

# R.8/9

**Power factor correction  
and harmonic filtering**



**MV capacitors banks and accessories**

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## Medium Voltage Compensation

MV Power factor correction is directly related to the different aspects that assist the technical management of transport and distribution networks. These are:

- **Power quality.** This involves the increase in the levels of voltage in substation busbars and line ends.

- **Optimisation of the installation's cost of operation.** In other words, the decrease of the reactive energy and, therefore, the reduction of apparent power entail two aspects of a strong technical relevance:

- Reduction of losses
- Increase in the performance of transformers and installations

- **Reduction of the economic cost of energy.**

An in-depth description of each point is provided in the following sections.

### Supply quality, voltage level

There are two cases: control of voltage in MV substation busbars and line ends.

- ▶ **Control of voltage in substation busbars**

One of the critical points in the distribution of electrical energy is maintaining voltage in line ends. Distribution companies usually maintain the MV levels above its nominal value.

Therefore, MV capacitor banks are used. In fact, the connection of capacitor banks has an associated increase in voltage in the connection points.

The **IEC 60871-1** Standard facilitates the expression to calculate the increase in voltage produced after the connection of capacitors (See table below), depending on the characteristics of the network where the capacitor bank is connected.

The power, type of unit and level of division depend on the criteria used by distribution Companies.

However, the division of total power in different steps can be used to improve the levels of voltage under different substation load conditions, avoiding an excess capacitive power in the network.

- ▶ **Control of voltage in line ends**

In the case of very long MV lines, the voltage in branch points might be decreased by the effects of the conductor cable. This is quite important in areas with a rural overhead distribution or with a high level of dispersion of consumers.

The connection of capacitor banks at the end of a line allows a decrease of voltage drops at the line end, as well as the reduction in the level of cable losses.

### Optimisation of the installation's cost of operation

The generation, transmission and distribution of energy entails an important amount of energy losses

In general, these losses are divided in the following:

- Generation losses and substations
- Losses in the transmission system
- Losses in MV/HV substations
- Losses in the distribution lines

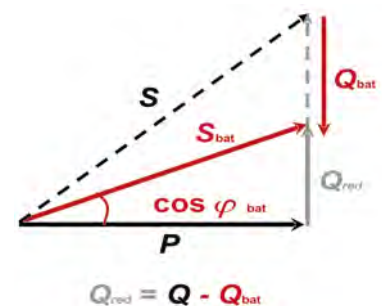


Comprehensive information about the losses in the MV distribution lines is shown next.

### Reduction of losses in MV lines.

Capacitor banks can be installed to decrease the level of losses in a MV distribution line.

In fact, the installation of the capacitor will produce a direct reduction of the reactive energy ( $Q$  network) and apparent energy requested from the system.



Therefore, in accordance with the direct relationship between current power values, the value of Joule effect losses will decrease.

The following table shows the expressions required for the calculation of Joule effect losses, the reactive energy consumption of the cable and decrease in the losses when a capacitor bank is connected.

Increase of the voltage when a capacitor bank is connected **IEC 60871-1**

$$\Delta U(\%) = \frac{Q_{\text{bat}}}{S_{\text{cc}}} \cdot 100$$

Line voltage drops

$$U(\%) = \frac{P \cdot L}{10 \cdot U^2} \cdot (R_1 + X_1 \tan \varphi)$$

Joule effect losses in a line

$$P(\text{kW}) = 3 \cdot R_1 \cdot I^2 \cdot L$$

Reactive energy consumption in a line

$$Q(\text{kvar}) = 3 \cdot X_1 \cdot I^2 \cdot L$$

Reduced losses after the connection of a capacitor bank

$$\Delta P = R_1 \cdot \frac{P^2 + (Q - Q_{\text{bat}})^2}{U^2} \cdot L$$

Units used to understand the calculation expressions:

$P$	active power transmitted by the line in kW
$Q$	reactive energy absorbed without capacitor banks
$Q_{\text{bank}}$	power of the capacitor bank in MV-A
$I$	current
$U$	Network voltage in kV
$R_1$	resistance of the cable in $\Omega/\text{km}$
$X_1$	reactor of the cable in $\Omega/\text{km}$
$L$	length of the line in km
$S_{\text{cc}}$	short-circuit power in the connection point in MV-A.

This point is important when making the economic assessment of the performance of an installation, since there is an added "hidden cost" to the payment for reactive energy consumption, which is represented by the active energy dissipated during distribution.

### Line and cable discharge

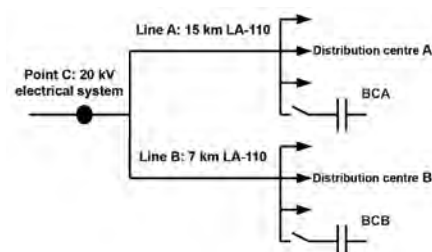
The decrease in apparent power after the connection of a capacitor bank entails two immediate consequences:

- Decrease of the load transmitted through cables
- Increase of the supply capacity of transformers
- Increase of the voltage at the end of the line

### Example of a reduction of Joule effect losses in an overhead distribution line system.

In this case, the evolution of the line losses and voltage drops is analysed in a distribution system rated at 20 kV with no capacitor banks connected.

The effect of capacitor banks in a MV overhead distribution line in a rural area is compared between banks, where there are two distribution centres, A and B.



### State of loads with no capacitor banks connected

The system's power situation is shown on the following table:

The connection conditions in the connection point with electrical system C are not very good, i.e., the apparent power volume is high and the power factor is low.

	C Connection point	A Distribution Centre	B Distribution Centre
Active power (MW)	7,39	2,7	4,39
Reactive energy (Mvar)	3,70	1,23	2,13
Apparent power (MV-A)	8,26	2,97	4,88
cos $\varphi$	0,89	0,91	0,9
Joule effect losses (kW)	-	114,5	185
reactive consumed by the line (kvar)	-	129	208
Voltage drops (%)	-	5,2	5,25

**Situation with connected capacitor banks**

A 1,100 kvar capacitor bank at 20 kV is connected to distribution centre A (BCA) and a 2,000 kvar capacitor bank at 20 kV is connected to distribution centre B (BCB) to improve the network conditions.

The balance of power is modified, as shown on the following table:

	C Connection point	A Distribution Centre with BCA	B Distribution Centre with BCB
Active power (MW)	7,33	2,7	4,39
Reactive energy (Mvar)	0,54	0,13	0,13
Apparent power (MV·A)	7,36	2,7	4,39
cos φ	0,99	0,99	0,99
Joule effect losses (kW)	-	94	150
Reactive consumed by the line (kvar)	-	106	170
Voltage drops (%)	-	3,9	3,8
Active power savings (kW)	-	20	35

In this case, the conditions in C have been substantially optimised. In addition, losses have decreased throughout the lines and the levels of voltage have increased in the distribution centres.

Therefore, the operation and performance of the line has been optimised and the level of voltage is guaranteed for users.

**Conclusions**

Capacitor banks are vital for the adequate technical and economic management of the electrical system, optimising its operation.

**Technical optimisation**

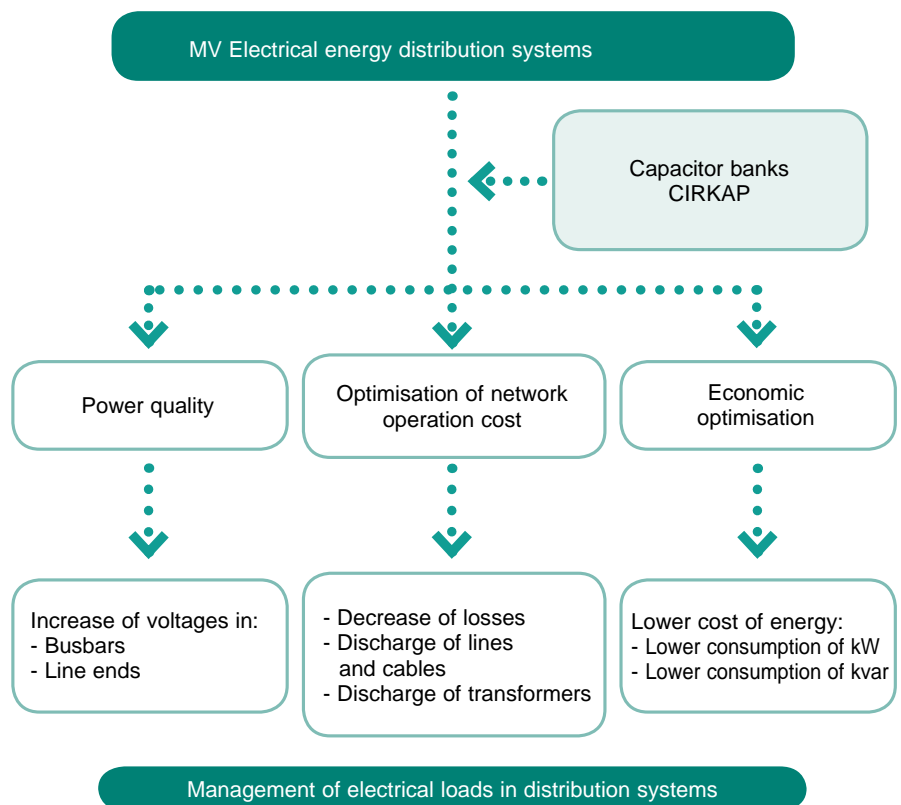
- Helping control voltage throughout the transmission and distribution system
- Discharging lines and transformers
- Reduction of the level of losses throughout the system

**Economic optimisation**

Reduction of the cost of energy with the decrease of the reactive energy consumed

Reduction of the hidden cost of losses in transmission and distribution lines

More efficient optimisation of installations



## Where to compensate in MV

### Electrical energy generation, transmission and distribution

Reactive energy transmission and distribution throughout the electrical system is noteworthy, as stated above. Therefore, the reactive energy must be compensated in determined points of the electrical network. These are:

- Generation stations: Such as low-powered hydroelectric power plants and wind farms
- Receiving / distribution substations. (for example, reception 400 kV, distribution at 20 kV)
- Distribution centres

### Industrial installations with MV distribution and consumption

In general, the installations that distribute and consume MV are likely to be compensated.

For example:

- Pumping stations
- Mining
- Industry: cement, chemical, steel, etc.

There are transformers, asynchronous motors or electric arc equipment in all of these industries, which are large reactive energy consumers.

### MV distribution and LV consuming installations

In MV receiving installations with a distribution and consumption of LV, the compensation must always be carried out in Low Voltage. The reasons are:

- Low power is cheaper in LV
- More accurate regulation

However, when there is a high number of LV / MV transformers, we recommend the installation of LV regulated capacitor banks and a fixed MV section.

## Components for MV capacitor banks

### CHV Capacitors



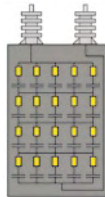
### Configuration of capacitors

#### ► Single-phase

Capacitor with two terminals. Capacitor bank installation in a star or double star arrangement. Common in networks with a power rating that exceeds 11 kV or in capacitor banks with lower voltages and higher power levels.

#### ► Three-phase

Capacitor with three terminals. Installation in low and medium-powered capacitor banks in networks with a power rating of up to 11 kV.



### Capacitor composition

The CHV Medium Voltage capacitors are composed of different basic capacitive elements. These basic units are connected in groups in series and in parallel with the purpose of achieving the power and voltage levels required.

After assembling the set of elements, the set is introduced in a stainless steel box, adding the porcelain terminals and impregnating the elements in oil (biodegradable), guaranteeing the unit's perfect insulation and operation.

## Insulation levels (BIL)

Maximum voltage supported by the material in two cases, in accordance with the IEC Standard:

- **At the industrial frequency during 1 minute.** Verification of the insulation of the unit, simulating a high network voltage ( $kV_{ef}$ )
- **Impulse, ray-type** (shockwave) 1.2 / 50  $\mu s$ . Verification of the insulation of the unit, simulating a ray discharge ( $kV_{peak}$ )

In the case of three-phase capacitors, the degree of insulation corresponds to that immediately above its nominal voltage.

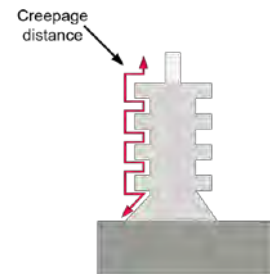
**Example:** Three-phase capacitor CHV-T 300 kvar, 6.6 kV. Level of insulation 7.2 kV

In single-phase capacitors, the selection criteria is different to that of three-phase capacitors. The levels of insulation correspond to the same levels of the network when it is connected to the capacitor bank in equipment that is not insulated from earth (IEC 60.671-1).

**Example:** Capacitor bank, 3 Mvar at 20 kV. Composed of 6 units, 500 kvar, 11.56 kV. Level of insulation of capacitors 24 kV, (50/125 kV)

### Leakage lines

Capacitor insulator flash-over perimeter. Directly related to the levels of pollution.



Insulation level (kV)	Voltage at industrial frequency ( $kV_{ef}$ )	Shockwave ( $kV_{peak}$ )	Leakage lines (mm)
7,2	20	60	190
12	28	75	190
17,5	38	95	300
24	50	125	435
36	70	170	600

Table 1

### Pollution levels

The pollution level defines the environmental contamination existing in the place where equipment is installed. Therefore, to avoid insulation defects as a consequence of flash-over, the greater the degree of environmental pollution, the greater the leakage of insulators.

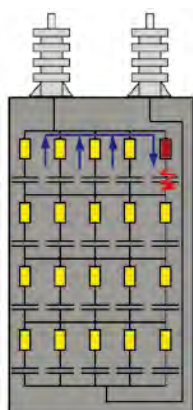
It is expressed in mm / kV. In other words, the relationship between the insulator leakage line and network voltage. The pollution levels defined are shown on the following table:

Classification	Pollution level
Low	16 mm/kV
Medium	20 mm/kV
High	25 mm/kV
Very high	31 mm/kV

### Protection of capacitors with internal fuses

The capacitor, as any element in an electrical installation, must be capable of eliminating the defects that can be caused inside. To do so, all basic capacitive elements of the capacitor are protected with an internal fuse.

In case of a defect in a basic capacitive element, the healthy elements will be discharged in parallel to the faulty element. The discharge will immediately melt the internal fuse of the damaged unit. This system has a series of advantages that are classified in two groups:



### Operational advantages

- Immediate disconnection of the damaged element
- Minimum generation of gases inside the capacitor, therefore, a very low internal overpressure effect
- Continuity of the service. The removal of the damaged unit means that the unit can remain connected. Optional planning of the capacitor bank's maintenance
- Simpler maintenance

### Design advantages

- Increase capacitor power
- Use of less capacitors in each capacitor bank
- Reduction of the size of frames or cabinet
- Cheaper capacitor banks

## MV Capacitor banks

### Configuration of capacitor banks

The use of different configurations is common in MV capacitor banks. These depend on the type of capacitor used and, above all, on the installation's electrical parameters.

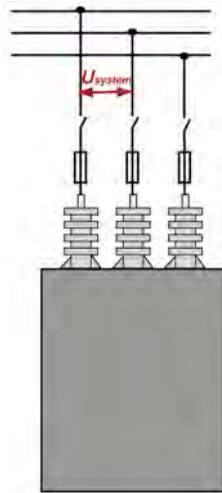
### Capacitor banks, three-phase capacitors

These units are useful in industrial installations, since they are capable of hosting low and medium-powered applications in small dimensions.

The maximum service voltage is 11 kV and the maximum power is 1.4 Mvar.

The most common applications are:

- Compensation of motors
- Compensation of transformers
- Automatic capacitor banks



### Capacitor banks with single-phase capacitors connected in a double-star arrangement

This is the most common configuration in medium and large-powered applications.

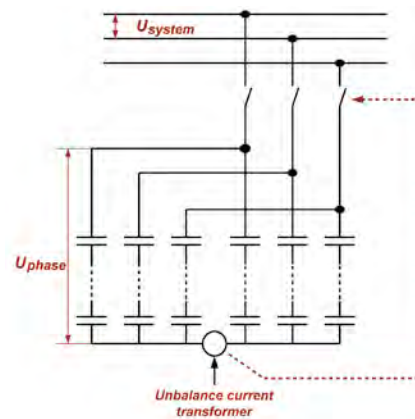
The double-star is formed by two stars joined by a common neutral.

A current transformer is connected to the neutral to detect the default currents of capacitors.

This arrangement of capacitors can be used to operate the unit, whatever the power and voltage levels required, based on the use of standard capacitors.

In fact, the capacitor or group of capacitors in each branch will have an applied voltage corresponding to the phase voltage, as seen on the figure.

After defining the voltage of each capacitor and, therefore, the number of units, so the power of each capacitor is defined.



$$Q_{\text{capacitor}} = \frac{Q_{\text{bank}}}{\text{Number of capacitor}} :$$

This configuration is used in the following cases:

- Networks with service voltages exceeding 11 kV
- Networks with voltages under 11 kV and power levels above 1.6 Mvar

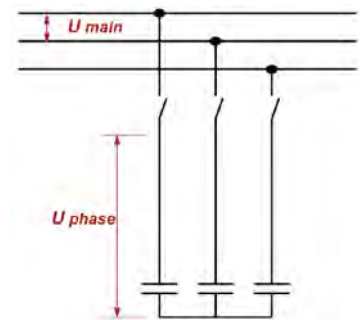
### Capacitor banks with single-phase capacitors connected in a star arrangement

The application of this configuration is limited to low-powered capacitor banks, which can not be resolved with three-phase capacitors due to the working voltage.

A practical case is, for example, a 450 kvar capacitor bank at 15 kv.

This case will be resolved with 3 capacitors, with a nominal voltage of 150 kvar at 8.67 kVl.

The level of insulation of capacitors corresponds to that of the network, i.e., 17.5 kV.



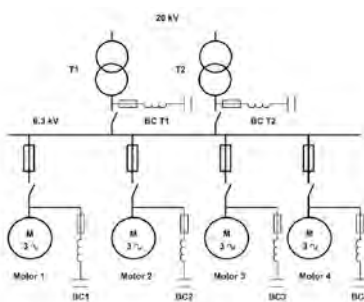
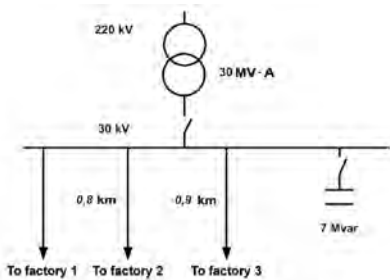
### Compensation method

The compensation method in MV installations is carried out with a fixed or automatic system, as in LV installations. It depends on the type of installation, its configuration, the load ratio, as well as the purpose for which the unit was installed.

### Fixed compensation

When the reactive energy levels are high and an important portion of these levels is more or less constant, a fixed compensation unit is installed. This is common in installations with a connection to High Voltage networks and Medium Voltage distribution.

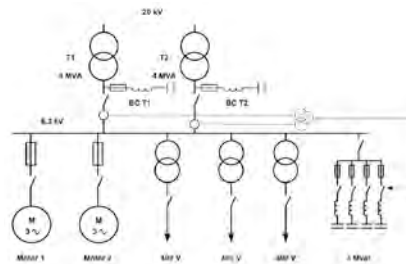
Another application is in industrial installations with a reduced number of receivers and where the operating ratios do not require the machines to interrupt their operation simultaneously.



### Automatic compensation

The installation of a unit that can follow the fluctuations is required in installations with large variations in load.

An example is the distribution branch of an industry at 6.3 kV with MV loads and LV transformers, as shown on the figure.



### Protection of capacitor banks

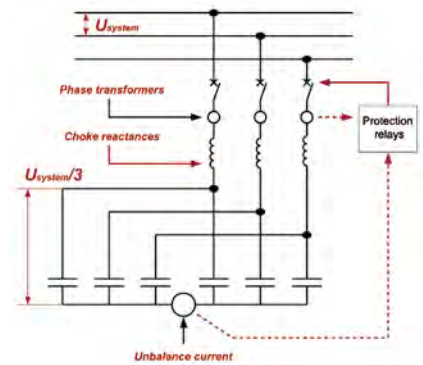
In general, capacitor bank protection systems are divided in external and internal protections.

### Internal protection

Internal protection systems protect units against defects inside capacitors. This type of protection is guaranteed by internal fuses. In capacitor banks configured in a double star arrangement, this is combined with an unbalanced protection. This system is composed of a current transformer and an associated relay.

In case of an internal fault in one of the capacitors, an unbalanced current will flow through the capacitor.

This current is detected by the current transformer. The associated relay will send an order to disconnect the switching and/or protection unit.



### External protection

The protection systems used in capacitor banks depend on the configuration of the bank and its application.

### General component design criteria

In accordance with the IEC 60871-1 Standard, capacitors are designed to support a 30% overload of permanent current.

Therefore, the Standard recommends that the components in the capacitor bank support a maximum of 1.43 times the nominal current. This criterion is applicable to the following:

- Power cables
- General devices
- Choke REACTORS

CAPACITOR BANKS WITH THREE-PHASE CAPACITORS	CAPACITOR BANKS WITH A DOUBLE-START ARRANGEMENT
Nominal voltages ≤ 11 kV Capacitor bank power ≤ 1.4 Mvar	Nominal voltages > 11 kV Capacitor bank power > 1.4 Mvar
<p><b>Fixed for motor:</b> High rupture power fuses (HRP) with meltdown indication.</p> <p><b>Automatic:</b> HRP fuses combined with a contactor</p>	<p>Automatic switch, with the following protection elements:</p> <ul style="list-style-type: none"> <li>• Overload and short-circuit</li> <li>• Homopolar</li> <li>• Unbalance</li> </ul> <p>Notes:</p> <ul style="list-style-type: none"> <li>• Overload protection is recommended in busbars.</li> <li>• The protection system can be installed on the same capacitor bank or in the centre of MV cabinet</li> </ul>

































