7. Reactive energy compensation

7. REACTIVE ENERGY COMPENSATION

Reactive energy compensation is an important element for reducing the electricity bill and improving the quality of the electrical network.

7.1. Reactive energy

It is important to clearly define reactive energy, where it comes from and its effects in electrical networks.

7.1.1. Nature of active and reactive energies and apparent power

Any electrical system (cable, line, transformer, motor, lighting, etc.) using alternating current brings into play two forms of energy: active energy and reactive energy.

■ **active energy consumed** (kWh)

This results from the active power P (kW) used essentially by loads.

It is completely transformed into mechanical, thermal or light energy.

■ **reactive energy consumed** (kvarh)

This magnetizes the magnetic circuits of machines (transformers and motors). Furthermore, lines or cables consume or produce reactive power depending on their load.

It corresponds to the reactive power Q (kvar) of loads.

■ **apparent power** (kVA)

This enables the value of the current absorbed by a load to be determined.

7.1.2. Current active and reactive components

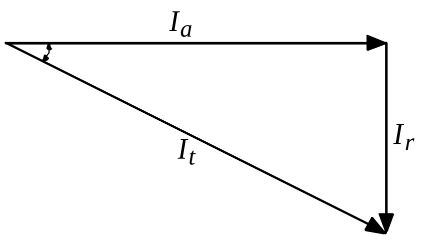
Each of these active and reactive energies has a corresponding current.

Active current (I_a) is in phase with the network voltage.

Reactive current (I_r) is phase shifted by 90 ° in relation to the active current, either lagging it (inductive load) or leading it (capacitive load).

(Total) apparent current (I_t) is the resulting current which flows through the electrical cable from the source to the load. This current is phase shifted by an angle j in relation to the active current (or in relation to the voltage).

For a current which does not comprise harmonic components (see § 8), these currents are vectorially composed in r.m.s. values as shown in figure 7-1.



I_t : apparent current
I_a : active current
I_r : reactive current
j : phase displacement between the apparent current and the active current (equal to the phase displacement between the apparent current and the voltage)

Figure 7-1: vectorial composition of active, reactive and apparent currents

The active, reactive and apparent currents and the phase displacement are related through the following relations:

$$I_t = \sqrt{I_a^2 + I_r^2}$$

$$I_a = I_t \cos j$$

$$I_r = I_t \sin j$$

In the case where there are no harmonics $\cos j$ is equal to the power factor.

7.1.3. Active and reactive power components

For currents and voltages which do not have harmonic components (see § 8), the previous diagram drawn up for currents is also valid for powers; it is simply a question of multiplying each current by the network voltage.

For a single-phase circuit, we can thus define:

Active power

$$P = VI \cos j \quad \text{(in } W \text{ or } kW\text{)}$$

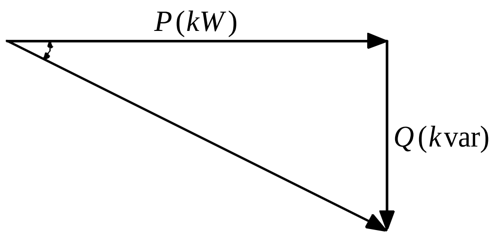
Reactive power

$$Q = VI \sin j \quad \text{(in var or } k\text{var)}$$

Apparent power

$$S = VI \quad \text{(in } VA \text{ or } kVA\text{)}$$

These powers are vectorially composed as shown in figure 7-2.



S : apparent power
P : active power
Q : reactive power
j : phase displacement between the apparent power and the active power (equal to the phase displacement between the current and voltage)

Figure 7-2: vectorial composition of active, reactive and apparent powers

In the case where there are no harmonics, the active, reactive and apparent powers are expressed as follows:

$$P = VI \cos j$$
$$Q = VI \sin j$$
$$S = VI$$

whence $S = \sqrt{P^2 + Q^2}$

In this case $\cos j = \frac{P}{S}$ is called the power factor.

7.1.4. Power factor

The power factor is defined by the following relation:

$$F = \frac{P}{S} = \frac{active\ power\ (kW)}{apparent\ power\ (kVA)}$$

In the absence of harmonics, the power factor is equal to $\cos j$.

However, in the presence of harmonics, these two values may be very different:

$$F = F_h \cos j$$ (see § 8.1.2)

F_h : harmonic factor

For example, for a speed variator (generator of high harmonic currents):

$$F = 0.54$$
$$\cos j = 0.85$$

The $\cos j$ (and thus the power factor) is all the better the closer it is to 1. We shall see that increasing the $\cos j$ optimises operation of the electrical network.

7.1.5. value of *tan j*

We often use $\tan j$ instead of $\cos j$.

In the absence of harmonics, $\tan j$ is expressed as follows:

$$\tan j = \frac{Q}{P} = \frac{reactive\ power\ (\text{kvar})}{active\ power\ (kW)}$$

And we have the relation:

$$\cos j = \frac{1}{\sqrt{1 + \tan j^{\,2}}}$$

7.1.6. Power factor and cos φ in the presence of harmonics

As shown in paragraph 8.1.2., in the presence of harmonics, the definitions are as follows:

$$F = \frac{P}{S}$$

P : total active power (including harmonics)
S : total apparent power (including harmonics)

$$\cos j = \frac{P_1}{S_1}$$

P_1 : active power of the fundamental component
S_1 : apparent power of the fundamental component
j : phase displacement between the current and voltage fundamental components

We often write $\cos j_1$ to specify that the phase displacement only applies to fundamental components.

Installing capacitors allows the reactive energy of the fundamental component to be compensated and a $\cos j$ roughly equal to 1 to be obtained.

On the other hand, it is not possible to compensate reactive energy due to harmonics with capacitors. The result is that when harmonics are present, it is impossible to obtain a power factor equal to 1 by installing capacitors. To obtain a power factor equal to 1, the harmonic currents must be eliminated by an active filter (see § 8.4.5).

However, it should be noted that the utility only makes the customer pay for reactive energy due to the fundamental component. It is thus necessary to calculate $\cos j_1$ (and not F) to determine the reactive power of the capacitors that must be installed to reduce or avoid the cost of reactive energy.

7.1.7. Circulation of reactive energy

The circulation of reactive energy considerably influences the selection of equipment and operation of networks. It therefore has economic consequences.

Indeed, for the same active power P used, figure 7-3 shows that the lower the $\cos j$, i.e. the greater the j angle, the more apparent power $\left(S_2 > S_1\right)$ must be supplied .

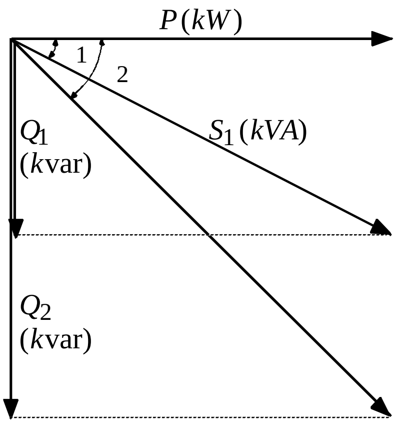


Figure 7-3: influence of $\cos j$ on the apparent power value

In exactly the same way (see fig. 7-4), for the same active current used I_a (for a constant network voltage U), the lower $\cos j$ (i.e. the greater angle j) the more apparent current must be supplied $\left(I_2 > I_1\right)$.

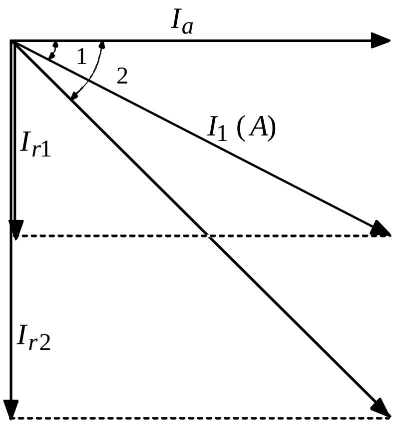


Figure 7-4 : influence of $\cos j$ on the apparent current value

Thus, due to the increase in apparent current, the circulation of reactive energy causes:

- overloads and extra overheating in the transformers and cables which results in active energy losses
- voltage drops.

The consequences of the circulation of reactive energy thus lead to oversizing of the network electrical equipment.

To prevent this reactive energy from circulating in the network, it must be produced near to consumers.

From a practical point of view, capacitors are installed to supply the reactive energy required by inductive equipment (see table 7-1).

Thus, this reactive energy only circulates between capacitors and consumers of reactive energy. It is then obvious that the closer capacitors are to consumers, the less considerable the consequences of reactive energy circulation will be.

To avoid the consequences of a lot of energy circulating on their network, utilities generally invoice reactive energy above a certain threshold; this encourages users to compensate the reactive energy that they consume.

7.1.8. Reactive energy and network elements

■ synchronous machines

These are generators and synchronous motors. By modifying the exciting current, the reactive power of the machine is varied. For a high exciting current, the machine supplies reactive power $(Q > 0)$ and for a low exciting current, it absorbs reactive power $(Q < 0)$ (see § 4.2.1.1.). The synchronous machines can thus supply part of the reactive power required (see § 12.2.8).

■ asynchronous machines

These are motors (see § 3.3.1.) and asynchronous generators (see § 4.3.). They absorb reactive power, with a lower $\cos \varphi$ the weaker the load is (see table 7-1).

■ lines and cables

The L and C characteristics of lines and cables are such that these elements consume or produce reactive energy depending on their load.

For a three-phase cable or line:

$$Q = 3\left(C w V^2 - L w I^2\right)$$

C : cable or line capacitance
L : cable or line inductance
V : single-phase voltage
I : current carried by the cable or line

From a practical point of view:

- lines consume reactive power
- MV cables produce reactive power at light load and consume reactive power at heavy load
- LV cables consume reactive power.

■ transformers

A transformer consumes reactive power which can be approximately determined by adding:

- a fixed part which depends on the off-load magnetizing current I_0 :

$$Q_0 = \sqrt{3}\, U_n\, I_0$$

- a part which is approximately proportional to the square of the apparent power that flows through it:

$$Q \cong U_{sc}\, \frac{S^2}{S_n}$$

U_{sc} : transformer short-circuit voltage in p.u.
S : apparent power flowing through the transformer
S_n : nominal apparent power of the transformer
U_n : nominal phase-to-phase voltage

The total reactive power consumed by the transformer is:

$$Q_t = Q_0 + Q$$

■ inductors

These consume reactive power; they are used, for example, to stabilize the arc of fluorescent lamps or furnaces.

■ capacitors

These supply reactive power with an extremely good efficiency which is why they are used for this application.

■ other loads

Table 7-1 gives the $\cos j$ and $\tan j$ for the most commonly-used loads.

Device	$\cos j$	$tg\ j$
Common asynchronous motor loaded at 0 %	0.17	5.80
25 %	0.55	1.52
50 %	0.73	0.94
75 %	0.80	0.75
100 %	0.85	0.62
Electronic speed variators for asynchronous motors (with a power below 300 kW) whatever the load	≈ 0.85	≈ 0.62
Incandescent lamps	≈ 1	≈ 0
Fluorescent lamps (uncompensated)	≈ 0.5	≈ 1.73
Fluorescent lamps (compensated) (0.93)	0.93	0.39
Discharge lamps (uncompensated)	0.4 to 0.6	2.29 to 1.33
Resistance furnaces	≈ 1	≈ 0
Induction furnaces (with integrated compensation)	≈ 0.85	≈ 0.62
Resistance welding machines	0.3 to 0.8	0.75 to 3.18
Fixed single-phase arc welding sets	≈ 0.5	1.73
Arc-welding motor-generating sets	0.7 to 0.9	1.02 to 0.48
Arc-welding transformer-rectifier sets	0.7 to 0.8	1.02 to 0.75
Arc furnaces	0.7 to 0.8	0.75 to 1.02

Table 7-1: $\cos j$ *and* $\tan j$ *for the most commonly-used loads*

7.2. Advantages of reactive energy compensation

■ avoidance of excessive reactive energy consumption bills

For large consumers, reactive energy is billed above a threshold for certain periods.

In France, reactive energy is billed for customers having a subscribed power higher than 250 kVA.

The French electricity authority, EDF, supplies reactive energy free of charge:

- up to a maximum of 40 % of the active energy consumed $(\tan j = 0.4)$ from 6 a.m. to 10 p.m. (the most heavily-loaded period) from November to March
- without limitation from 10 p.m. to 6 a.m. (light-load period) from November to March and throughout the day from April to October.

During the periods of limitation, reactive energy consumption exceeding $\tan j = 0.4$ is billed monthly at the current rates.

The quantity of reactive energy billed W_b is equal to:

$$W_b = W_r - W_{fr} = W_a \left(\tan j - 0.4\right)$$

W_r $(k\text{var}h)$	:	reactive energy consumed monthly during the period of limitation
W_a (kWh)	:	active energy consumed monthly during the period of limitation
$W_{fr} = 0.4\ W_a$	:	amount of reactive energy supplied free of charge

Reactive energy compensation allows $\tan j \leq 0.4$ to be obtained and thus reactive energy costs to be avoided.

■ reduction of subscribed maximum apparent power in kVA

For small consumers, the utility bills "a standing charge" which depends on the subscribed apparent power. Above this power the consumer pays tariff penalties.

Reactive energy compensation allows the standing charge to be reduced by decreasing the subscribed apparent power.

In France, the standing charge on apparent power is paid by customers having a subscribed power between 36 and 250 kVA.

■ reduction of losses in conductors at constant active power

Losses in cables are proportional to the square of the current carried (loss = RI^2) and they decrease as the $\cos j$ increases.

Indeed, let us assume that a conductor carries an apparent power S, where:

$$S = VI$$
$$P = S \cos j$$
$$Q = S \sin j$$

If there is compensation, at constant active power, so that an apparent power S' is obtained, where:

$$S' = VI'$$
$$P' = P = S' \cos j'$$
$$Q' = S' \sin j'$$

then we have:

$$S^2 = P^2 + Q^2 = P'^2 + Q^2 = S'^2 \cos^2 j' + S^2 \sin^2 j$$

whence $$\frac{S'^2}{S^2} = \frac{1 - \sin^2 j}{\cos^2 j'} = \frac{\cos^2 j}{\cos^2 j'}$$

while $$\frac{S'^2}{S^2} = \frac{I'^2}{I^2}$$

whence $$\boxed{\frac{R\,I'^2}{R\,I^2} = \frac{\cos^2 j}{\cos^2 j'}}$$

The losses are inversely proportional to $\cos^2 j$.

□ example

Let us take the example in paragraph 6.2.9., figure 6-17 for the W1 wiring system which has the following characteristics:

$$\ell = 1200\, m$$

$$I = 66\ A$$

$$\cos j = 0.6$$

$S = 70\ mm^2$ in aluminium

$$U_n = 5.5\, kV$$

The conductor resistance is:

$$R = \frac{r\,\ell}{S} = \frac{0.036 \times 1\,200}{70} = 0.62\ \Omega$$

r : aluminium resistivity taken to be equal to 1.25 times that at 20 °C, in Ω.mm²/m.

The Joule losses are thus:

$$W = 3\,R\,I^2 = 8.1\ kW$$

For an annual operating time of 7 000 h and an average kWh cost of 0.061 Euros, the annual cost of Joule losses is:

C = 8.1 x 7 000 x 0.061 = 3 459 Euros/year

Let us assume that compensation allows $\cos j' = 0.95$ to be obtained; we then have:

$$\frac{R\,I'^2}{R\,I^2} = \frac{\cos^2 j}{\cos^2 j'} = 0.40$$

Installing capacitors allows a gain of 60 % to be obtained on the Joule losses, which represents an annual saving of $\Delta C = 3\,459 \times 0.6 = 2\,075\ Euros\,/\,year$.

■ **increase in active power carried at constant apparent current**

Installing capacitor banks downstream of a cable (or on a transformer secondary) having a load with a weak $\cos j$, allows a higher active power to be carried for the same apparent current in the conductors (or transformer).

Indeed, let us assume that a cable (or a transformer) carries an active power P , where:

$$P = \sqrt{3}\,U_n\ I\cos j$$

If we compensate so that $\cos j'$ is obtained, at constant apparent current (constant I), we will be able to carry an active power of:

$$P' = \sqrt{3}\,U_n\ I\cos j'$$

whence $$\boxed{\frac{P'}{P} = \frac{\cos j'}{\cos j}}$$

For the same apparent current, the active power which can be carried is thus proportional to $\cos j$.

□ **example**

Let us again take the example in paragraph 6.2.9., figure 6-17, for the W1 wiring system which has the following characteristics:

$$I = 66\ A$$

$$\cos j\ = 0.6$$

$$U_n = 5.5\ kV$$

We can deduce from this that $P = \sqrt{3} \times 5\,500 \times 66 \times 0.6 = 377\ kW$

Let us assume that the compensation allows $\cos j' = 0.95$ to be obtained, we then have:

$$\frac{P'}{P} = \frac{0.95}{0.6} = 1.58$$

whence $\boxed{P' = 596\ kW}$

Installing capacitors thus allows a 58 % higher active power to be carried for the same apparent current.

■ **reduction of voltage drop**

The relative voltage drop in a three-phase cable or transformer is expressed as follows:

$$\frac{\Delta V}{V_n} = \frac{R\,P + X\,Q}{3V_n^2}$$

R : conductor or transformer resistance
X : cable or transformer reactance
P : load active power
Q : load reactive power
V_n : nominal single-phase voltage

Compensation at the terminals of the load reduces the value of Q and thus the voltage drop.

The gain is considerable when $X \geq R$, i.e. for transformers $(X > 3R)$ and cables with a large cross-sectional area ($\geq 240\ mm^2$ copper, $\geq 350\ mm^2$ aluminium).

☐ **example**

Let us consider a 20 kV/400 V transformer with a nominal power of $S_n = 1\,000\ kVA$ having a load with the following characteristics:

$$S = 1000\ kVA$$
$$\cos j = 0.8\ (\sin j = 0.6)$$

whence
$$P = S \cos j = 800\ kW$$
$$Q = S \sin j = 600\ k\text{var}$$

According to table 4-10 in the *Protection guide*, the transformer characteristics are:

$$U_{sc} = 5\,\%$$
$$R = 2.03\ m\Omega$$
$$X = 8.16\ m\Omega$$

From this we can deduce the voltage drop through the transformer:

$$\frac{\Delta V}{V_n} = \frac{R\,P + X\,Q}{3\,V_n^2} = \frac{2.03 \times 800 + 8.16 \times 600}{3 \times (230)^2} = 4.1\,\%$$

Let us assume that compensation allows $\cos j' = 0.99\ (\tan j' = 0.14)$ to be obtained, we then have:

$$P = 800\ kW$$

$$Q = P \tan j' = 800 \times 0.14 = 112\ k\text{var}$$

whence
$$\frac{\Delta V}{V_n} = \frac{2.03 \times 800 + 8.16 \times 112}{3 \times (230)^2} = 1.6\,\%$$

Installing capacitors thus allows the voltage drop through the transformer to be reduced from 4.1 % to 1.6 %.

7.3. Relationship between the power of the capacitors and the improvement of *cos j*

This is a question of determining the reactive power to be installed in order to obtain the required $\cos j$.

Let us assume that at an active power P and reactive power Q point of the network we wish to improve $\cos j$ in order to obtain $\cos j'$, or change from $\tan j$ to $\tan j'$.

If we install reactive power Q_C capacitors then we have:

$$\tan j = \frac{Q}{P}$$

$$\tan j' = \frac{Q'}{P}$$

$$Q' = Q - Q_C$$

From this we can deduce $\boxed{Q_C = P\left(\tan j - \tan j'\right)}$

Figure 7-5 gives a graphic illustration of the variation of j as a function of Q_C .

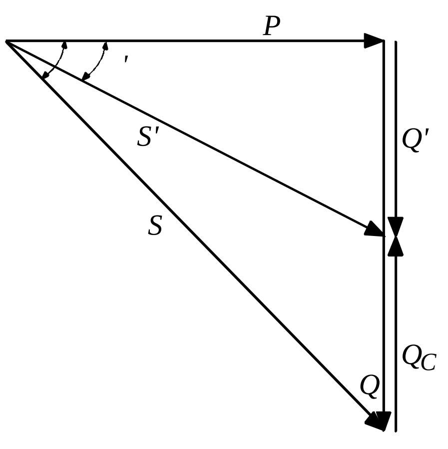


Figure 7-5: variation of j *as a function of the reactive power* Q_C *of the capacitors*

7.4. Equipment for compensating reactive energy

Compensation can be carried out by two families of products:

- fixed-valued capacitor banks
- automatically-controlled stepped capacitor banks which allow compensation to be adjusted to variations in installation consumption.

■ Fixed capacitor banks

Capacitor banks have a constant power.

They are preferably used:

- at the terminals of loads
- on the busbars having a weak load variation.

■ automatically-controlled stepped capacitor banks

This type of equipment allows the reactive power supplied to be adjusted to variations in consumption and thus $\cos j$ to be maintained at the required value.

It is used in cases where the reactive power consumed is high in relation to the transformer power and varies in considerable proportions, i.e. mainly:

- at the terminals of the main LV switchboards
- on high power outgoing feeders.

■ **principle and advantage of automatic compensation**

A bank of capacitors is divided into sections (see fig. 7-6). The value of $\cos \varphi$ is detected by a varmeter relay which automatically controls closing and opening of the sections in relation to the load and required $\cos \varphi$.

The current transformer must be placed upstream of the loads and capacitor banks.

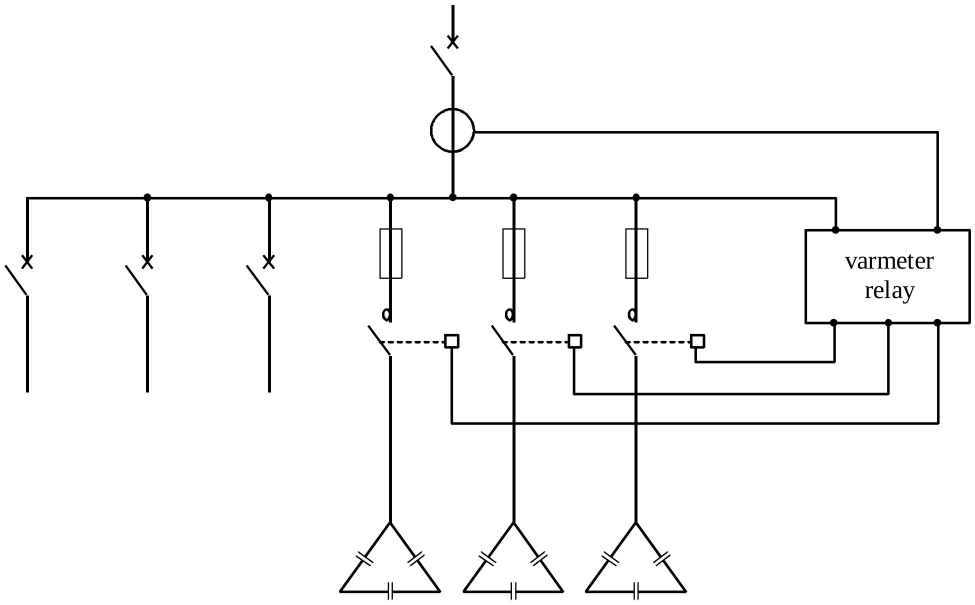


Figure 7-6: principle of automatic compensation of an installation

Overcompensation is prejudicial as it abnormally increases the duty voltage.

Automatic compensation thus allows steady-state overvoltages resulting from overcompensation when the network has a small load to be avoided.

Thus a regular duty voltage is maintained while paying the utility for reactive energy during periods of high consumption is avoided.

☐ **usual rule in low voltage**

If the power of the capacitors (kvar) is lower than 15 % of the power of the transformer, a fixed capacitor bank is chosen.

If the power of the capacitors (kvar) is higher than 15 % of the power of the transformer, an automatically-controlled stepped capacitor bank is chosen.

7.5. Where to install capacitors

Compensation may be global, by sector or individual. In theory, ideal compensation is that which allows reactive energy to be produced at the place where it is consumed and in quantities adapted to the demand.

This compensation mode is very costly and, in practice, a technical-economic solution is aimed at.

■ global compensation

☐ principle

The bank is connected at the origin of the installation (see fig. 7-7) and ensures compensation for the entire installation. It remains in continuous service during the reactive energy billing period for normal plant operation.

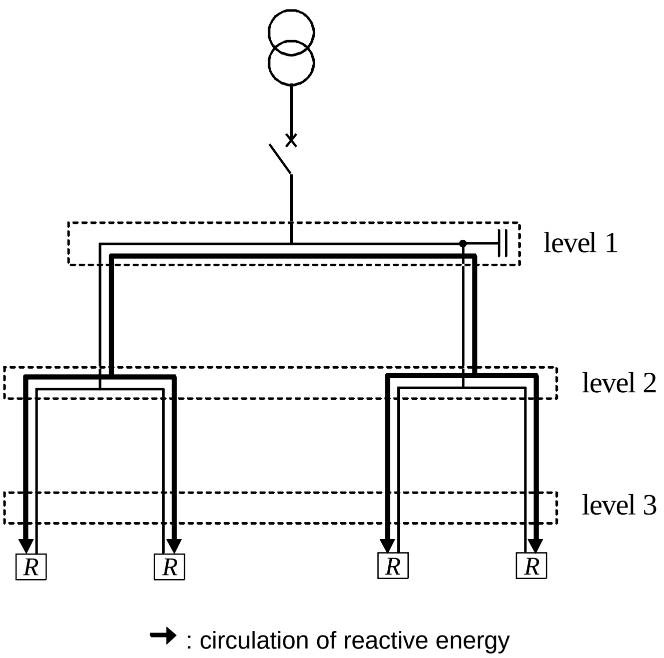


Figure 7-7: global compensation

☐ **advantages**

Due to the coincidence factor lower than 1 the bank has a smaller rating. It is continuously in service and there is therefore a much quicker return on investment.

Depending on the case, this type of compensation can:

- avoid costs for excessive consumption of reactive energy
- reduce apparent power by adjusting it to the installation's active power requirement
- increase the available active power of the supply transformer.

☐ **remarks**

- reactive current circulates in the installation from level 1 to the loads
- Joule losses (kWh) and voltage drops in the feeder cables located downstream of the bank are not reduced.

☐ **use**

When the load is regular, global compensation is suitable.

■ **compensation by sector**

☐ **principle**

The bank is connected to the switchboard (see fig. 7-8) and supplies the reactive energy required by a sector of the installation.

A significant part of the installation benefits from this arrangement, notably the feeder cables supplying each sector.

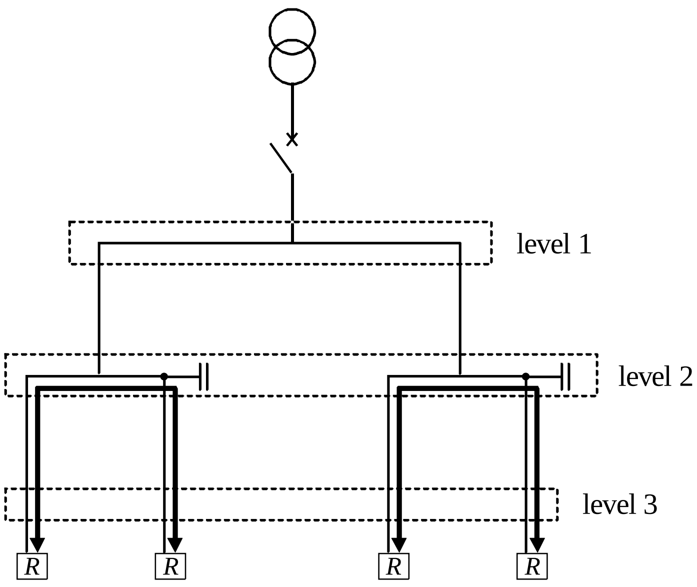


Figure 7-8: compensation by sector

☐ advantages

This type of compensation:

- avoids costs for excessive consumption of reactive energy
- optimizes one part of the network, since reactive current is not carried between levels 1 and 2
- increases the available active power of the transformer and the active power that can be carried in the feeder cables located upstream of the compensated sector.

☐ remarks

- reactive current circulates in the installation from level 2 to the loads
- Joule losses (kWh) and voltage drops in the feeder cables connecting level 2 to level 1 are reduced
- there is risk of overcompensation in the event of significant variations in load (this risk can be eliminated by installing stepped banks).

☐ use

Compensation by sector is advisable when the installation is extensive and has sectors of high reactive energy consumption.

■ individual compensation

□ principle

The bank is directly connected to the terminals of the load (see fig. 7-9).

Individual compensation should be used when the load power is considerable in relation to the transformer power.

When it is possible, this compensation produces reactive energy at the place where it is consumed and in quantities adapted to the requirements.

Additional compensation at the origin of the installation may also be necessary.

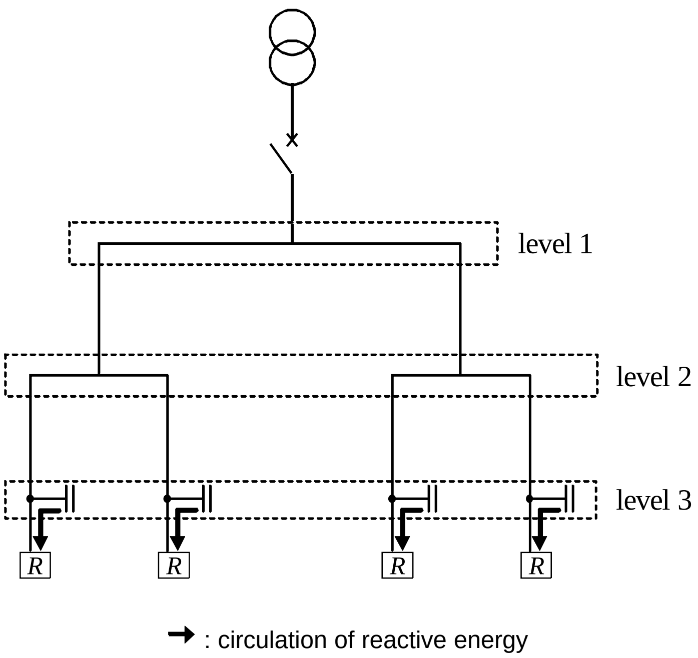


Figure 7-9: individual compensation

□ advantages

This type of compensation:

- avoids costs for excessive consumption of reactive energy
- increases the available active power of the transformer and the active power that can be carried in the feeder cables located upstream of the load
- reduces Joule losses (kWh) and voltage drops in feeder cables between level 3 and level 1.

☐ remarks

Reactive current is no longer carried in the installation feeder cables.

☐ use

Individual compensation is preferable when the power of certain loads is considerable in relation to the transformer power.

This type of compensation offers the most advantages but it is the most costly.

7.6. Determining compensation power in relation to the energy bill

The power to be installed depends on the reactive energy consumption and the utility tariff rating.

We shall examine the case of France.

■ **method based on the avoidance of reactive energy costs**

The following method can be used to calculate the compensation power to be installed based on reactive energy bills.

It determines the minimum compensation power which avoids reactive energy costs.

The process is as follows:

- from amongst the electricity bills for November to March inclusive (period when reactive energy is billed), choose the maximum amount of reactive energy during one month, e.g. 15 966 kvarh in January.

- assess the operating time of the installation during this month, e.g. 10 h x 22 days = 220 h.

  Important: the only periods to be taken into account are those when reactive energy is billed.

- the value of the reactive power Q_C required is:

$$Q_C = \frac{k\text{var}h \; billed}{operating \; time}$$

For the example in question, we find that:

$$Q_C = \frac{15\,966 \; k\text{var}h}{220 \; h} = 73 \; k\text{var}$$

The value to be taken is the value just above the power calculated so that the standard powers are taken into account.

■ **method based on the reduction of subscribed maximum apparent power (yellow tariff)**

For subscribed power between 36 kVA and 250 kVA, the French electricity authority, EDF, bills a standing charge which depends on this power. Above it, the consumer pays tariff penalties.

Compensating reactive energy thus enables the standing charge to be reduced by decreasing the apparent power (see fig. 7-5).

The reactive energy consumed by a customer subscribing to this tariff contract does not appear on the electricity bill.

To determine the value of the reactive power to be installed, the cost of investing in capacitors must be compared with the gains on the standing charge paid to EDF.

We can show that the optimum solution is generally obtained for a $\cos j$ close to 0.928;
i.e. $\tan j$ close to 0.4.

Indeed, above this value, the installation of extra capacitors is not worth the investment (return time too long). Moreover, care must be taken not to overcompensate, as this causes the same effects as under-compensating, with the extra cost of the capacitors.

The maximum power of the capacitors to be installed is thus equal to the reactive power consumed during the peak period less 0.4 times the corresponding active power.

The peak is considered here to be the maximum apparent power allowed over a period of several minutes.

The power of the capacitors to be installed is thus, as shown in paragraph 7.3.

$$Q_C = P\left(\tan j - 0.4\right) = S \sin j - 0{,}4\, P$$

S : apparent power at the consumption peak
P : active power at the consumption peak
$\tan j$: average value recorded

□ **example**

An industrial company takes out a contract with a power S equal to 84 kVA.

The average recorded value of $\tan j$ is equal to 0.75 $(\cos j = 0.8)$.

At the consumption peak, the power reached is close to the power subscribed.

This installation therefore consumes an active power P and a reactive power Q during the peak period, such that:

$$\begin{aligned} P &= S \times \cos j \\ &= 84 \times 0.8 = 67.2\ kW \end{aligned}$$

$$\begin{aligned} Q &= P \times \tan j \\ &= 67.2 \times 0.75 = 50.4\ k\text{var} \end{aligned}$$

The value of $\tan j$ is relatively high (0.75); it is preferable to improve it in order to decrease the power S to be subscribed.

Indeed, by reducing $\tan j$ to 0.4 $(\cos j = 0.928)$, it is possible to subscribe a power $S' < S$, such that:

$$S' = P / 0.928 = 67.2 / 0.928 = 72\ kVA$$

The gain on subscribed power is then:

$$84 - 72 = 12\ kVA$$

For a unit cost of 51 Euros the kVA, the yearly gain on the standing charge is:

12 x 51 = 612 Euros.

To obtain $\tan j = 0.4$, it is necessary to install a capacitor power of:

$$\begin{aligned} Q_C &= P \times (\tan j - 0.4) \\ &= 67.2 \times (0.75 - 0.4) = 23.50\ k\text{var} \end{aligned}$$

It is assumed that the minimum reactive power consumed by the installation is higher than 23.50 kvar. It is thus possible to install a fixed bank without any risk of overcompensating (overcompensating has prejudicial effects, see § 7.4.).

The cost of the kvar installed is thus approximately 20 Euros, i.e. a total compensation cost of:

23.5 x 20 = 470 Euros.

The return on investment time is:

$$\frac{470}{612} = 0.77\ year \approx 9\ months$$

7.7. Compensation at the terminals of a transformer to increase its available power

The active power available on the secondary of a transformer is all the higher the greater the power factor of its load.

Consequently, to provide for future extensions, or even when an extension is being added, it is advisable to increase the power factor to avoid having to purchase a new transformer.

■ **example**

A transformer with a power of $S = 630\,kVA$ supplies a load with an active power of $P_1 = 450\,kW$ with an average $\cos j$ equal to 0.8.

Let us determine:

- the apparent power $S_1 = \dfrac{450}{0.8} = 563\,kVA$

- the reactive power $Q_1 = \sqrt{S_1^2 - P_1^2} = 338\,k\text{var}$

The planned extension requires an extra active power of $P_2 = 100\,kW$ with $\cos j = 0.7$. Let us deduce from this the characteristics of this extra power:

- apparent power $S_2 = \dfrac{100}{0.7} = 143\,kVA$

- reactive power $Q_2 = \sqrt{S_2^2 - P_2^2} = 102\,k\text{var}$

Without compensation, the apparent power at the terminals of the transformer would be:

$$S' = \sqrt{(P_1 + P_2)^2 + (Q_1 + Q_2)^2} = 704\,k\text{var}$$

It is higher than the nominal power of the transformer.

Let us determine the minimum power of the capacitors enabling the replacement of the transformer to be avoided.

The total active power to be supplied is:

$$P = P_1 + P_2 = 550\,kW$$

For $P = 550\ kW$, the maximum reactive power that the 630 kVA transformer can supply is:

$$Q_m = \sqrt{S^2 - P^2} = \sqrt{630^2 - 550^2} = 307\ k\text{var}$$

The total reactive power to be supplied to the load before compensation is:

$$Q_1 + Q_2 = 338 + 102 = 440\ k\text{var}$$

The minimum power of the bank to be installed is therefore:

$$Q_C = 440 - 307 = 133\ k\text{var}$$

We thus obtain $\cos j = \frac{P}{S} = \frac{550}{630} = 0.873$

It would be possible to carry out total compensation $(\cos j = 1)$, which would lead to a power reserve of 630 - 550 = 80 kW; the capacitor bank to be installed would thus be 439 kvar. We notice that total compensation would require a considerable amount of capacitors to be installed for little gain on the active power available.

The diagram of powers in figure 7-10 illustrates the calculations carried out.

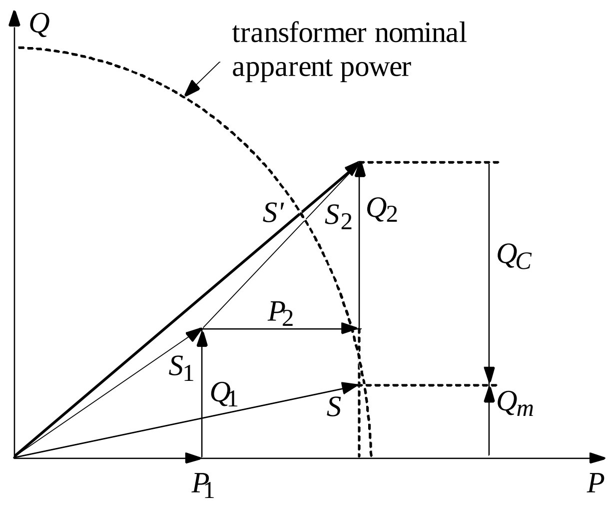


Figure 7-10: diagram of powers for the example

7.8. Compensation of reactive energy absorbed by a transformer alone

A transformer absorbs reactive energy depending on its no-load magnetizing current and the power that flows through it (see § 7.1.8.).

For example, table 7-2 gives the reactive power consumption of 20 kV/400 V liquid-insulated transformers. This is not negligible; it is equal to 6 to 9 % of the transformer power.

This consumption must be added to that of the installation located downstream in order to obtain the required $\cos j$ on the 20 kV side.

In France, for an MV customer with LV metering, EDF takes account of the consumption of reactive energy of the transformer by systematically adding 0.09 to the value of $\tan j$ measured on the LV installation.

The French authority therefore bills reactive energy as soon as the value of $\tan j$ exceeds 0.31 instead of 0.4 for HV metering.

Transformer power (kVA)	Reactive power consumption (kvar)	
	no-load	full-load
100	2.5	6.1
160	3.7	9.6
250	5.3	14.7
315	6.3	18.4
400	7.6	22.9
500	9.5	28.7
630	11.3	35.7
800	20	54.5
1 000	23.9	72.4
1 250	27.4	94.5
1 600	31.9	126.2
2 000	37.8	176

Table 7-2: reactive power consumption of 20 kV/400 V liquid-insulated transformers

7.9. Compensation of asynchronous motors

When a motor is driving a high-inertia load it may, after interruption of the supply voltage, continue to rotate using its kinetic energy and be self-excited by a capacitor bank installed at its terminals. These supply it with the reactive energy necessary for it to operate as an asynchronous generator. This self-excitation causes the voltage to be maintained and sometimes high overvoltages.

■ **connection of capacitors to the motor terminals** (see fig. 7-11)

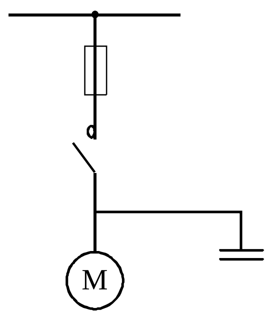


Figure 7-11: connection of capacitors to the motor terminals

To avoid dangerous overvoltages due to the self-excitation phenomenon, it is necessary to make sure that the bank power meets the following relation:

$$Q_C \leq 0.9\sqrt{3}\,U_n\,I_0$$

I_0 : motor no-load current

I_0 may be estimated by the following expression:

$$I_0 = 2\,I_n\left(1 - \cos j_n\right)$$

I_n : nominal current value of the motor
$\cos j_n$: $\cos j$ of the motor at nominal power
U_n : nominal phase-to-phase voltage

Tables 7-3 and 7-4 give the maximum compensation values at the terminals of usual LV and MV motors which avoid dangerous overvoltages by self-excitation.

Maximum compensation of reactive energy (kvar)				
LV motor nominal power (kW)	Number of pairs of poles			
	1	2	3	4
22	6	8	9	10
30	7.5	10	11	12.5
37	9	11	12.5	16
45	11	13	14	17
55	13	17	18	21
75	17	22	25	28
90	20	25	27	30
110	24	29	33	37
132	31	36	38	43
160	35	41	44	52
200	43	47	53	61
250	52	57	63	71
280	57	63	70	79
355	67	76	86	98
400	78	82	97	106
450	87	93	107	117

Table 7-3: maximum compensation of reactive energy (kvar) at the terminals of LV asynchronous motors

Maximum compensation of reactive energy (kvar)				
MV motor nominal power (kW)	Number of pairs of poles			
	1	2	3	4
140	30	35	40	50
160	30	40	50	60
180	40	45	55	65
280	60	70	90	100
355	70	90	100	125
400	80	100	120	140
500	100	125	150	175
1 000	200	250	300	350
1 400	280	350	420	490
1 600	320	400	480	560
2 000	400	500	600	700
2 240	450	560	680	780
3 150	630	800	950	1 100
4 000	800	1 000	1 200	1 400
5 000	1 000	1 250	1 500	1 750

Table 7-4: maximum compensation of reactive energy (kvar) at the terminals of MV asynchronous motors

The maximum compensation value corresponds to no-load motor compensation, which may only represent 50 % of on-load reactive power requirements. Additional compensation may be carried out upstream (global or by-sector compensation) with that of other loads.

Capacitor bank control equipment must be designed so that in the event of the supply source being disconnected, there is no electrical connection between a bank and the motor; this prevents self-excitation by another capacitor bank.

The setting of the motor protection against overloads (thermal overload, thermal relay, etc.) must take into account the reduction of the current value due to compensation.

This arrangement has the advantage of only requiring one switching device.

Important, in the case where there are several banks of this type in the same network, it is advisable to provide inrush current limiting reactors as this arrangement is similar to the case of the "stepped" system (see § 10.6. of the *Protection guide*).

■ **connection of capacitors in parallel with separate control** (see fig. 7-12)

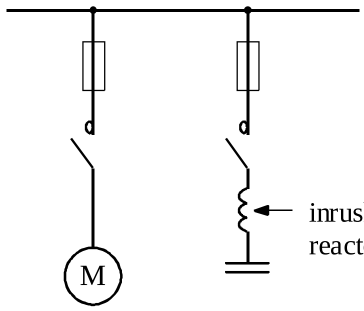


Figure 7-12: connection of capacitors in parallel with separate control

To avoid any risk of dangerous overvoltages caused by self-excitation or in the case where the motor is started with the help of special equipment (resistors, reactors, auto-transformers - see § 3.3.4.1), the capacitors will only be energized after starting.

Similarly, the capacitors must be disconnected before the motor is de-energized.

In this case, the reactive power of the motor on full load can be compensated.

Important: in the case where there are several banks of this type in the same network, it is advisable to provide inrush current limiting reactors as this arrangement is similar to the case of the "stepped" system (see § 10.6. of the *Protection guide*).

7.10. Search for optimum compensation

After having calculated the global reactive power to be installed (see § 7.6.), the optimum places to install the capacitors and the type of capacitor bank (fixed or automatic) must be determined in order to obtain as short a return on investment as possible.

First of all, it is necessary to determine the value of the reactive power and if possible the load curve for different places where the capacitors may be installed. Using these curves, information about the minimum, average and maximum reactive power required at these different places is obtained.

The compensation mode depends on the value of the minimum reactive power consumed by the installation compared with the global power to be installed.

- **case where the minimum reactive power consumed by the installation is greater than the planned compensation power**

Compensation may be global as there is no risk of overcompensating during normal operation, which would cause abnormal rises in voltage.

However, when the installation is stopped, the capacitors must be disconnected so that no steady-state overvoltages are caused on the public distribution network, due to overcompensation.

Indeed, maintaining the capacitors in service, when the installation is stopped, would cause an overvoltage on the public distribution network:

$$\frac{\Delta U}{U_n} = \frac{Q}{S_{sc}}$$

U_n : duty voltage of the public distribution network
Q : capacitor power
S_{sc} : short-circuit power at the connection point of the capacitors

- **case where the minimum reactive power consumed by the installation is lower than the planned compensation power**

When the reactive power consumed is minimum, there would be overcompensation with global compensation which would cause an abnormal rise in voltage. For example, experience has shown that overcompensation at the terminals of a transformer must not exceed 15 % of its nominal power.

To avoid overcompensation, it is possible to:

- install an automatically-controlled stepped capacitor bank which enables the load curve to be respected

- install, at the origin of the installation, compensation equal to the minimum power consumed and locally compensate loads or sectors consuming a large amount of reactive power, as long as capacitor switching is controlled by the load or sector.

- in the case of an installation containing several MV/LV transformers, transfer part of the compensation of a transformer to another transformer.

- **selection criteria**

Compensation may be:

- carried out in MV and/or in LV; it is more economical to install medium voltage capacitors for power greater than roughly 800 kvar.

- global, by sector, individual.

- carried out by fixed bank or automatically-controlled stepped capacitor bank; in the case where the stepped bank is selected, it may be preferable to install sections of different powers in order to obtain better adjustment. For example, with sections of 800, 400, 200 and 100 kvar, it is possible to obtain all powers from 0 to 1 500 kvar in steps of 100 kvar.

To determine the optimum solution, the following criteria must be taken into account:

- avoidance of reactive energy costs or reduction of subscribed power

- reduction of Joule losses in conductors and in transformers

- regular voltage at any point of the installation

- cost of investment, installation and maintenance of every solution.

7.11. Energization of capacitor banks and protections

Energizing capacitor banks causes considerable overcurrents and overvoltages in the network. These pose a problem for capacitor switching devices and for protections (especially in MV).

These problems are studied in paragraph 10.6. of the *Protection guide*.

7.12. Problems relating to capacitors in the presence of harmonics

In the presence of harmonics, installing capacitors is likely to cause an amplification of harmonic currents and voltages and related problems. In this case, it is necessary to carry out an analysis.

These problems are studied in paragraph 8.

CHAPTER 7 BIBLIOGRAPHY

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- □ **LV application guide: power factor correction and harmonic filtering**, **Rectiphase**, ref. CG0064E
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