead>
<tr>
<th>Type of steam generator</th>
<th>Installed power</th>
<th>Steam generator supply voltage</th>
<th>Public network connection voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low voltage (400 V)</td>
</tr>
<tr>
<td>Immersion heaters</td>
<td>&lt; 250 kW 250 to roughly 8000 kW</td>
<td>400 V 400 V or 690 V **</td>
<td>yes no yes* yes possible*</td>
</tr>
<tr>
<td>Induction</td>
<td>&lt; 250 kW 500 to 4500 kW 20 kV</td>
<td>400 V ≤ 20 kV</td>
<td>yes no yes* possible*</td>
</tr>
<tr>
<td>Electrodes</td>
<td>≤ 3.6 MW 3.6 to 30 MW roughly 30 to 60 MW 20 kV</td>
<td>400 or 690 V ≤ 20 kV</td>
<td>possible no yes* yes possible* possible*</td>
</tr>
</tbody>
</table>

(*) the steam generator (or the user's network) is separated from the public distribution network by a transformer.

(**) a 690 V connection should be used when the steam generator requires a transformer to be installed. This type of connection is all the more economic the higher the steam generator power is.

**Table 3-18: electric steam generator connection voltage**

- voltage drop

An electric steam generator can generally be assimilated to a purely resistive load which does not consume any reactive power.

The voltage drop created by such a charge on the network at the connection point is thus:

\[
\Delta U \over U = \frac{P \times R}{U_n^2}
\]

\(P\) : power consumed by the steam generator

\(R\) : network resistance upstream of the connection point

\(U_n\) : nominal steam generator supply voltage
connection of an indirect resistance heating steam generator

Indirect resistance heating generators have satisfactory insulation between the resistor and fluid to be heated. They can be connected, **without taking any specific precautions**, like most electric equipment and can be assimilated to three-phase loads.

- **TT earthing system connection**

Generally, only low power steam generators (< 250 kW) are connected according to this arrangement. It is not advisable to connect high power steam generators in a TT earthing system; the low leakage current which may occur on the resistors, especially on cold starting, could cause spurious tripping of the differential protection device.

- **TN (TNC) earthing system connection**

The TN earthing system is the most often used arrangement for connecting electric resistance steam generators. Operation of the steam generator does not in the least disturb the user's network.

- **IT earthing system connection**

Connecting electric resistance steam generators in an IT earthing system is quite possible. It is however necessary to check that the permanent insulation monitor alarm threshold is higher than the eventual steam generator leakage current (1 mA/kW maximum).

connection of direct electrode heating steam generators

From an electrical point of view, an electrode steam generator can be assimilated to a three-phase load, always star-connected and made up of pure resistors. To make construction simple, the neutral point and frame (steam generator body) are one and the same and are earthed either intentionally (earthing connection, raft, etc.) or unintentionally (trunkings, etc.). (See fig. 3-72).

![Figure 3-72: connection arrangement of a direct electrode heating steam generator](image)
Owing to their operating principle, the impedances of each phase on the one hand vary in relation to the steam generator consumption and, on the other hand, are never strictly equal.

This unbalance of the equivalent single-phase resistances may reach 10% during normal operation, which may cause a residual current equal to 10% of the nominal current. This residual current is likely to cause tripping of the circuit-breakers.

• in low voltage

The TT earthing system cannot be used as the residual current created by the steam generator would cause the residual current devices to be tripped.

The IT earthing system cannot be used either as the permanent insulation monitor would permanently detect an insulation fault since the steam generator neutral is earthed.

The TN earthing system is the only one that can be used as it does not pose any particular problem.

• in medium voltage

- operation of the steam generator as an earthing transformer (see fig. 3-73)

In the case of a phase-earth fault in the network supplying the steam generator, the generator acts as an earthing transformer since its neutral is earthed. The steam generator will thus supply an earth fault current equal to 3 times its nominal current. This is added to the fault current which returns via the earthing resistor (or an eventual earthing transformer). It is thus very difficult to master the earth fault current and maintain protection selectivity.

![Diagram](image)

*Figure 3-73: operation of the steam generator as an earthing transformer*
It is notably not possible to install medium voltage motors fed by the same network as the steam generator as they require earth fault limitation of roughly 20 to 30 A (see Industrial Network Protection Guide § 10.1.1).

- **permanent residual current due to steam generator unbalance**

In France, it is not possible to feed the steam generator directly from the utility distribution network. Indeed, the utility supply substation has a detection system for low current earth faults (highly resistive) which would be activated by the steam generator's permanent residual current.

- **installation of a specific steam generator transformer**

It is generally essential to install a specific steam generator transformer. In fact, a delta-star transformer can be used to eliminate the primary side residual current. This current only circulates on the secondary side and does not therefore disturb the rest of the installation.

The specific transformer neutral is directly earthed. In fact, it is not useful to limit the earth fault current since the characteristic operation of the machine is the passage of a three-phase current from the electrodes to earth.

**Note:** the IT earthing system cannot be used as the permanent insulation monitor would permanently detect an insulation fault since the steam generator neutral is earthed.

### 3.4.9. Lighting

There are two types of lamps used in industrial environments: incandescent lamps and discharge lamps.

- **sensitivity to disturbance**

Discharge lamps, and incandescent lamps especially, are highly sensitive to the flicker phenomenon. Paragraph 3.2 explains how to prevent flicker.

Discharge lamps are highly sensitive to voltage dips: a dip of 30% for longer than 10 ms causes them to be extinguished. It may then take several minutes to light them again.

In some cases, magnetic ballast discharge lamps may be disturbed by a power line carrier system. A notch filter must therefore be connected in series.
This filter is made up of a reactor in parallel with a capacitor. A step-up magnetic coupling can be used to install a standard capacitor with a nominal voltage of 230 V (see fig. 3-74).

![Diagram of lighting system with filter](image)

*Figure 3-74: stop filter eliminating centralised remote control signals*

- **disturbance produced**

  Incandescent lamps do not cause disturbance as long as they are not fed by a static voltage variator.

  Discharge lamps produce disturbance due to the ballast.

- **discharge lamps with electronic ballast**

  They have a \( \cos \varphi = 1 \), but supply extremely high harmonic currents:

  - roughly 130 % of number 3 harmonics
  - current distortion rate, \( \tau_I \equiv 160 \% \).

- **discharge lamps with magnetic ballast**

  Their power factor is on average equal to 0.45.

  A compensation system can be integrated in the lamp switchgear; the resulting power factor is thus of the order of 0.8 to 0.9.
A compensation system can also be installed on the lighting supply switchboard. In this case, the current in the cables supplying the lamps is higher and the conductor cross-sections should be sized accordingly. Furthermore, Joule loss in the cables is increased (see § 7.2).

It supplies harmonic current:
- roughly 35% of number 3 harmonics
- current distortion rate, $\tau_I \approx 45\%$.

### 3.4.10. Electron torches

#### Operating principle

Electron torches use an electric arc between two electrodes in a plasmagene gas (see fig. 3-75).

Electron torches have various industrial applications: melting, cutting, surface treatment of metal parts and waste recycling (household, asbestos, nuclear, etc.).
**Power supply constraints**

So that the arc remains stable, electron torches mostly have a d.c. electrical supply.

A series reactor at the rectifier outlet helps to stabilise the arc.

The arc is in fact subjected to external disturbance due, notably, to variations in the plasmagene gas flow. This disturbance leads to large variations in arc voltage which can lead to the arc being extinguished. A certain amount of immunity can be obtained by adopting one of the following means:

- a large voltage setting range which means that the transformer and rectifier must be oversized and which makes the power factor drop

- an oversized reactor, which nonetheless takes up space and is costly.

The rectifier feeding the electron torch causes a lot of harmonic disturbance; it is often advisable to use a rectifier with two bridges or more in order to reduce harmonic current injected onto the network (see § 8.4.6).

3.4.11. Sensitive electronics

This concerns laboratory apparatus, computer systems, etc.

This equipment is sensitive to disturbance (see table 3-20). The means to solve this problem are explained in table 3-19.
### Recapitulative table of disturbance caused and load sensitivity

<table>
<thead>
<tr>
<th></th>
<th>Flicker</th>
<th>Harmonics</th>
<th>Unbalance</th>
<th>Radiation</th>
<th>Reactive energy</th>
<th>Voltage dips</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motors</strong></td>
<td>A, B, F</td>
<td>A, B, D *</td>
<td>A, B, H **</td>
<td>E</td>
<td>C</td>
<td>A, B</td>
</tr>
<tr>
<td><strong>Arc furnaces</strong></td>
<td>A, B, F</td>
<td>A, B, D</td>
<td></td>
<td>E</td>
<td>C</td>
<td>A, B</td>
</tr>
<tr>
<td><strong>Induction furnaces</strong></td>
<td></td>
<td>A, B, D *</td>
<td>A, B, G, H</td>
<td>E *</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td><strong>Resistance furnaces</strong></td>
<td>A, B, F</td>
<td>A, B, D *</td>
<td>A, B, G, H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Resistance welding machines</strong></td>
<td>A, B, F</td>
<td>A, B, D *</td>
<td>A, B, G, H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Arc welding machines</strong></td>
<td>A, B, F</td>
<td>A, B, G, H</td>
<td>E</td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td><strong>H. F. equipment</strong></td>
<td>A, B, D</td>
<td></td>
<td></td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Steam generators</strong></td>
<td>A, B, F</td>
<td>A, B, D</td>
<td></td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Power electronics</strong></td>
<td>A, B, D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lighting</strong></td>
<td>A, B, D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td><strong>Induction lighting</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E</td>
</tr>
</tbody>
</table>

(*) for power supply via a power electronic system  
(**) if single-phase motors

| A | increase in network short-circuit power  
| B | separation of the load from the rest of the installation (specific transformer, etc.)  
| C | installation of capacitors  
| D | installation of anti-harmonic filters  
| E | shielding  
| F | installation of equipment for reducing flicker  
| G | installation of a Steinmetz bridge in the case of a single-phase machine  
| H | installation of single-phase capacitors in the case of a single-phase machine.

*Table 3-19: disturbance generated and solutions*
<table>
<thead>
<tr>
<th></th>
<th>Voltage dips</th>
<th>Flicker</th>
<th>Harmonics</th>
<th>Unbalance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Power electronics</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sensitive electronics</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X*</td>
</tr>
</tbody>
</table>

(*) in the case of a ballast with reactive compensation

*Table 3-20: sensitivity to disturbance*
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