4. **POWER SUPPLY SOURCES**

4.1. **Public distribution network power supply**

The main characteristics of the voltage supplied by a medium and low voltage distribution network in normal operating conditions are defined in standard EN 50160.

The purpose of this standard is to define and describe the values characterising the supply voltage supplied such as:

- frequency
- magnitude
- waveform
- symmetry of the three-phase voltages.

Table 4-1 specifies the values chosen by the standard.

The voltage characteristics given in this standard are not designed to be used as electromagnetic compatibility levels (see § 3.1.).

**Note:** in France, the characteristics of the voltage supplied by HV and MV public distribution networks are defined in a contract between the French electricity authority EDF and users. This contract stipulates the obligations of EDF in relation to energy quality and the customer's obligations in relation to emitted disturbances (see § 8.3.2.2., harmonics, flicker, unbalance).

Another value, which is not defined in this standard, is important: the short-circuit power at the utility take-over point:

$$ S_{sc} = \frac{U_n^2}{Z} = \frac{3 V_n^2}{Z} = \sqrt{3} U_n I_{sc} $$

$U_n, V_n$: network phase-to-phase and single-phase voltage

$Z$: equivalent upstream network impedance seen from the utility take-over point

$I_{sc}$: three-phase short-circuit current value at the utility take-over point

A high short-circuit power has the advantage of making the network less sensitive to disturbance produced by users such as flicker, harmonics, motor starting current, etc. (see table 3-19). On the other hand, it has the drawback of requiring switchgear able to carry or cut a high short-circuit current.

In France, the MV short-circuit power varies between 40 and 250 MVA according to:

- the network configuration
- the voltage level (10; 15 or 20 kV)
- the take-over point distance in relation to the utility substation.
<table>
<thead>
<tr>
<th>Standard EN 50160</th>
<th>Low voltage power supply</th>
<th>Medium voltage power supply</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>50 Hz ± 1 % during 95 % of a week 50 Hz + 4 % / - 6 % during 100 % of a week</td>
<td>50 Hz ± 1 % during 95 % of a week 50 Hz + 4 % / - 6 % during 100 % of a week</td>
</tr>
<tr>
<td><strong>Supply voltage variations (1)</strong></td>
<td>During each period of one week, 95 % of the 10 minute mean rms values of the supply voltage shall be within the range $U_{n} ± 10%$</td>
<td>During each period of one week, 95 % of the 10 minute mean rms values of the supply voltage shall be within the range $U_{n} ± 10%$</td>
</tr>
<tr>
<td><strong>Rapid voltage changes (2)</strong></td>
<td>Generally &lt; 5 % of $U_{n}$ but able to reach 10 %</td>
<td>Generally &lt; 4 % of $U_{n}$ but able to reach 6 %</td>
</tr>
</tbody>
</table>
| **Voltage dips**  | - depth (3) :  
  between 10 % and 99 % of $U_{n}$  
  (majority of voltage dips < 60 % of $U_{n}$)  
  - duration:  
  between 10 ms and 1 minute  
  (majority of voltage dips < 1 s)  
  - number:  
  several dozen to a thousand per year | - depth:  
  between 10 % and 99 % of $U_{n}$  
  (majority of voltage dips < 60 % of $U_{n}$)  
  - duration:  
  between 10 ms and 1 minute  
  (majority of voltage dips < 1 s)  
  - number:  
  several dozen to a thousand per year |
| **Short supply interruptions** | - supply voltage < 1 % of $U_{n}$  
  - duration:  
  up to 3 min.  
  70 % of short supply interruptions have a duration of < 1 s  
  - number:  
  several dozen to several hundred per year | - supply voltage < 1 % of $U_{n}$  
  - duration:  
  up to 3 min.  
  70 % of short supply interruptions have a duration of < 1 s  
  - number:  
  several dozen to several hundred per year |
| **Long supply interruptions** | - supply voltage < 1 % of $U_{n}$  
  - duration: over 3 minutes  
  - number: between 10 and 50 per year | supply voltage < 1 % of $U_{n}$  
  - duration: over 3 minutes  
  - number: between 10 and 50 per year |
| **Flicker**       | $P_{fl} \leq 1$ (4) for 95 % of the time in any period of one week | $P_{fl} \leq 1$ (4) for 95 % of the time in any period of one week |
| **Temporary power frequency overvoltages between phase and earth** | - in general, the magnitude can reach the phase-to-phase voltage value owing to the displacement of the neutral point (see § 5.1.2.1.)  
  - a fault on the upstream side of a transformer can produce low voltage side overvoltage for the duration of the fault current. The overvoltage does not generally exceed 1.5 kV (see § 5.3.2.) | - for networks with directly or impedance earthed neutral, the overvoltage must not exceed 1.7 $U_{n}$  
  - for networks with an unearthed neutral or compensation coil, the overvoltage must not exceed 2 $U_{n}$ |
### Table 4-1: main characteristics of the MV and LV voltage supplied by a public distribution network

<table>
<thead>
<tr>
<th>Standard EN 50160</th>
<th>Low voltage power supply</th>
<th>Medium voltage power supply</th>
</tr>
</thead>
</table>
| Transient phase-to-earth overvoltages | - magnitude generally < 6 kV peak  
- rise time varying between less than several µs to several ms (5) | The industrial user must plan an insulation coordination scheme compatible with that of the supplier. |
| Supply voltage unbalance (6) | During each period of one week, 95 % of the 10 minute mean rms values of the negative-sequence component shall be less than 2 % | During each period of one week, 95 % of the 10 minute mean rms values of the negative-sequence component shall be less than 2 % |
| Harmonic voltages | - during each period of one week, 95 % of the 10 minute mean rms values must not exceed the values given in table 4-2  
- the overall voltage distortion rate (including all harmonics up to order 40) must not exceed 8 %  
- interharmonic voltage levels are being studied | - during each period of one week, 95 % of the 10 minute mean rms values must not exceed the values given in table 4-2  
- the overall voltage distortion rate (including all harmonics up to order 40) must not exceed 8 %  
- interharmonic voltage levels are being studied |
| Mains signalling voltage on the utility voltage (power line carrier system) | The three second mean of signal voltages must never exceed the values given in figure 4-1. | The three second mean of signal voltages must never exceed the values given in figure 4-1. |

(1) : the variation in the voltage supplied is a slow increase or decrease in the voltage caused by a variation in the public distribution network load

(2) : the rapid changes in voltage supplied are a short (lasting several seconds) modification in voltage magnitude essentially due to variations in the user’s load (motor starting, energization of large loads, etc.)

(3) : the depth of a voltage dip is defined as being the difference between the rms voltage during the voltage dip and the duty voltage

(4) : the $P_{TI}$ is the measurement of the intensity of the visual annoyance caused by flicker. Its evaluation is highly complex. The evaluation method is given in standard EN 60868

(5) : overvoltages of less than several µs are due to lightning (see § 5.1.3) while those of several ms are due to switching operations (see § 5.1.2)

(6) : the negative-sequence component of the voltage is that defined by the symmetrical component method (see § 4.2.2. of the Protection guide).
### Table 4-2: maximum values of harmonic voltages at supply point of MV and LV networks

<table>
<thead>
<tr>
<th>Harmonic order $p$</th>
<th>Harmonic voltage %</th>
<th>Harmonic order $p$</th>
<th>Harmonic voltage %</th>
<th>Harmonic order $p$</th>
<th>Harmonic voltage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>9</td>
<td>1.5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>3.5</td>
<td>15</td>
<td>0.5</td>
<td>6 to 24</td>
<td>0.5</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>21</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Problems relating to harmonics are dealt with in paragraph 8.

Disturbances such as frequency variation, flicker, unbalance and the solutions to such problems are dealt with in paragraph 3.

Overvoltage problems are dealt with in paragraph 5.

Thus, in the following part of this chapter we shall deal with problems relating to slow voltage change, voltage dips and short and long supply interruptions.
4.1.1. **Solution for providing against slow voltage changes**

Variations in the utility network's and user's load can cause unacceptable voltage variations in the industrial network.

For example, let us consider a user with a utility power supply of 20 kV and a 20 kV/5.5 kV transformer with a short-circuit voltage of $U_{sc} = 7\%$. The voltage drop through the transformer is roughly 4% of its nominal load (with $\cos \varphi = 0.86$).

Thus, the supplier voltage variation ($\pm 10\%$ of $U_n$, see table 4-1) added to that of the transformer (-4%) may be unacceptable for the transformer loads.

To overcome this drawback, a transformer fitted with an on-load tap changer must be installed.

This system consists in changing a connection, from one tap to the neighbouring tap of the transformer winding, without interrupting the flow of current. The turns ratio is then modified as well as the secondary voltage.

This system is associated with a regulator to maintain the voltage within a range corresponding to the voltage difference between two neighbouring taps.

The on-load tap changer usually allows a variation range of $\pm 14\%$ in 2% steps.

MV/LV transformers are fitted with no-load tap changers. A turns ratio adjuster is used to change the winding taps. It does not have any breaking capacity and must therefore only be operated when the transformer is de-energized. The taps are changed from the outside via a wheel located on the tank.

The variation range is generally $\pm 2.5\%$ and/or $\pm 5\%$.

The no-load tap changer allows the turns ratio to be adjusted in relation to the most usual MV voltage value.
4.1.2. Solutions for providing against voltage dips and utility short supply interruptions

There are two groups of solutions depending on whether the energy is stored by a storage battery or inertia of rotating masses.

- compensation of energy loss by storage battery

- no break set (see fig. 4-2)

![Diagram](image)

\[ M \] : motor  
\[ G \] : generator  
\[ SC \] : static contactor

*Figure 4-2: compensation of energy loss by storage battery*
- **operation**

During normal running, the load is fed by the motor-generator set via:

- the rectifier, storage battery, inverter assembly
- the static contactor (SC).

In case of loss of supply, the battery's autonomy allows start up, rise in speed and coupling of the diesel without interrupting the supply.

The battery is immediately recharged by the motor which is thus operating as a generator and the inverter operating as a rectifier. Thus, the battery can supply extra energy to allow the diesel to maintain the frequency in case of a large load impact.

During maintenance of the system, the load is directly fed by the utility.

The static contactor can be used to avoid a power cut in case of a loss of supply by the inverter. It thus improves dependability. Furthermore, it reduces the harmonic energy sent back by the rectifier onto the network by supplying the main part of the energy to the motor-generator set.

- **main electrical characteristics given by manufacturers**

- unit power from 200 to 1100 kVA
- efficiency during normal operation from 91 to 96 %
- generator short-circuit power \( I_{sc} > 10 I_n \)
- voltage quality:
  - ± 1% variation under normal operating conditions
  - ± 10 % on load impact of ± 100 %
  - generator voltage distortion rate from 1.5 to 3 % on linear load.
- consumption of harmonic current from the load up to a distortion rate of 100% without derating
- no derating for a load current peak factor equal to 5
- possibility of operating with a load current unbalance rate of 100 %
- possibility of operating with a load \( \cos \varphi \) of 0.5 to 1.
uninterruptible power supplies (UPS)

The operating principle and different uninterruptible power supply systems are described in paragraph 1.6.3.

It is useful to give the main UPS electrical characteristics in this part.

main electrical characteristics

- unit power from several kVA to 600 kVA
- voltage quality:
  - voltage distortion rate of 5 % on linear load
  - + 10 % / - 8 % for a load impact of ± 100 %.
- overload capacity:
  - 50 % for 1 min.
  - 25 % for 10 min.
- battery autonomy:
  - 10, 15 or 30 min.
compensation of energy loss by inertia of rotating masses (see figure 4-3)

Figure 4-3: compensation of energy loss by inertia of rotating masses
**system make-up**

This system is mainly made up of a diesel motor, an induction coupling, a three-phase synchronous machine and an inductor.

The induction coupling has two rotating parts. The external part has an a.c. three-phase winding and a d.c. winding. The internal part has an asynchronous motor rotor type three-phase winding. The inside part and the diesel motor are connected to each other by a freewheel coupling. The outside rotating part and the synchronous machine rotor are mechanically coupled.

The synchronous machine stator is connected, via the inductor, to the utility and loads.

A shunt circuit allows the loads to be directly fed by the utility.

**operation**

- **normal operation**

During normal use, electrical energy is directly supplied to the loads by the supplier without flowing through the inductor (contactors \( C_1 \) and \( C_2 \) are closed).

The synchronous machine (2 pairs of poles), which is fed by the network, operates as a synchronous motor and drives the external part of the induction coupling at a speed of 1 500 tr/min.

The three-phase winding of the external part (2 pairs of poles) is fed; the internal part operating as an asynchronous motor rotates at a speed of 1 500 tr/min. in relation to the external part, i.e. 3 000 tr/min. in relation to fixed parts.

The diesel motor is at a halt and is isolated from the induction coupling by the freewheel.

During supply by the utility, the synchronous machine acts as a voltage stabilizer for the loads and as a reactive energy compensator for the network (synchronous compensator).
• transfer from normal operation to back-up operation

The utility incoming feeder contactor \( C_2 \) and the three-phase winding contactor of the induction coupling \( C_{coup} \) open when the characteristics of the utility network are unacceptable:

- absence of voltage
- upstream short circuit
- voltage too high or too low
- phase-to-phase voltage unbalance
- frequency too high or too low.

At the same time, the induction coupling d.c. winding is excited by the closing of the thyristor. The internal part rotating field (3 000 tr/min.) then turns at a speed above that of the rotating field of the external part (1 500 tr/min.). Thus, the excitation which is controlled by a frequency control system, causes the internal part to decelerate and this then becomes the system's source of energy.

The external part then drives the synchronous machine which consequently becomes a generator.

During deceleration, the internal part of the induction coupling goes from 3 000 tr/min. to about 1 500 tr/min. and thus supplies its kinetic energy which is transformed into electrical energy for a duration which allows the diesel motor to start.

The motor starts and reaches a speed of 1 600 tr/min. in less than a second and a half.

• back-up operation

As soon as the diesel rotation speed reaches that of the induction coupling internal part, the freewheel transmits the diesel torque. The diesel motor then becomes the system's source of energy.

By controlling the exciting direct current of the induction coupling, the torque transmitted between the diesel motor and the synchronous machine is adjusted in such a way that the output frequency remains constant and independent of variation in the diesel's operating conditions.
• transfer from back-up operation to normal operation

When the utility network characteristics become acceptable once more, the synchronous machine and network are automatically connected in parallel. The synchronous machine then operates as a motor once more.

The freewheel coupling no longer transmits the diesel torque and the induction coupling internal part is accelerated up to its initial speed; i.e. 3000 tr/min. The diesel motor automatically stops 3 minutes later.

☐ main electrical characteristics given by manufacturers

- unit power from 160 to 500 kVA
- voltage quality:
  . ± 1 % variation in steady-state operating conditions (up to ± 10 % of load impact)
  . - 8 % / + 6 % for 50 ms and return to normal voltage after 1 s in case of:
    - utility network loss
    - upstream short circuit
    - load impact of ± 50 %.
  . generator voltage distortion rate of 5 % on linear load
  . voltage unbalance rate of 2 %, if load current unbalance is below 20 %.
4.2. Synchronous generators

**make-up of synchronous generators**

The generator is a rotating machine made up of two cylindrical and coaxial armatures which move in relation to each other:

- the fixed armature (stator) is made up of a magnetic sheet metal ring held by the frame. The stator has a **three-phase armature winding** spread over the internal periphery of the ring and housed in slots

- the moving armature (rotor) rotates inside the stator. The rotor has a **field magnet made up of a winding through which a direct current flows**. The field magnet creates successive north and south magnetic poles at the rotor periphery.

The generator rotors are built to meet the mechanical specifications required by the drive systems. There are two types of rotor:

**non-salient pole rotors** (see fig. 4-4)

![Diagram of a non-salient pole rotor](image)

*Figure 4-4: non-salient pole rotor*

In non-salient pole machines, the field magnet is placed in specifically designed slots at the rotor periphery, along the machine axis.

This arrangement gives a very good mechanical withstand and well-balanced assemblies. These machines are adapted to high speeds (1 500 to 3 000 turns/minute) and are suitable for steam turbine driving. They are called turbo-generators.
■ salient pole rotors (see fig. 4-5)

![Diagram of salient pole rotor](image)

Figure 4-5: salient pole rotor (4 poles)

The rotors of salient pole machines have a wheel on which magnetic cores are fixed, physically separated and surrounded by a coil. These machines are for lesser drive speeds and are better suited for diesel or hydraulic turbine driving systems. Above 4 poles, the salient pole rotor is practically the only one to be used.

Practically all the electrical energy is produced by generators. This shows the important role of these machines in a network.

It should also be remembered that generators can also operate as motors without any modification:

- a generator supplies the network with electrical energy transformed from mechanical energy
- a motor, on the other hand, takes electrical energy from the network in order to reconstitute mechanical energy.

It should also be noted that generators can supply reactive energy alone (synchronous compensators).
■ operating principle

We shall first of all study no-load operation and then on-load operation.

□ no-load operation

In the case of a salient pole machine, let us take an overall view of the armature winding and successive $N$ and $S$ poles of the field magnet (see fig. 4-6).

![Diagram](image)

**Figure 4-6: overall view of the armature winding and field magnet poles**
In the position shown in figure 4-6, the magnetic induction \( \vec{B} \) of the north pole \( N_1 \), causes a maximum positive flux \( \phi = \int \vec{B} \cdot d\vec{s} \) in the turn \( ab \). During displacement of the rotor, the south pole \( S_2 \) will take the place of the north pole \( N_1 \) and cause a maximum negative flux through the same turn \( ab \).

A variation in flux, and thus an induced voltage, occurs at the turn \( ab \). The shape of the poles (or the arrangement of the windings, in the case of non-salient pole machines) is such that the magnetic induction has an approximately sinusoidal spatial distribution. The flux in each armature winding (stator) turn thus varies sinusoidally in relation to the time:

\[
\phi = \hat{\phi} \sin \omega t
\]

We can thus determine the induced voltage:

\[
v = -\frac{d\phi}{dt} = -\hat{\phi} \omega \cos \omega t = \hat{\phi} \omega \sin \left( \omega t - \frac{\pi}{2} \right)
\]

The induced voltage in the turn thus has a phase lag of \( \frac{\pi}{2} \) in relation to the flux which flows through it.

The turn \( ab \) is connected in series with the turn \( a_1 b_1 \) (see fig. 4-6), the voltages induced in these turns will thus be added.

The total induced voltage of the machine thus depends on the number of turns simultaneously receiving the same polarity (North, South) and connected in series.

**on-load operation - armature reaction**

In no-load operation, only the field magnet flux from the rotor \( \phi_{r1} \), played a role by causing a voltage \( V \) in the armature winding (stator), with a phase lag of \( \frac{\pi}{2} \).

Let us now connect a circuit to the machine terminals. Let \( I \) be the current flowing through the external circuit phase shifted by \( \phi \) in relation to the stator voltage \( V \). This current circulates in the turns (such as \( ab \)) of the armature winding and causes an "armature reaction" flux \( \phi_i \) which tends to oppose the variation in field magnet flux.
The flux $\phi_i$ is in phase with the current $I$ which generates it. To maintain $V$ at its initial no-load value, it was necessary to increase the exciting direct current of the rotor circuit (case of a non capacitive load) in order to create a flux $\phi_{r2}$ such that the sum of this flux $\phi_{r2}$ together with the armature reaction flux $\phi_i$ gives the flux $\phi_{r1}$ required to maintain the voltage $V$ (see fig. 4-7): $\phi_{r2} + \phi_i = \phi_{r1}$.

It can be seen that the armature reaction and thus the exciting current to be applied depend on the $\cos \varphi$ of the stator load.

![Figure 4-7: on-load operation diagram](image-url)
equivalent wiring diagram of the synchronous generator under steady-state operating conditions

The wiring diagram which we shall draw up is only strictly valid in the case of non-salient pole machines. For salient pole machines, operation is qualitatively comparable. This is why this diagram will always be used in what follows.

If the magnetic circuits are not saturated, the resulting flux through the armature turns is the result of the fluxes generated separately by each of the field magnet and armature circuits taken separately. We can show these circuits in diagramatic form as in figure 4-8.

Considered alone, the field magnet (rotor) would generate a flux \( \phi_r \) in the common magnetic circuit. It also generates a leakage flux \( \phi_{fr} \) which does not reach the armature circuit.

Considered alone, the armature (stator) generates a flux \( \phi_i \) in the common magnetic circuit. It also generates a leakage flux \( \phi_f \) which does not reach the field magnet circuit.

The common flux \( \phi_e \), which flows through the two magnetic circuits is the sum of the field magnet and armature flux:

\[
\phi_e = \phi_r + \phi_i
\]

It is this flux that ensures the transmission of energy between the rotor and stator.

Figure 4-8: diagram of flux circulating in the machine
A total flux $\phi_t$ equal to the common flux $\phi_e$ and leakage flux $\phi_f$ flows through the armature magnetic circuit:

$$\dot{\phi}_t = \dot{\phi}_e + \dot{\phi}_f$$

whence

$$\dot{\phi}_t = \dot{\phi}_r + \dot{\phi}_i + \dot{\phi}_f$$

By deriving this equation in relation to the time, we obtain:

$$\frac{d\phi_t}{dt} = \frac{d\phi_r}{dt} + \frac{d\phi_i}{dt} + \frac{d\phi_f}{dt}$$

- $\frac{d\phi_t}{dt} = V$ : voltage at armature (stator) terminals, i.e; the voltage at the generator output terminals (neglecting the armature resistance, see note hereafter)

- $\frac{d\phi_r}{dt} = E$ : voltage that would be developed at the armature terminals if the winding was in an open circuit. $E$ is said to be the internal electromotive force (e.m.f.). Its value varies in proportion to the direct current which circulates in the rotor (not taking into account saturation)

- $\frac{d\phi_i}{dt} = -jL\omega I$ : armature reaction. For the armature circuit, $L$ is a self inductance since the flux $\phi_i$ is generated by the armature itself

- $\frac{d\phi_f}{dt} = -j\lambda\omega I$ : voltage drop caused by leaks in the armature circuit. $\lambda$ is said to be a leakage inductance

We thus have:

$$V = E - j(L + \lambda)\omega I$$

$X_d = (L + \lambda)\omega$ is said to be a direct-axis synchronous reactance, referred to simply as a synchronous reactance.

whence

$$E = V + jX_d I$$

It should be noted that the numbers $E$, $V$ and $I$ are complex (see fig. 4-9).
Let us consider a generator supplying a voltage $V$ at its terminals and a current $I$ phase shifted by $\varphi$. Its operating diagram is shown in figure 4-9.

![Figure 4-9: generator operating diagram](image)

The equivalent wiring arrangement of the generator under steady-state operating conditions is thus that shown in figure 4-10.

![Figure 4-10: equivalent wiring arrangement of the generator under steady-state conditions](image)

**Note:** theoretically, the generator operating equation is $E = V + (R + jX_d)I$, $R$ being the armature resistance. But $R$ is very weak and always negligible compared with $X_d$ ($X_d = \text{several hundred times } R$).
**Induced voltage frequency and number of pairs of poles** (see fig. 4-11)

Let us consider a machine whose rotor has \( p \) pairs of poles.

When the rotor has rotated once, the turn \( ab \) has seen the north pole go round \( p \) times and thus generates \( p \) voltage periods.

Let \( n \) be the number of rotor turns per second, the frequency of the induced voltage on the turn \( ab \) is:

\[
f = pn
\]

If we call \( N \) the number of turns per minute: \( N = 60n \)

whence

\[
f = \frac{pN}{60}
\]

where

\[
N = \frac{60}{p} f
\]

Thus, to obtain a frequency of 50 Hz the machine speed must be:

- 3 000 tr/min with one pair of poles
- 1 500 tr/min with two pairs of poles
- 1 000 tr/min with three pairs of poles.
4.2.1. Characteristics and behaviour of a.c. generators

Let us consider a generator supplying a voltage \( V \) and a current \( I \) phase shifted by \( \varphi \). Its operating diagram is shown in figure 4-12.

![Figure 4-12: generator operating diagram](image)

First of all, it is essential to fully understand the physical signification of the internal electromotive force \( E \). Its amplitude is proportional to the direct current \( I_f \) circulating in the rotor if we neglect saturation. It is then obvious that \( E \) depends on the value given to the exciting current \( I_f \). If \( I_f \) is not modified, \( E \), i.e. the length \( OM \) in figure 4-12, remains constant. If \( I_f \) is varied, then \( E \) varies in the same direction and in proportion to \( I_f \) in the absence of saturation.

The phase angle \( \delta \) of \( E \) in relation to \( V \), called the angular variation, also has a precise signification. \( E \) is a vector linked to the axis of the rotor. The angle \( \delta \) characterises the angle difference between the magnetic axis of the rotor (or \( E \)) and the synchronous reference (i.e. the complex number rotating at a speed \( \omega \)) made up of the voltage \( V \) at the stator terminals.

A variation in \( \delta \) corresponds to a variation in angle difference between the rotor and this synchronous reference. We shall see later on that there is a close correlation between \( \delta \) and the energy exchange between the rotor and the stator, i.e. the energy transformed from a mechanical form to an electrical form. For the moment, we can already see that if \( I = 0 \) (no-load operation, no energy exchanged) \( E \) is the same as \( V \) and \( \delta = 0 \).
expression of the active power, reactive power and torque

In the specific case of figure 4-12, the phase angle $\varphi$ is between 0 and $\frac{\pi}{2}$.

In such conditions, the generator supplies active power:

$$P = 3V I \cos \varphi$$

and reactive power:

$$Q = 3V I \sin \varphi$$

to a three-phase external circuit.

From point $A$ let us draw an axis $AQ$ continuing on from $V$, and an axis $AP$ leading $\frac{\pi}{2}$ in relation to $AQ$, and let us project the point $M$ from $Q_1$ and $P_1$ along the axes $AQ$ and $AP$.

In figure 4-12, we determine the value:

$$AP_1 = X_d I \cos \varphi$$

From this we can deduce:

$$P = AP_1 \times \frac{3V}{X_d}$$

Thus, when the voltage at the generator terminals is constant (as during normal running), with $X_d$ being constant, the height of $M$ above the axis $V$ is proportional to the active power supplied. The vertical axis thus represents the active power.

Let us express $AP_1$ as a function of $\delta$:

$$AP_1 = E \sin \delta$$

We then obtain:

$$P = \frac{3E V}{X_d} \sin \delta$$  \hspace{1cm} (1)

The relation linking the angular variation $\delta$ of the machine with the active power supplied appears. This represents the power transformed from a mechanical form to an electrical form.
In the same way, we can determine the value:

$$AQ_1 = X_d \ I \ \sin \ \varphi$$

From this we can deduce:

$$Q = AQ_1 \times \frac{3 \ V}{X_d}$$

The value of $AQ_1$ represents the reactive power supplied by the generator. The horizontal axis thus represents the reactive power.

Let us express $AQ_1$ as a function of $\delta$:

$$AQ_1 = E \ \cos \ \delta - V$$

We thus obtain:

$$Q = \frac{3 \ E \ V}{X_d} \ \cos \ \delta - \frac{3 \ V^2}{X_d}$$

Any machine loss has been neglected, and the machine is assumed to rotate at a synchronism speed of $\frac{\omega}{p}$, the electromagnetic load torque $T_{el}$ (counted positively when it tends to brake the machine) is obtained by dividing the expression of $P$ by $\frac{\omega}{p}$:

$$T_{el} = \frac{p}{\omega} \times P = \frac{p}{\omega} \times \frac{3 \ E \ V}{X_d} \ \sin \ \delta$$

(2)
4.2.1.1. **Generator supplying an "infinite" power network**

When the generator is connected to the distribution or transmission network, the network frequency and voltage are applied.

We assume that the generator has been started, has reached the synchronism speed and has been coupled to the network and that the drive machine does not supply any power.

The operating point on figure 4-13 is at \( M_1 \) where point \( A \) is also located.

There are two ways of making the generator supply the network:

- increase the mechanical power supplied by the drive machine
- modify the exciting current \( I_f \).

### Adjusting the active power

If we increase the mechanical power leaving \( I_f \) constant, we know that the length \( OM = E \) remains unchanged. The electrical power thus increases by the same quantity, otherwise the generator would accelerate and no longer rotate at the synchronism speed \( \frac{\omega}{p} \), which is essential for its operation.

The point \( M_1 \) is thus raised above the horizontal axis since its height is proportional to the active power, and it describes a circle with a radius of \( OM = E \). It thus goes to \( M_2, M_3 \) etc.

We can observe that the reactive power during this time started at 0 and has become negative (abscissa of \( M_3 \) in relation to \( A \)).

---

*Figure 4-13: operating diagram of the generator connected to the infinite power network*
■ adjusting the reactive power

If we now leave the mechanical power corresponding to point $M_3$ constant, and if we make the exciting current $I_f$ vary, we know that $M$ must move along a horizontal line (constant active power and thus an ordinate of $M$ constant), such that the length $OM$, proportional to $E$, varies in proportion to the current $I_f$. Modifying $I_f$ alone does not therefore change the active power but allows the reactive power to be adjusted.

At $M_3$, the reactive power is negative (absorbed by the machine), the angle $\phi$ is negative (see Note) and the machine is said to be underexcited. We increase $I_f$ and we arrive at $M_4$ and the reactive power is zero (angle $\phi$ zero, $\cos \phi = 1$). We increase $I_f$ again and we arrive at $M_5$, the reactive power is positive (supplied by the machine), the angle $\phi$ is positive and the machine is said to be overexcited.

Note: In order not to complicate figure 4-13, $I$ is not drawn, but we know that in each case, $AM$ leads $\frac{\pi}{2}$ in relation to $I (AM = jX_d \, I)$, and from this we can deduce the angle $\phi$.

■ static stability

If, from $M_3$, we continue to increase the mechanical power without modifying $I_f$, the electrical power will go via a maximum corresponding to the point $M_6$. Equality of the mechanical and electrical powers is only possible up to this point. If we increase the mechanical power again, they are no longer equal, the machine accelerates and there is no more synchronism. Furthermore, $\delta$ increases in relation to the time, the point $M$ thus rotates, which according to (1) indicates that the electrical power will reach zero as a mean value (the mean value of $\sin \delta(t)$ is zero). The generator goes above the synchronism speed, it accelerates too much and must therefore be disconnected from the network and the mechanical power must be cancelled before the generator is started up again.

According to (1) the maximum power corresponds to $\sin \delta = 1$ and is thus given by:

$$P_m = \frac{3 \, E \, V}{X_d}$$

It is therefore higher if $E$, i.e. the exciting current, is high. To avoid risking loss of synchronism, we make the generator normally operate with $\delta$ angles much smaller than $\frac{\pi}{2}$. 

This notion of stability can be specified by observing the expression (1) of the power, or better still, the expression of the electromagnetic load torque:

\[ T_{el} = \frac{P}{\omega} \times \frac{3EV}{X_d} \sin \delta \]

This expression shows that the load torque, and thus the electrical power supplied, can only have a non-zero mean value if \( \delta \) is not a continually increasing function in relation to the time, \( \delta \) must therefore be a variable function within the zone \( \left[ 0 \rightarrow \frac{\pi}{2} \right] \).

\( \delta \) is the electrical angle made by the rotor with the synchronous reference. This results in the machine only being able to exchange power with the network at the synchronism speed of \( \frac{\omega}{p} \).

For any other speed, \( \delta \) continually increases and the torque given by (2) (called synchronous torque) and the power given by (1) undergo variations of broad amplitude and sign reversals which are incompatible with any kind of practical use.

The load torque of a synchronous machine must therefore be considered, during normal operation, not as a function of the speed (case of asynchronous motor, see § 3.3.1), but as a function of the angular variation \( \delta \).

Figure 4-14 illustrates the expression of the electromagnetic load torque \( T_{el} \) as a function of the angular variation \( \delta \).

![Figure 4-14: expression of the electromagnetic load torque as a function of the angular variation](image)

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This curve is a sinusoid with a peak value of \( \frac{P}{\omega} \times \frac{3EV}{X_d} \).

Generator operation corresponds to the area where \( P \) is positive; i.e. \( \sin \delta > 0 \) or \( 0 < \delta < \frac{\pi}{2} \).

The curve, which is plotted assuming that \( E \) and \( V \) are stationary, represents the electromagnetic load torque. The mechanical motor torque \( T_m \) supplied by the drive machine is, on the other hand, independent of \( \delta \). It is represented by the horizontal line of ordinate \( T_m \).

Synchronous operation requires that \( T_{el} = T_m \) (otherwise the machine would accelerate or decelerate and its speed would be out of synchronism), there are thus two possible operating points, \( A \) and \( B \). It is easy to show that only point \( A \) \( (0 < \delta < \frac{\pi}{2}) \) is stable. Indeed, starting from \( A \), if the machine undergoes a slight acceleration, \( \delta \) increases and \( T_{el} \) increases above \( T_m \) which tends to slow the machine down and thus bring it back to operation at point \( A \). The same reasoning applied to point \( B \) shows that operation is unstable. The area of generator stability is thus limited to \( 0 < \delta < \frac{\pi}{2} \). This reasoning is however only valid if the variations are slow, since in the event of fast variations (see dynamic stability § 9) the equation (2) is no longer valid.

The above reasoning showed us that the condition for stability can be written as:

\[ \frac{\partial T_{el}}{\partial \delta} > 0 \]

Let us calculate:

\[ \frac{\partial T_{el}}{\partial \delta} = \frac{p}{\omega} \frac{3EV}{X_d} \cos \delta \]

In the stability zone \( (0 < \delta < \frac{\pi}{2}) \), operation is all the more stable (i.e. the return to equilibrium after a disturbance is all the more energetic) the greater \( \frac{\partial T_{el}}{\partial \delta} \) is, and thus the smaller \( \delta \) is.

\( \frac{\partial T_{el}}{\partial \delta} \) is called the synchronising torque \( T_S \). Indeed, when the value of \( T_S \) is high, synchronism is all the better maintained.

Operations such as \( \frac{\partial T_{el}}{\partial \delta} = 0 \) make up what is called the static stability limit, and such operations are characterised by \( \delta = \frac{\pi}{2} \).
In practice, industrial generators are generally built in such a way that the angular variation is more or less equal to 70° for the nominal active power and a zero reactive power, in order to keep a stability margin in case of transient disturbance. However, if the generator consumes reactive power, $\delta$ comes close to 90° and the risk of instability is greater when disturbance occurs (see § 9).

### Operating Limit

The nominal operation of a generator is characterised by the nominal voltage $U_n = V_n \sqrt{3}$, the nominal current $I_n$, and the nominal power factor $\cos \varphi_n$. The diagram corresponding to the nominal operation is plotted in figure 4-15, point $M$. It always corresponds to $\varphi_n > 0$ since for the nominal exciting current $I_{fn}$, the machine is overexcited and therefore supplies reactive power. Thus, there is no ambiguity with respect to the sign of $\varphi_n$. The active and reactive power axes are also indicated on the diagram.

The nominal value $E_n$ of the internal e.m.f. produced by the nominal exciting current $I_{fn}$ corresponds to these operating conditions.

![Figure 4-15: generator operating limits](image)

The generator is sized so that the temperature rise tolerated is reached or nearly reached when $I = I_n$ and $I_f = I_{fn}$. These values cannot therefore be exceeded for any length of time.
- \( I \), circle with a centre \( O \) and radius \( OM \)

- \( I = I_n \), circle with a centre \( A \) and radius \( AM \), since \( AM = X_d I \)

- The horizontal line drawn from \( M \), which characterises the nominal active power, i.e. the maximum power that the drive machine can normally supply

- the vertical line, drawn from \( O \), corresponding to \( \delta = \frac{\pi}{2} \), stability limit.

The possible operating points are thus located inside the outline \( L M N R O \).

**Note:** it is possible to stretch the limit \( \delta = \frac{\pi}{2} \), i.e. to operate in a stable manner above the stability limit, using a suitable voltage regulator.

### 4.2.1.2. Generator supplying an independent network

When the generator is not connected to the distribution network and supplies an independent network, the frequency and voltage are not applied by the network.

The speed must be adjusted so that the frequency is correct, by modifying the mechanical power. This is done using a speed regulator.

The voltage must be maintained at a correct value. We shall see that it is necessary to modify the exciting current \( I_f \), and thus modify the internal e.m.f. value \( E \). A voltage regulator modifying the exciting current thus allows the voltage to be maintained almost at its nominal value.

Let us assume that the frequency and thus the mechanical power are constantly adjusted and study the voltage variations in relation to the load, with a constant exciting current. The operating equation is of course always:

\[
E = V + j X_d I
\]

and the vector diagram is always that shown in figure 4-16.

---

**Figure 4-16: vector diagram of generator operation**
Applying Pythagorus' theorem to the triangle $OA'M$ gives the following equality:

$$E^2 = (V + X_d I \sin \phi)^2 + (X_d I \cos \phi)^2$$

whence:

$$E^2 = V^2 + X_d^2 I^2 + 2 V X_d I \sin \phi$$  \hspace{1cm} (3)

If we assume that $I_f$ (thus $E$) is constant, we can study the law of variation of $V$ in relation to $I$ for different values of $\phi$. In the axes $OI, OV$ in figure 4-17, this law corresponds to a family of ellipses, parametered by $\phi$, centred on $O$, and going through $A (I = 0, V = E)$, the no-load operating point, and $B (V = 0, I = E / X_d)$, the short-circuit operating point.

We are only interested in the surrounding area of $A$, thus:

- if $\phi = 0, (\cos \phi = 1)$, the ellipse admits $OI, OV$ as the main axes, and $V$ decreases slowly and then faster and faster when $I$ increases

- $\phi = + \pi / 2$ (purely inductive load), the operation describes the segment $AB$ (linear voltage drop)

- if $\phi = - \pi / 2$ (purely capacitive load), the operation describes the segment $AB'$ with the same arithmetic slope as $AB$ (linear voltage increase).

For intermediary values of $\phi$, we arrive at intermediary results. This diagram shows in which direction we must modify the exciting current $I_f$ (i.e. $E$), in order to keep the voltage $V$ at the terminals constant when the load varies.

Thus, when the voltage $V$ tends to decrease, $E$ must be increased in order for it to reach its nominal value.
4.2.2. Synchronous motor operation

Synchronous machine operation is perfectly reversible. If the armature (stator) is fed by a three-phase current system and the field magnet (rotor) by a direct current, the electrical energy can be transformed into mechanical energy, on condition that the machine is rotating at a synchronism speed of $\frac{\omega}{p}$. 

In order to simplify this paragraph, we will use the sign conventions relating to generator operation.

Motor operation thus corresponds to a negative power. This gives us two angular criteria to distinguish between the two operations:

- $P = 3VI \cos \varphi$, generator operation thus corresponds to $|\varphi| < \frac{\pi}{2}$, and motor operation to $|\varphi| > \frac{\pi}{2}$

- $P = \frac{3EV}{X_d} \sin \delta$, generator operation thus corresponds to $\delta > 0$, and motor operation to $\delta < 0$. 
**vector diagram of operation**

The synchronous motor operating equation is thus the same as that of the generator:

\[ E = V + j X_d I \]

It corresponds to the equivalent diagram in figure 4-18.

**Remark:** the conventional direction of \( I \) in figure 4-18 is opposed to the usual direction for a load since the generator operation sign conventions have been applied.

![Diagram](image)

*Figure 4-18: synchronous motor equivalent wiring diagram*

The angle \( \varphi \) must be greater than \( \frac{\pi}{2} \) as an absolute value, the vector diagram of operation is thus that shown in figure 4-19, to which the following cases have been added:

a) \( \frac{\pi}{2} < \varphi < \pi \) and b) \( \pi < \varphi < \frac{3\pi}{2} \)

If, as in the case of the generator, we plot axes \( AP \) and \( AQ \), we notice that the operating point \( M \) is always located in the \( P \) negative zone.

![Diagram](image)

*Figure 4-19: vector diagram of synchronous motor operation*
From the following equalities:

\[ P = 3VI \cos \phi \]

and:

\[ X_d I \cos \phi = E \sin \delta \]

we can deduce that the expression of \( P \):

\[ P = \frac{3EV}{X_d} \sin \delta \]

is always valid, with \( \sin \delta \) negative here.

Similarly, the expression of \( Q \) is always:

\[ Q = \frac{3V}{X_d} - \frac{3V^2}{X_d} \]

We can distinguish between the two diagrams a) and b) in figure -19 by the sign of the

In the case of figure -19 a), the reactive power \( M \) in relation to \( A \), this situation corresponds to a high value of \( E \), and thus of the exciting current. The motor is said to be overexcited, and supplies reactive power to the network (\( Q \) positive).

In the case of figure 4-19 b) the motor is underexcited, and consumes reactive power (\( Q \) negative).

The four operating possibilities of a synchronous machine are all shown in figure 4-20.

\[ \text{overexcited generator} \quad P > 0 \quad Q > 0 \]
\[ \text{underexcited generator} \quad P > 0 \quad Q < 0 \]
\[ \text{overexcited motor} \quad P < 0 \quad Q > 0 \]
\[ \text{underexcited motor} \quad P < 0 \quad Q < 0 \]

Figure 4-20: recap of the four operating possibilities of a synchronous machine
operation of a synchronous motor: stability and $V$ curves (or Mordey curves)

The easiest and the most common way of analysing the operation of a synchronous motor consists in assuming that the supply voltage, frequency and mechanical power consumed are constant, and examining the consequences of modifying the exciting current $I_f$.

In the vector diagram in figure 4-21, the voltage $V$, taken to be the origin of the phases, corresponds to a constant length $OA$; point $M$ moves along a horizontal line (constant active power). The position of $M$ along this horizontal line is fixed by the length $OM$, equal to the e.m.f. $E$, and thus proportional to the exciting current $I_f$. Furthermore, the length $AM = X_d I$ is proportional to the armature current $I$.

Thus, if at constant active power, $I_f$ is given a high value (point $M_1$), and then it is made to decrease, $I$ begins to decrease (from $M_1$ to $M_2$). At $M_2$, $I$ goes via a minimum, the power factor $\cos \phi$ is thus equal to -1. Next $I$ increases (point $M_3$). It is not possible to make $I_f$ decrease beyond the value corresponding to the point $M_L$ as in this case the electrical power becomes lower than the mechanical power, the motor pulls out of synchronism and stops.

We see that the stability limit corresponds to $\delta = -\pi/2$, just as for the generator it corresponds to $\delta = +\pi/2$ (see fig. 4-15).

![Figure 4-21: different operating conditions of a synchronous motor, at constant active power](image)

$M_L$ : stability limit

The stability reasonings can be carried out in figure 4-14, with motor operation corresponding to $T_{el} \leq 0$ or $-\pi < \delta < 0$.
Two possible operating points $A'$ or $B'$ correspond to a mechanical torque of $T'_m$ (conventionally negative). Only $A'$, corresponding to $|\delta| < \pi/2$, is stable. Indeed, if $\delta$ slightly decreases (i.e. if $|\delta|$ increases), this means that the motor tends to slow down; but then $T_{el}$ drops below $T'_m$ thus, as an absolute value, the motor torque $|T_{el}|$ becomes greater than the load torque $|T'_m|$, which tends to bring operation back to $A'$.

The $V$ curves are curves $I = f(I_f)$ at constant power. They are plotted on figure 4-22 for different values of $P$. They are limited to the right by the maximum value authorised for $I_f$, and to the left, either by the maximum value authorised for $I$, or by the stability limit. The locus of minimums of these curves separates operations where the synchronous motor supplies reactive power (on the right) or where it consumes reactive power (on the left).

![Figure 4-22: synchronous motor (or synchronous generator) $V$ curves](image)
4.2.3. Description of different synchronous motor excitation systems

To supply exciting direct current to a synchronous motor, it is necessary to have a source of d.c. voltage, which is variable in fairly large proportions, since between no-load operation and operation in nominal conditions, the exciting current of a salient-pole machine varies approximately doubling and, in the case of a machine with a constant air gap, it may vary approximately tripling. Furthermore, the machine must have an exciting current reserve margin in order to help its dynamic stability (see § 9.1).

In an analysis of the exciting system then, the choice of main exciting source must be taken into account on the one hand, and the means implemented to make the exciting current vary on the other hand.

**Main sources of excitation**

There are three large categories of main sources of excitation:

- direct current exciter
- exciter-generator supplying a rectifier
- rectifier directly fed from the terminals of the main synchronous machine (self-excitation).

To understand the descriptions which are to follow, it should be noted that:

- a direct current generator is a rotating machine with an immobile field magnet through which a direct current flows, at the terminals of the rotating armature a d.c. voltage occurs which, as a first approximation, is proportional to the field magnet current and the rotation speed

- seen from its terminals, a rectifier bridge can be considered like a converter transforming the power it receives in three-phase alternating form $3 V_{ac} I_{ac} \cos \varphi_{ac}$ to the same power (to the nearest loss) but in direct current:

$$V_{dc} I_{dc} \equiv 3 V_{ac} I_{ac} \cos \varphi_{ac}$$

Two types of rectifiers can be used:

- **Diodes**, the ratio $\frac{V_{dc}}{V_{ac}}$ is applied; the bridge itself does not therefore allow the direct current to be adjusted

- **Thyristors**, the ratio $\frac{V_{dc}}{V_{ac}}$ can be modified; the direct current can be adjusted at the rectifier bridge itself.
**direct current exciter** (see fig. 4-23)

\[ V_{dc} \]: adjustable d.c. voltage  
\[ Ex \]: exciter  
\[ MM \]: main machine

*Figure 4-23: direct current machine excitation principle*

The exciter is fitted with a separate exciting winding \( L_{sep} \), by which the variations in flux will be obtained enabling variation of its voltage at the terminals \( V_f \). In order to decrease the size of the source feeding the winding \( L_{sep} \), the exciter can be fitted with a self-exciting shunt winding \( L_{sh} \) which alone is able to supply the voltage \( V_f \) and current \( I_f \) corresponding to no-load operation of the main machine.

It has to be noted that the current \( I_f \) is necessarily transferred to the main machine rotor via slip-rings and brushes.

The exciter is generally coupled to the same shaft as the generator rotor.
exciter-generator supplying rectifiers

There are two types depending on whether the exciter-generator has a conventional design, i.e. it has a rotating field magnet and a stationary armature, or vice versa. These two variants are shown in figure 4-24. To make them clearer, the demarcation between the stationary parts and rotating parts has been indicated. When current has to cross through this demarcation, it is necessary to use slip-rings and brushes.

Figure 4-24: exciter-generator excitation principle

The exciter-generator is coupled to the same shaft as the main machine rotor and thus the advantage of the solution in figure 4-24-b is that no sliding contact is required. This advantage is very important in the case of very large generators, the exciting current of which reaches high values.

However, the system in figure 4-24-b is difficult to build. On the one hand, it is more difficult to make an armature rotate than a field magnet, as the first withstands much higher voltages and currents, and, on the other hand, the rectifiers, which rotate at high speeds, are subjected to considerable mechanical stress. This is why both systems are currently used to excite very big turbo-generators.
**self-excitation system (or shunt excitation)**

There are two self-excitation systems: shunt type and compound type.

- **shunt type self-excitation** (see fig. 4-25)

![Diagram of shunt type self-excitation principle](image)

**Figure 4-25: shunt type self-excitation principle**

The thyristor bridge feeding the field magnet winding is itself supplied with alternating current via the secondary of a three-phase transformer the primary of which is connected to the terminals of the main synchronous machine.

The rectifiers must be thyristors and not diodes, so that the current $I_f$ can be varied in relation to the load, in such a way that the voltage at the main machine terminals, and thus at the bridge input terminals also, remains constant.

In general, the voltage due to the main machine remanent flux is too weak to be able to allow starting (taking into account the voltage drop in the thyristors); an auxiliary source must therefore be used during the starting period.
• compound type self-excitation

The most usual arrangement is that shown in figure 4-26.

![Diagram of compound type self-excitation principle](image)

The excitation voltage $V_f$ is the sum of two terms, $V_f = V_Y + V_C$:

- the d.c. voltage $V_Y$, proportional to the voltage at the main machine terminals obtained by a transformer and a thyristor bridge as in the case of figure 4-25.

- the d.c. voltage $V_C$, depending on the current supplied by the main machine, obtained by three current transformers placed in the neutral side outlets of the main machine phases. These three current transformers supply a diode bridge. They cannot be current transformers in the strict sense of the word, i.e. such that the secondary current is strictly proportional to the primary current, otherwise $I_f$ would be imposed by the primary current whatever the value of $V_Y$ and there would be no compounding applied. It is thus necessary to partially break the relation between the primary and secondary currents of the current transformers, forcing them to have a high magnetizing current, which is obtained by creating a large air-gap in their magnetic circuit. This results in non negligible oversizing.

With this system, the exciting current increases at the same time as the main machine armature current, which precisely corresponds to the requirements of the theory (when the load phase displacement $\phi$ is constant). But the exciting current does not exactly adjust to the required value, notably because the load phase displacement $\phi$ is variable; this is why adjustment is perfected using the thyristor bridge.
use of excitation systems

Direct current machines are used less and less. On the other hand, rotating diode systems are tending to become more widespread for small and medium powers. Rotating thyristor systems are still rare as it is difficult to control the thyristors. Let us now examine, according to the various categories of use, the most used systems.

- **turbo-generator supplying the public network**

  There is no marked preference between exciter-generators (most often with either fixed or rotating diodes) and the self-excitation system (most often the shunt type).

- **hydraulic generators supplying the public network**

  The shunt-type self-excitation system is the one most often encountered. When exciter-generators are used, they most often have rotating diodes.

- **generators supplying an independent network**

  The most frequent solution is the compound-type self-excitation system.

- **synchronous motors**

  The most frequent solution is the exciter-generator with rotating diodes.

excitation adjustment methods

In the diagrams in figures 4-23 and 4-24, an adjustable source of d.c. voltage must be applied between terminals \( A \) and \( B \), with the power of this source being considerably weaker (roughly 100 times) than the exciting power to be adjusted.

This source can again be a direct current machine. But at the moment purely static systems tend to be used; a thyristor bridge is used for the power supply of the exciter or exciter-generator field magnet, and for the associated adjustment.

In self-excitation systems (see fig. 4-25 et 4-26), adjustment is carried out directly by modifying the delay angle of the thyristor bridge. This last method is much faster and the modification of the voltage \( V_f \) via an external command is almost instantaneous while in systems using rotating machines, the variation of \( V_f \) does not instantaneously follow a variation in voltage applied between \( A \) and \( B \) due to the inductance of the exciting circuit connected between these two points; the time constant of this circuit is roughly 0.1 to 0.3 s. However, this value is generally considered to be acceptable in relation to the stability recovery performances after a strong disturbance (see § 9).
Let us note finally that in the arrangements in figure 4-24, the power rectifier bridge diodes may be replaced by thyristors; this technique is not yet very developed due to the difficulties controlling the rotating thyristors (case of figure 4-24-b).

### 4.2.4. Main electrical characteristics of generators given by manufacturers

- the short-circuit impedance values (subtransient, transient and synchronous reactances) and the associated time constants are given in paragraph 4.1.2. of the *Protection guide*
- \( \cos \varphi \) of the load from 0.8 to 1
- efficiency from 95 to 97 % with full load
- voltage quality:
  - voltage distortion rate of 4 % on linear load
  - \( \pm 5 \% \) variation under steady-state operating conditions
  - \( \pm 15 \) to 20 % for a load impact of \( \pm 100 \% \).
4.3. Asynchronous generators

■ make-up

An asynchronous generator (AG) is any asynchronous rotating electric machine, used to produce electrical energy.

The mechanical drive energy is supplied to the rotor shaft. The electrical energy produced is recovered on the stator.

The construction of an AG is not basically different from that of an asynchronous motor (see § 3.3.1.). The main components are:

- a wound stator
- a rotor, generally a cage rotor.

Any asynchronous motor, whatever the type (cage or slip-ring, three-phase or single-phase), can be used as an asynchronous generator.

For current applications (up to several tens of kW), standard asynchronous motors can be used as AG without any modification.

For the highest powers and when the best performances are required (efficiency, power factor), machines specially built to operate as AG will be used.

■ operation

The theoretical operation of an AG is explained in paragraph 3.3.1. (asynchronous motor operation).

Without torque or current discontinuity, an asynchronous machine goes from operating as a motor to operating as a generator once its slip changes direction, i.e. once it rotates faster than its synchronism speed.

In practice, it is simply necessary to:

- on the one hand, create the rotating magnetic flux by giving the stator the necessary reactive energy
- on the other hand, mechanically drive the machine beyond its synchronism speed, i.e. supply it with at least the mechanical energy equivalent to its losses; beyond this, the excedentary mechanical energy is transformed into active electrical energy. The efficiency is determined by the power loss in the machine.
4.3.1. Asynchronous generator connected to an infinite power network

When the $AG$ is connected to the distribution or transmission network, the network voltage and frequency are applied. Furthermore, the network supplies the $AG$ with the reactive energy that it requires whatever its operating conditions.

**characteristic operating curves**

The torque and current curves in relation to the speed are shown in figure 4-27.

![Figure 4-27: asynchronous machine: characteristic operating curves](image)

- $T_n$: nominal torque
- $s_n$: nominal slip
- $I_n$: nominal current
- $I_s$: current at synchronism speed
- $N_{nM}, N_{nG}$: nominal motor and generator speed respectively
- $N_s$: synchronism speed

We observe that the **torque** $AG$ is more or less symmetrical with that of the motor in relation to the synchronism point.

The **current** curve is more or less symmetrical in relation to the zero slip axis.
**Example**

Let us consider a 45 kW asynchronous motor, with 4 poles and operating at a frequency of 50 Hz and at 400 V. As a first approximation, we can deduce its AG characteristics from its nominal motor characteristics, by applying the rules of symmetry (see table 4-3).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Motor</th>
<th>AG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronism speed (tr/min)</td>
<td>1 500</td>
<td>1 500</td>
</tr>
<tr>
<td>Nominal speed (tr/min)</td>
<td>1 465</td>
<td>1 535</td>
</tr>
<tr>
<td>Nominal torque (N.m)</td>
<td>+ 287</td>
<td>- 287</td>
</tr>
<tr>
<td>Nominal current at 400 V (A)</td>
<td>83 A (consumed)</td>
<td>83 A (supplied)</td>
</tr>
</tbody>
</table>

*Table 4-3: comparison of AG and motor characteristics*

### Active Power and Efficiency

In practice, the same machine, operating as a motor and as a generator with the same slip, will have more or less the same loss in both cases, and thus a practically identical efficiency.

We may deduce from this that the nominal electrical power supplied, with the same slip, will be more or less equal to the electrical power consumed by the machine when operating as a motor, i.e. the nominal mechanical power of the motor divided by its efficiency (see fig. 4-28).

![Figure 4-28: Asynchronous machine - power spread](image)

The figures in square brackets give the orders of magnitude, in kW of transmitted power.
**Example**

A 100 kW electrical motor having an efficiency of 94% will, as an asynchronous generator, supply in theory a nominal power of:

$$P_n = \frac{100}{0.94} = 106\ kW$$

**Coupling**

To couple an AG to the network, the AG is gradually accelerated up to its synchronism speed $N_s$ and then the stator is energized. At this speed, the machine torque is zero and the current is minimum under steady-state operating conditions (see fig. 4-27).

The coupling order is given by a threshold tachometer, which is also used to detect the beginning of runaway.

The threshold setting is adjusted when the machine is put in service. In practice, it is set at approximately 95% of the synchronism speed in order to take into account the response time of the contactors.

We can note here the considerable advantage in relation to synchronous generators; with the AG rotor not being polarized when the stator has still not been energized, it is not necessary to synchronise the network and the machine the instant they are coupled. The coupling of an AG to the network is thus much simpler than that of a synchronous generator.

Nevertheless, it is necessary to mention a phenomenon which occurs during AG coupling and which can, in certain cases, pose a problem. Although not excited, the AG rotor always has a certain amount of remanent magnetization. On coupling, when the two magnetic fluxes, the one created by the network and the one due to the remanent magnetization of the rotor, are not in phase, a very brief current peak (one or two periods), associated with an instantaneous overtorque of the same length of time, is observed on the stator.

In order to limit this peak (and the corresponding overtorque), it is possible to use:

- coupling resistors inserted in series with the stator phases for about one second at the instant of coupling. They are then short-circuit ed by a time-delayed contact

- a static voltage variator in series with the stator phases, in order to carry out coupling at a lower voltage. The voltage is then progressively increased up to the nominal voltage and the variator is then short-circuit ed.

**Remark:** before any network coupling test, the phase connection order must be checked. The asynchronous machine is fed for a fraction of a second as a motor and it has to rotate in the same direction as the drive machine.
Decoupling

Unintentional decoupling caused by a protection device generally results in the drive machine-generator assembly reaching overspeeds, unless the assembly can be braked very quickly.

Owing to these overspeeds, also referred to as runaway, two-pole $AG$ (synchronism speed of 3,000 tr/min at 50 Hz) are practically never used. Four-pole $AG$ are only used at low power or when the assembly has a mechanical no-current brake. The most widely used $AG$ have 6 and 8 poles if not more (slower machines, but to the detriment of $\cos \phi$).

A new advantage of $AG$ over self-excited generators should be noted here; when the machine is disconnected, it is quickly (several seconds) de-excited and has no more voltage at its terminals, as long as the capacitors have been simultaneously disconnected (otherwise, the generator is self-excited by the capacitors). This is an important advantage as far as safety is concerned. In particular, it prevents a local network being fed unintentionally when the general network has been cut.

This is why in France, the French electricity authority, EDF, stipulates the use of $AG$ for $LV$ connections below 100 kVA.

Reactive power compensation

The capacitors are not inserted at the $AG$ terminals until the machine has been coupled to the network in order to avoid the machine being self-excited through the remanent magnetization during the rise in speed.

When unintentional decoupling occurs through operation of a protection device, the machine is self-excited by the capacitor; the resulting overvoltage is high. Furthermore, in order to limit this overvoltage to an acceptable value for the capacitors and the machine, no more than 90% of the no-load reactive power must be compensated. In low voltage, the problem is not as great as the capacitor-generator connection resistances damp these overvoltages.

For intentional decoupling, it is therefore preferable to disconnect the capacitors before the carrying out the decoupling operation.

Compensation is carried out by a capacitor bank with a reactive power of:

$$Q = P \tan \phi \quad \text{(see § 7)}$$

$P$ : active power
protections

There are two categories of protections:

- those concerning the network
- those concerning the generating set.

The first are dealt with in specific regulations common to all types of electric power plants.

The main network protections are as follows:

- over and undervoltage
- over and underfrequency
- underpower or reversals in active power (motor operation)
- overcurrent to detect $AG$ coupling faults.

The main generating set protections are:

- stop when start of runaway is detected
- thermal overload protection (see § 7.7. of Protection guide), generally completed by temperature probes in the winding
- maximum negative phase unbalance protection (see § 7.8 of Protection guide).

specific uses

Certain types of installation use asynchronous machines connected to the network and operating part of the time as a motor and the other part of the time as a generator. We shall look at two fairly common examples of use.

hypersynchronous braking

The asynchronous machine is used as a brake when the load begins to drive. This use is especially encountered in lifting to brake the descent of a load.

Let us also cite the specific case of two-speed electric motors. During the change from high to low speed, there is a hypersynchronous braking phase which is in fact quite abrupt. Indeed, when the speed changes, the machine is still quite far off from its synchronism speed and the braking torque may reach very high values (several times the nominal torque, see § 3.3.5).
mixed motor-generator use

This type of installation can be found in particular in certain flour trades where the milling machines are driven by hydraulic turbines.

Connected to the network, the asynchronous machine is used both as a motor and a generator.

When the turbine does not supply enough power in relation to the needs of the mill, the generator set tends to slow down; the asynchronous machine then works as a motor and supplies the extra power necessary. Inversely, when the turbine supplies too much power, the generator set tends to accelerate; the asynchronous machine then works as a generator and supplies the extra power to the network.

This type of assembly is simple and reliable. The speed is regulated and the power distributed naturally without any extra automatic control.

Conclusion

Provided that a few basic precautions are taken, the use of an asynchronous generator connected to the network is simple and offers numerous advantages compared with the use of a synchronous generator.

This explains why asynchronous generators are almost always used in this type of application for small and medium power ratings (1 to 800 kW). An asynchronous generator is almost always chosen.

4.3.2. Asynchronous generator supplying an independent network

Using $AG$ in this way is less usual and kept in practice for low or medium power machines (but always below roughly 100 kW).

The problem is two-fold:

- it does not supply reactive energy, unlike the synchronous generator. Furthermore, it needs exciting energy.

- as for any autonomous source of energy, the network voltage and frequency have to be stabilised.
**mixed motor-generator use**

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- it does not supply reactive energy, unlike the synchronous generator. Furthermore, it needs exciting energy.

- as for any autonomous source of energy, the network voltage and frequency have to be stabilised.
reactive power supply

Operation of the asynchronous machine requires a rotating magnetic flux, created by the stator winding and passing through the air-gap. This excitation consumes a certain amount of reactive power $Q$, which varies with the machine’s active power $P$:

$$Q = S \sin \varphi = P \tan \varphi$$

$S$: machine apparent power

The reactive energy consumed by certain loads on the network (e.g. electric motors) may eventually be added to the reactive energy consumed by the asynchronous generator.

It will therefore be necessary to incorporate a suitably rated source of reactive energy into the network. Switched steps capacitor banks allowing the compensation to be adjusted in relation to needs are generally used.

example

In an independent network consuming 50 kW where $\cos \varphi = 0.9$ (i.e. $\tan \varphi = 0.48$), fed by an asynchronous generator having a $\cos \varphi$ of 0.8 at 50 kW (i.e. $\tan \varphi = 0.75$), a capacitor bank supplying:

$$50 \times 0.48 + 50 \times 0.75 = 62 \text{ kvar}$$

will be used.

excitation, de-excitation

The magnetic flux in the generator is created as follows: let as assume that the $AG$ is at a halt, with its exciting capacitors at the terminals, but that it is not connected to any active loads. When the $AG$ is gradually accelerated, a voltage occurs at the terminals when a certain speed is reached (about half the synchronism speed). This voltage increases with the speed.

When the synchronism speed has been reached, the $AG$ can be loaded.

The creation of the magnetic flux is due to the remanent magnetization of the generator. This is sufficient to trigger excitation of the generator-capacitor assembly. As long as the $AG$ has been energized at least once (in general, during series testing by the manufacturer) then durable remanent magnetization can be kept.
Remark: an AG can nevertheless become totally de-magnetized. This happens, in particular, when it has undergone a very heavy overload or when there has been an attempt to start it with a load at its terminals.

If the machine is totally de-magnetized, it will not be excited on starting. But it is, in this case, easy to re-magnetize it by, for example, momentarily (for several seconds) applying even a weak d.c. voltage (from a battery or storage battery) to the terminals of one phase.

De-magnetization can be easily avoided by providing a correct starting sequence and protecting the generator against overloads.

■ characteristic curves

At nominal frequency, an AG supplies a voltage which depends on the active power supplied and the value of the exciting capacitors.

For each AG a family of curves, such as those shown in figure 4-29, can be plotted.

\[
\begin{align*}
\text{stable zone} & \quad \text{unstable zone} \\
U_n & \quad 400 & 420 & 440 & 470 & 520 & 545 \\
\text{power} & \quad 0 & \frac{1}{4} & \frac{1}{2} & \frac{3}{4} & 1 & 2 & 3 & 4 & 4 \\
U \quad & \quad P_n \quad \text{nominal power} \quad U_n \quad \text{nominal voltage}
\end{align*}
\]

*Figure 4-29: characteristic operating curves of an asynchronous generator - example of a 13 kW, 6 pole machine*
It is assumed that the network only has resistive loads, in other words, the capacitors are only used for exciting the $AG$. It is also assumed that the driving machine is regulated so that the nominal frequency is maintained. The shape of the curves is about the same for all $AG$.

In the example in figure 4-29, we can see in particular that:

- at the **nominal operating point** (13 kW), a nominal voltage of $U_n = 400V$ is obtained on condition that a 11 kvar capacitor bank is used
- when **half loaded**, $U = 520V$ is obtained, i.e. 130 % of $U_n$, if the 11 kvar bank is kept; to recover $U_n$, only 6 kvar capacitors have to be in service
- when **not loaded**, the voltage is 545 V for 11 kvar, 480 V for 6 kvar, 470 V for 5 kvar
- if the machine is **overloaded** we see that the curve suddenly bends for a given excitation: the machine is quickly de-magnetized.

To **sum up**, in order to maintain constant voltage, the reactive power supplied must be adapted to the active power consumed.

### practical use

For an $AG$ to feed an independent network in good conditions, the following equalities must be established at nominal voltage and frequency:

- active power consumed = active power produced
- reactive power consumed = reactive power produced.

To obtain the right result, the following will be modified, depending on the installation:

- the power supplied by the driving machine
- the active power consumed, by modifying the installation’s active load
- the capacitance, thus the reactive power of the capacitor bank.
uses without a regulator

When certain voltage and frequency variations are tolerated, it is not necessary to provide a sophisticated regulator. Let us look at two current cases:

- for small generator sets of several kVA, some manufacturers use special \(AG\) without regulation.
  
  These generators have very flat characteristic curves; the voltage remains within a range of ± 10%, whatever the active load on the generator, from 0 to full load.
  
  These small generator sets are simple and robust. They are highly suitable for current low power applications (lighting, resistors, small universal motors), but are unsuitable for driving asynchronous motors which consume a non-negligible amount of reactive power.

- when the \(AG\) only feeds a heating installation, via overhead resistors or immersion heaters, regulation is not necessary. In fact, the voltage and frequency may reach notably different values from their nominal values without this causing a problem for the user.
  
  The most frequent case of application concerns the use of hydraulic turbines for heating houses. Frequency and/or voltage variations of the order of 20% are readily admitted.
  
  The turbine-\(AG\)-capacitors-resistors system naturally balances out without any complex automatic control.
  
  It is nevertheless advisable to protect the installation when the characteristics exceed their tolerance levels.

regulation

When the power consumed by the user or the power supplied by the drive machine vary and it is nevertheless necessary to maintain the frequency and voltage within reduced tolerance levels, a regulation device must be provided. The purpose of this device is to maintain the electrical characteristics at a correct level by modifying one or more parameters:

- active power supplied (drive machine)
- active power consumed (loads on the load circuit)
- reactive power supplied (capacitors generally).

The drive machine is adjusted using conventional systems; in general, the drive machine is adjusted, i.e. the supply to a thermal engine or the consumption of a hydraulic turbine, using the generator set speed indication (tachometer) or the load circuit frequency indication.

However, these systems generally have rather long reaction times (at least a second). When there is an abrupt variation in consumption, the frequency and voltage do not recover their values very quickly; this especially causes problems for lighting and electric motor starting.
Even when this type of regulation is used, it is increasingly associated with the electronic regulation of the power consumed (e.g. regulation by consumption of energy, see following section) in order to get over this drawback.

**simplified regulation**

The principle is based on adapting the power consumed to the power produced by automatically modifying the load.

The most common case concerns the use of a hydraulic turbine for feeding heating resistors in air or water. The system is outlined in figure 4-30.

![Figure 4-30: simplified regulation](image)

\[
\begin{align*}
C_f & : \text{fixed capacitor bank} \\
C_s & : \text{secondary capacitor bank} \\
R_1, R_2, R_3 & : \text{heating resistors}
\end{align*}
\]

This very simple system allows the voltage to be maintained within the correct range (e.g. ± 5 %).

When the \( AG \) has a fairly flat voltage-load characteristic curve, only a fixed capacitor bank is required. Otherwise, the main capacitor bank is completed by parallel-connected secondary capacitors on the resistors, behind the contactors.

Some manufacturers offer standard electric switchboards based on this principle; they include this type of regulation as well as the automatic start and stop systems and the protections.
• regulation by energy consumption

This type of regulation is being more and more used. The principle, outlined in figure 4-31, is as follows: a second, non-priority circuit is placed in a shunt arrangement on the load circuit.

---

**Figure 4-31: regulation by energy consumption**

This circuit's loads are operated or, on the other hand, cancelled on instruction from a load regulator. The regulator continuously tries to maintain the correct frequency and voltage ratings on the main load circuit by adding or removing loads on the secondary circuit.

It behaves like a switching system sharing the power $P_p$ produced by the $AG$ between the load network (power $P_c$) and the secondary circuit (power $P_{sh}$).

The following equality permanently applies:

$$P_p - P_{sh} = P_c$$

The frequency and voltage on the load network remain stable when $P_p$ and/or $P_c$ vary.

---

$P_c$ : power consumed
$P_{sh}$ : power shunted
$P_p$ : power produced
$LR$ : load regulator
Figure 4-32 outlines the spread of power produced when the power levels vary in time:

- variations in consumed power are due to variations in user needs
- variations in produced power are due to natural causes (variation in flow for a hydraulic turbine, wind speed for a wind power engine) or to a drive machine adjustment when it is necessary to economise on primary energy (hydraulic turbine flow adjustment, thermal motor consumption).

![Diagram showing power consumption and production over time](image)

- $P_c$ : power consumed
- $P_{sh}$ : power shunted
- $P_p$ : power produced

**Figure 4-32: spread of power produced**

A detailed description of the different energy consumption regulators offered by manufacturers would be too long.

But, we can make the following remarks:

- the regulation parameter may be the frequency or the voltage on the load network or even a combination of the two. The most advanced regulators include both parameters so that the voltage and frequency are kept very close to their nominal values in all operating conditions

- regulation by energy consumption only works if the regulator has a power reserve on the secondary circuit. If it does not, and there is a power demand on the load network, it will not be able to meet it
- the energy in the secondary circuit required for proper operation is generally dissipated in overhead resistors. It is thus lost, which is often not important when the primary energy is free and non-storable (case of mini power plants with no storage dam or wind power engines). It is still possible to use this energy, but this use will not take priority and it must be possible to interrupt it for the benefit of the main load network.

- regulation by energy consumption can be combined without any drawback with regulation of the power produced (see previously described simplified regulation). This therefore gives regulation which is said to be mixed. For example, the conventional regulation of a hydraulic turbine can be completed with regulation by energy consumption which can thus only be sized for a small fraction of the total installation.

- this type of energy consumption regulator is being more and more used for autonomous energy sources such as hydroelectric or wind driven mini power plants. Some manufacturers offer regulation systems for power ratings able to reach 500 kW. Above this value, mixed regulation systems are preferably used.

**reactive power compensation**

In the most general case, reactive energy must be supplied:

- to the asynchronous generator
- to the loads which consume it.

To supply these two types of reactive energy consumption, an adequate source of reactive energy is installed in parallel on the circuit. This is generally a switched steps (one or more) capacitor bank which, depending on the case, will be fixed or manually (in steps) or automatically adjustable.

**generator compensation**

The characteristic curves give the exciting energy value in relation to the machine load:

- if the load varies little, a fixed capacitor bank is sufficient; the voltage will vary very little
- if the load varies a lot, the voltage variations may become too large; an adjustable system is therefore necessary.
• reactive load compensation

The most common case concerns asynchronous electric motors. Depending on their number and power, either one or the other or both solutions will be used:

- individual motor compensation by direct connection of permanent capacitors to their terminals
- Fixed, manually or automatically adjustable overall circuit compensation.

This compensation problem somewhat complicates the installation in relation to a synchronous generator which automatically supplies the reactive current consumed by the load.

This is the only considerable advantage of synchronous generators over $AG$, but it can be a decisive advantage when the load circuit has a highly variable $\cos \phi$.

□ control and protection

The only specific systems are:

- the time delay of load circuit coupling to avoid de-excitation of the machine on starting
- the manual or automatic control, depending on the case, of exciting capacitors.

□ parallel coupling of several generators

The parallel coupling of several asynchronous generators feeding an independent network does not pose any specific problem. If the generators are used with an energy consumption regulation system, a single regulator is sufficient.

The parallel coupling of two generators, one made up of an asynchronous generator, the other made up of a synchronous generator, to an independent network is different depending on the respective power of the two generators:

- if the synchronous generator is more powerful than the $AG$, then it is the synchronous generator that will control the network; without regulation, the $AG$, will be coupled in the same way as it would be to an infinite power network
- if the synchronous generator has a lower power than the $AG$, then the $AG$ must be regulated. The reactive current required by the excitation and the load must be correctly adjusted for the synchronous generator to operate with the correct power factor.
4.4. Comparative advantages of synchronous generators and asynchronous generators

- connection to an "infinite" power network

For powers up to several MW, the asynchronous generator has only advantages compared with the synchronous generator:

- **better reliability**: simpler and generally more robust construction, no rotating winding (no slip-rings or brushes), massive rotor able to withstand runaway (hydraulic turbines, wind power engines)

- **simplicity and safety of use**: easier coupling, simpler switchgear, no risk of unintentionally feeding a network part (see § 4.3.1., decoupling).

The only advantage of the synchronous generator is its capacity to supply reactive energy. This advantage is only useful if the synchronous generator has sufficient power in relation to the local network needs.

- power supply to an independent network

The simple and robust qualities of $AG$ still apply.

$AG$ can be used to supply an independent network containing simple installations (household needs, heating, resistive loads).

On the other hand, when the network to be supplied is more complex, in particular when its $\cos \varphi$ constantly varies, the synchronous generator is then much more suitable. Indeed, it supplies the reactive energy required by the network at any moment while, in the same conditions, an asynchronous generator must be associated with a complex automatic reactive power compensation system.

Choosing between the two types of generators thus depends on the characteristics of the network to be fed. Table 4-4 provides a number of basic indications.

<table>
<thead>
<tr>
<th>Network characteristics</th>
<th>Type of generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low power</td>
<td>$AG$</td>
</tr>
<tr>
<td>Air or water heating</td>
<td></td>
</tr>
<tr>
<td>Lighting</td>
<td></td>
</tr>
<tr>
<td>Small electrical household appliances</td>
<td></td>
</tr>
<tr>
<td>variable $\cos \varphi$</td>
<td>synchronous generator</td>
</tr>
<tr>
<td>Numerous electric motors</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4-4: choice of generator type depending on the characteristics of an independent network*
■ operating zones of synchronous generators and asynchronous generators (see table 4-5)

<table>
<thead>
<tr>
<th>Power ratings</th>
<th>Connection to distribution network</th>
<th>Independent network power supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (up to roughly 50 kW)</td>
<td>AG</td>
<td>AG preferably</td>
</tr>
<tr>
<td>Average (50 kW to 5 MW roughly)</td>
<td>AG preferably</td>
<td>synchronous generator preferably</td>
</tr>
<tr>
<td>High (&gt; 5 MW)</td>
<td>synchronous generator</td>
<td>synchronous generator</td>
</tr>
</tbody>
</table>

*Table 4-5: synchronous generator and asynchronous generator operating zones*

4.5. **Uninterruptible power supplies (UPS)**

The operating principle and different uninterruptible power supply arrangements are described in paragraph 1.6.3.

It is useful to give the main UPS electrical characteristics in this part.

- **main electrical characteristics**
  - unit power of several kVA to 600 kVA
  - voltage quality:
    - voltage distortion rate of 5 % on linear load
    - + 10 % / - 8 % for a load impact of ± 100 %.
  - overload capacity:
    - 50 % for 1 min.
    - 25 % for 10 min.
  - battery autonomy:
    - 10, 15 or 30 min.