Chapter L
Power factor correction and harmonic filtering

Contents

1 Reactive energy and power factor

Alternating current systems supply two forms of energy:
- "Active" energy measured in kilowatt hours (kWh) which is converted into mechanical work, heat, light, etc
- "Reactive" energy, which again takes two forms:
  - "Reactive" energy required by inductive circuits (transformers, motors, etc.),
  - "Reactive" energy supplied by capacitive circuits (cable capacitance, power capacitors, etc)

1.1 The nature of reactive energy

All inductive (i.e. electromagnetic) machines and devices that operate on AC systems convert electrical energy from the power system generators into mechanical work and heat. This energy is measured by kWh meters, and is referred to as "active" or "wattful" energy. In order to perform this conversion, magnetic fields have to be established in the machines, and these fields are associated with another form of energy to be supplied from the power system, known as "reactive" or "wattless" energy.

The reason for this is that inductive circuit cyclically absorbs energy from the system (during the build-up of the magnetic fields) and re-injects that energy into the system (during the collapse of the magnetic fields) twice in every power-frequency cycle.

An exactly similar phenomenon occurs with shunt capacitive elements in a power system, such as cable capacitance or banks of power capacitors, etc. In this case, energy is stored electrostatically. The cyclic charging and discharging of capacitive circuit reacts on the generators of the system in the same manner as that described above for inductive circuit, but the current flow to and from capacitive circuit in exact phase opposition to that of the inductive circuit. This feature is the basis on which power factor correction schemes depend.

It should be noted that while this "wattless" current (more accurately, the "wattless" component of a load current) does not draw power from the system, it does cause power losses in transmission and distribution systems by heating the conductors.

In practical power systems, "wattless" components of load currents are invariably inductive, while the impedances of transmission and distribution systems are predominantly inductively reactive. The combination of inductive current passing through an inductive reactance produces the worst possible conditions of voltage drop (i.e. in direct phase opposition to the system voltage).

For these reasons (transmission power losses and voltage drop), the power-supply authorities reduce the amount of "wattless" (inductive) current as much as possible.

"Wattless" (capacitive) currents have the reverse effect on voltage levels and produce voltage-rises in power systems.

The power (kW) associated with "active" energy is usually represented by the letter P.

The reactive power (kvar) is represented by Q. Inductively-reactive power is conventionally positive (+ Q) while capacitively-reactive power is shown as a negative quantity (- Q).

The apparent power S (kVA) is a combination of P and Q (see **Fig. L1**).

Sub-clause 1.3 shows the relationship between P, Q, and S.

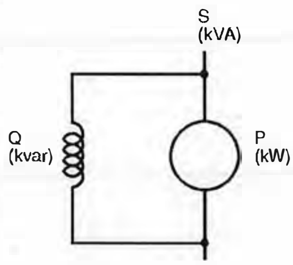


Fig. L1 : An electric motor requires active power P and reactive power Q from the power system

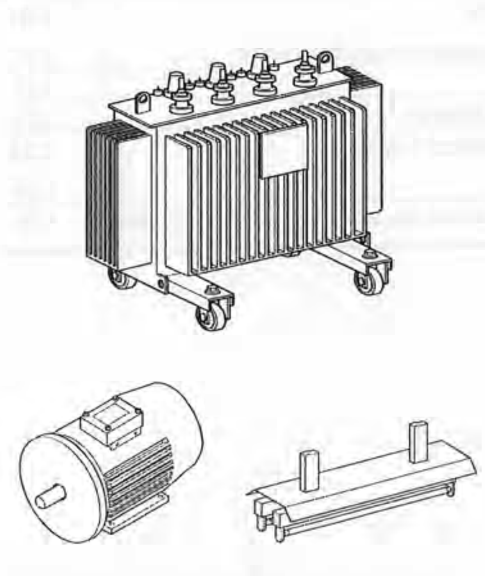


Fig. L2 : Power consuming items that also require reactive energy

1.2 Equipement and appliances requiring reactive energy

All AC equipement and appliances that include electromagnetic devices, or depend on magnetically-coupled windings, require some degree of reactive current to create magnetic flux.

The most common items in this class are transformers and reactors, motors and discharge lamps (with magnetic ballasts) (see **Fig. L2**).

The proportion of reactive power (kvar) with respect to active power (kW) when an item of equipement is fully loaded varies according to the item concerned being:
- 65-75% for asynchronous motors
- 5-10% for transformers

1 Reactive energy and power factor

The power factor is the ratio of kW to kVA. The closer the power factor approaches its maximum possible value of 1, the greater the benefit to consumer and supplier.
PF = P (kW) / S (kVA)
P = Active power
S = Apparent power

1.3 The power factor

Definition of power factor

The power factor of a load, which may be a single power-consuming item, or a number of items (for example an entire installation), is given by the ratio of P/S i.e. kW divided by kVA at any given moment.

The value of a power factor will range from 0 to 1.

If currents and voltages are perfectly sinusoidal signals, power factor equals cos φ.

A power factor close to unity means that the reactive energy is small compared with the active energy, while a low value of power factor indicates the opposite condition.

Power vector diagram

- Active power P (in kW)
  - Single phase (1 phase and neutral): $P = V\ I \cos\varphi$
  - Single phase (phase to phase): $P = U\ I \cos\varphi$
  - Three phase (3 wires or 3 wires + neutral): $P = \sqrt{3}\,U\ I \cos\varphi$
- Reactive power Q (in kvar)
  - Single phase (1 phase and neutral): $P = V\ I \sin\varphi$
  - Single phase (phase to phase): $Q = U\ I \sin\varphi$
  - Three phase (3 wires or 3 wires + neutral): $P = \sqrt{3}\ U\ I \sin\varphi$
- Apparent power S (in kVA)
  - Single phase (1 phase and neutral): $S = V\ I$
  - Single phase (phase to phase): $S = U\ I$
  - Three phase (3 wires or 3 wires + neutral): $P = \sqrt{3}\ U\ I$

where:
V = Voltage between phase and neutral
U = Voltage between phases
I = Line current
φ = Phase angle between vectors V and I.
- For balanced and near-balanced loads on 4-wire systems

Current and voltage vectors, and derivation of the power diagram

The power "vector" diagram is a useful artifice, derived directly from the true rotating vector diagram of currents and voltage, as follows:

The power-system voltages are taken as the reference quantities, and one phase only is considered on the assumption of balanced 3-phase loading.

The reference phase voltage (V) is co-incident with the horizontal axis, and the current (I) of that phase will, for practically all power-system loads, lag the voltage by an angle φ.

The component of I which is in phase with V is the "wattful" component of I and is equal to I cos φ, while VI cos φ equals the active power (in kW) in the circuit, if V is expressed in kV.

The component of I which lags 90 degrees behind V is the wattless component of I and is equal to I sin φ, while VI sin φ equals the reactive power (in kvar) in the circuit, if V is expressed in kV.

If the vector I is multiplied by V, expressed in kV, then VI equals the apparent power (in kVA) for the circuit.

The simple formula is obtained: $S^2 = P^2 + Q^2$

The above kW, kvar and kVA values per phase, when multiplied by 3, can therefore conveniently represent the relationships of kVA, kW, kvar and power factor for a total 3-phase load, as shown in **Figure L3** .

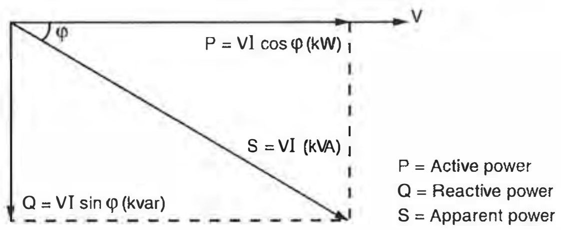


Fig. L3 : Power diagram

L3

An example of power calculations (see **Fig.** L4)

Type of circuit		Apparent power S (kVA)	Active power P (kW)	Reactive power Q (kvar)
Single-phase (phase and neutral)		S = VI	P = VI cos φ	Q = VI sin φ
Single-phase (phase to phase)		S = UI	P = UI cos φ	Q = UI sin φ
Example	5 kW of load cos φ = 0.5	10 kVA	5 kW	8.7 kvar
Three phase 3-wires or 3-wires + neutral		S = √3 UI	P = √3 UI cos φ	Q = √3 UI sin φ
Example	Motor Pn = 51 kW cos φ = 0.86 ρ = 0.91 (motor efficiency)	65 kVA	56 kW	33 kvar

Fig. L4 : Example in the calculation of active and reactive power

1.4 Practical values of power factor

The calculations for the three-phase example above are as follows:
Pn = delivered shaft power = 51 kW
P = active power consumed

$$P = \frac{Pn}{\rho} = \frac{51}{0.91} = 56 \text{ kW}$$

S = apparent power

$$S = \frac{P}{\cos\varphi} = \frac{56}{0.86} = 65 \text{ kVA}$$

So that, on referring to diagram **Figure L5** or using a pocket calculator, the value of tan φ corresponding to a cos φ of 0.86 is found to be 0.59
Q = P tan φ = 56 x 0.59 = 33 kvar (see Figure L15).
Alternatively

$$Q = \sqrt{S^2 - P^2} = \sqrt{65^2 - 56^2} = 33 \text{ kvar}$$

Average power factor values for the most commonly-used equipment and appliances (see **Fig.** L6)

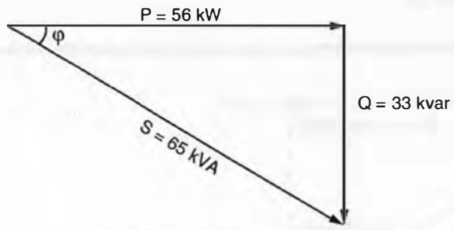


Fig. L5 : Calculation power diagram

Equipment and appliances			cos φ	tan φ
■ Common induction 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
■ Incandescent lamps			1.0	0
■ Fluorescent lamps (uncompensated)			0.5	1.73
■ Fluorescent lamps (compensated)			0.93	0.39
■ Discharge lamps			0.4 to 0.6	2.29 to 1.33
■ Ovens using resistance elements			1.0	0
■ Induction heating ovens (compensated)			0.85	0.62
■ Dielectric type heating ovens			0.85	0.62
■ Resistance-type soldering machines			0.8 to 0.9	0.75 to 0.48
■ Fixed 1-phase arc-welding set			0.5	1.73
■ Arc-welding motor-generating set			0.7 to 0.9	1.02 to 0.48
■ Arc-welding transformer-rectifier set			0.7 to 0.8	1.02 to 0.75
■ Arc furnace			0.8	0.75

Fig. L6 : Values of cos φ and tan φ for commonly-used equipment

2 Why to improve the power factor?

An improvement of the power factor of an installation presents several technical and economic advantages, notably in the reduction of electricity bills

2.1 Reduction in the cost of electricity

Good management in the consumption of reactive energy brings economic advantages.

These notes are based on an actual tariff structure commonly applied in Europe, designed to encourage consumers to minimize their consumption of reactive energy.

The installation of power-factor correction capacitors on installations permits the consumer to reduce his electricity bill by maintaining the level of reactive-power consumption below a value contractually agreed with the power supply authority. In this particular tariff, reactive energy is billed according to the tan φ criterion. As previously noted:

$$\tan \varphi = \frac{Q\ (\text{kvarh})}{P\ (\text{kWh})}$$

The power supply authority delivers reactive energy for free:

■ If the reactive energy represents less than 40% of the active energy ($\tan \varphi < 0.4$) for a maximum period of 16 hours each day (from 06-00 h to 22-00 h) during the most-heavily loaded period (often in winter)

■ Without limitation during light-load periods in winter, and in spring and summer.

During the periods of limitation, reactive energy consumption exceeding 40% of the active energy (i.e. $\tan \varphi > 0.4$) is billed monthly at the current rates. Thus, the quantity of reactive energy billed in these periods will be:

kvarh (to be billed) = kWh ($\tan \varphi > 0.4$) where:

□ kWh is the active energy consumed during the periods of limitation

□ kWh tan φ is the total reactive energy during a period of limitation

□ 0.4 kWh is the amount of reactive energy delivered free during a period of limitation

$\tan \varphi = 0.4$ corresponds to a power factor of 0.93 so that, if steps are taken to ensure that during the limitation periods the power factor never falls below 0.93, the consumer will have nothing to pay for the reactive power consumed.

Against the financial advantages of reduced billing, the consumer must balance the cost of purchasing, installing and maintaining the power factor improvement capacitors and controlling switchgear, automatic control equipment (where stepped levels of compensation are required) together with the additional kWh consumed by the dielectric losses of the capacitors, etc. It may be found that it is more economic to provide partial compensation only, and that paying for some of the reactive energy consumed is less expensive than providing 100% compensation.

The question of power-factor correction is a matter of optimization, except in very simple cases.

Power factor improvement allows the use of smaller transformers, switchgear and cables, etc. as well as reducing power losses and voltage drop in an installation

2.2 Technical/economic optimization

A high power factor allows the optimization of the components of an installation. Overating of certain equipment can be avoided, but to achieve the best results, the correction should be effected as close to the individual inductive items as possible.

Reduction of cable size

Figure L7 shows the required increase in the size of cables as the power factor is reduced from unity to 0.4, for the same active power transmitted.

Multiplying factor for the cross-sectional area of the cable core(s)	1	1.25	1.67	2.5
cos φ	1	0.8	0.6	0.4

Fig. L7 : Multiplying factor for cable size as a function of cos φ

2 Why to improve the power factor?

Reduction of losses (P, kW) in cables

Losses in cables are proportional to the current squared, and are measured by the kWh meter of the installation. Reduction of the total current in a conductor by 10% for example, will reduce the losses by almost 20%.

Reduction of voltage drop

Power factor correction capacitors reduce or even cancel completely the (inductive) reactive current in upstream conductors, thereby reducing or eliminating voltage drops.

Note: Over compensation will produce a voltage rise at the capacitor level.

Increase in available power

By improving the power factor of a load supplied from a transformer, the current through the transformer will be reduced, thereby allowing more load to be added. In practice, it may be less expensive to improve the power factor [1], than to replace the transformer by a larger unit.

This matter is further elaborated in clause 6.

(1) Since other benefits are obtained from a high value of power factor, as previously noted.

3 How to improve the power factor?

Improving the power factor of an installation requires a bank of capacitors which acts as a source of reactive energy. This arrangement is said to provide reactive energy compensation

3.1 Theoretical principles

An inductive load having a low power factor requires the generators and transmission/distribution systems to pass reactive current (lagging the system voltage by 90 degrees) with associated power losses and exaggerated voltage drops, as noted in sub-clause 1.1. If a bank of shunt capacitors is added to the load, its (capacitive) reactive current will take the same path through the power system as that of the load reactive current. Since, as pointed out in sub-clause 1.1, this capacitive current Ic (which leads the system voltage by 90 degrees) is in direct phase opposition to the load reactive current (IL), the two components flowing through the same path will cancel each other, such that if the capacitor bank is sufficiently large and Ic = IL there will be no reactive current flow in the system upstream of the capacitors.

This is indicated in **Figure L8** (**a**) and (**b**) which show the flow of the reactive components of current only.

In this figure:

R represents the active-power elements of the load

L represents the (inductive) reactive-power elements of the load

C represents the (capacitive) reactive-power elements of the power-factor correction equipment (i.e. capacitors).

It will be seen from diagram (**b**) of **Figure L9**, that the capacitor bank C appears to be supplying all the reactive current of the load. For this reason, capacitors are sometimes referred to as "generators of lagging vars".

In diagram (**c**) of Figure L9, the active-power current component has been added, and shows that the (fully-compensated) load appears to the power system as having a power factor of 1.

In general, it is not economical to fully compensate an installation.

Figure L9 uses the power diagram discussed in sub-clause 1.3 (see Fig. L3) to illustrate the principle of compensation by reducing a large reactive power Q to a smaller value Q' by means of a bank of capacitors having a reactive power Qc. In doing so, the magnitude of the apparent power S is seen to reduce to S'.

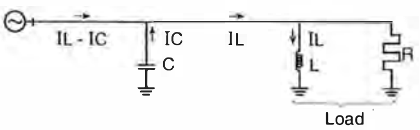
Example:

A motor consumes 100 kW at a power factor of 0.75 (i.e. tan φ = 0.88). To improve the power factor to 0.93 (i.e. tan φ = 0.4), the reactive power of the capacitor bank must be : Qc = 100 (0.88 - 0.4) = 48 kvar

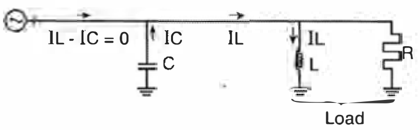
The selected level of compensation and the calculation of rating for the capacitor bank depend on the particular installation. The factors requiring attention are explained in a general way in clause 5, and in clauses 6 and 7 for transformers and motors.

Note: Before starting a compensation project, a number of precautions should be observed. In particular, oversizing of motors should be avoided, as well as the no-load running of motors. In this latter condition, the reactive energy consumed by a motor results in a very low power factor (≈ 0.17); this is because the kW taken by the motor (when it is unloaded) are very small.

a) Reactive current components only flow pattern



b) When IC = IL, all reactive power is supplied from the capacitor bank



c) With load current added to case (**b**)

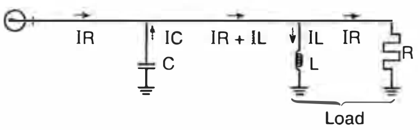


***Fig. L8** : Showing the essential features of power-factor correction*

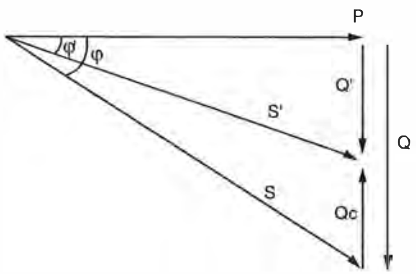


***Fig. L9** : Diagram showing the principle of compensation: Qc = P (tan φ - tan φ')*

3.2 By using what equipment?

Compensation at LV

At low voltage, compensation is provided by:

- Fixed-value capacitor
- Equipment providing automatic regulation, or banks which allow continuous adjustment according to requirements, as loading of the installation changes

Note: When the installed reactive power of compensation exceeds 800 kvar, and the load is continuous and stable, it is often found to be economically advantageous to instal capacitor banks at the medium voltage level.

Compensation can be carried out by a fixed value of capacitance in favourable circumstances

Fixed capacitors (see Fig. L10)

This arrangement employs one or more capacitor(s) to form a constant level of compensation. Control may be:

- Manual: by circuit-breaker or load-break switch
- Semi-automatic: by contactor
- Direct connection to an appliance and switched with it

These capacitors are applied:

- At the terminals of inductive devices (motors and transformers)
- At busbars supplying numerous small motors and inductive appliance for which individual compensation would be too costly
- In cases where the level of load is reasonably constant

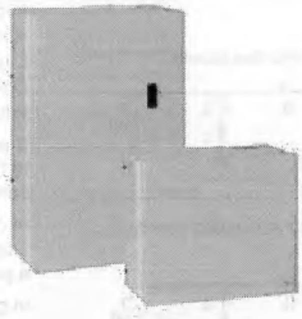


Fig. L10 : Example of fixed-value compensation capacitors

Compensation is more-commonly effected by means of an automatically-controlled stepped bank of capacitors

Automatic capacitor banks (see Fig. L11)

This kind of equipment provides automatic control of compensation, maintaining the power factor within close limits around a selected level. Such equipment is applied at points in an installation where the active-power and/or reactive-power variations are relatively large, for example:

- At the busbars of a general power distribution board
- At the terminals of a heavily-loaded feeder cable

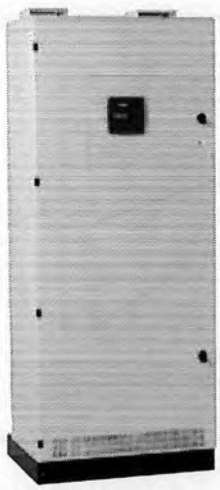


Fig. L11 : Example of automatic-compensation-regulating equipment

Automatically-regulated banks of capacitors allow an immediate adaptation of compensation to match the level of load

The principles of, and reasons, for using automatic compensation

A bank of capacitors is divided into a number of sections, each of which is controlled by a contactor. Closure of a contactor switches its section into parallel operation with other sections already in service. The size of the bank can therefore be increased or decreased in steps, by the closure and opening of the controlling contactors.

A control relay monitors the power factor of the controlled circuit(s) and is arranged to close and open appropriate contactors to maintain a reasonably constant system power factor (within the tolerance imposed by the size of each step of compensation). The current transformer for the monitoring relay must evidently be placed on one phase of the incoming cable which supplies the circuit(s) being controlled, as shown in **Figure L12**.

A Varset Fast capacitor bank is an automatic power factor correction equipment including static contactors (thyristors) instead of usual contactors. Static correction is particularly suitable for a certain number of installations using equipment with fast cycle and/or sensitive to transient surges.

The advantages of static contactors are :

- Immediate response to all power factor fluctuation (response time 2 s or 40 ms according to regulator option)
- Unlimited number of operations
- Elimination of transient phenomena on the network on capacitor switching
- Fully silent operation

By closely matching compensation to that required by the load, the possibility of producing overvoltages at times of low load will be avoided, thereby preventing an overvoltage condition, and possible damage to appliances and equipment. Overvoltages due to excessive reactive compensation depend partly on the value of source impedance.

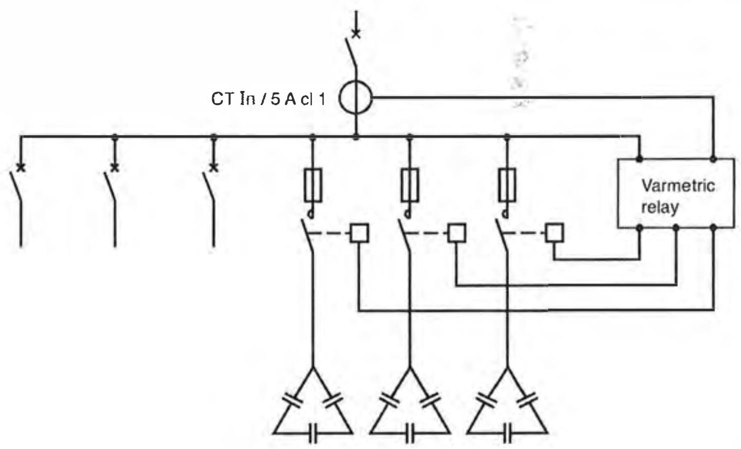


Fig. L12 : The principle of automatic-compensation control

3.3 The choice between a fixed or automatically-regulated bank of capacitors

Commonly-applied rules

Where the kvar rating of the capacitors is less than, or equal to 15% of the supply transformer rating, a fixed value of compensation is appropriate. Above the 15% level, it is advisable to install an automatically-controlled bank of capacitors.
The location of low-voltage capacitors in an installation constitutes the mode of compensation, which may be global (one location for the entire installation), partial (section-by-section), local (at each individual device), or some combination of the latter two. In principle, the ideal compensation is applied at a point of consumption and at the level required at any instant.

In practice, technical and economic factors govern the choice.

4 Where to install correction capacitors?

Where a load is continuous and stable, global compensation can be applied

4.1 Global compensation (see Fig. L13)

Principle

The capacitor bank is connected to the busbars of the main LV distribution board for the installation, and remains in service during the period of normal load.

Advantages

The global type of compensation:

■ Reduces the tariff penalties for excessive consumption of kvars

■ Reduces the apparent power kVA demand, on which standing charges are usually based

■ Relieves the supply transformer, which is then able to accept more load if necessary

Comments

■ Reactive current still flows in all conductors of cables leaving (i.e. downstream of) the main LV distribution board

■ For the above reason, the sizing of these cables, and power losses in them, are not improved by the global mode of compensation.

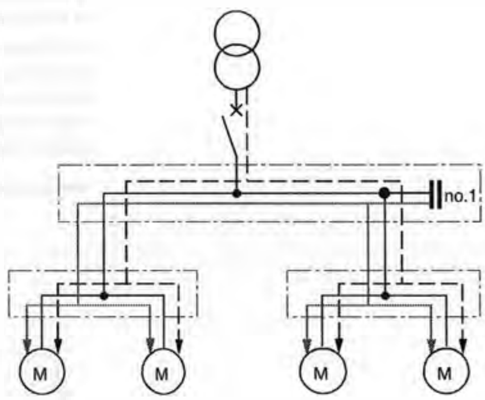


Fig. L13 : Global compensation

Compensation by sector is recommended when the installation is extensive, and where the load/time patterns differ from one part of the installation to another

4.2 Compensation by sector (see Fig. L14)

Principle

Capacitor banks are connected to busbars of each local distribution board, as shown in Figure L14.

A significant part of the installation benefits from this arrangement, notably the feeder cables from the main distribution board to each of the local distribution boards at which the compensation measures are applied.

Advantages

The compensation by sector:

■ Reduces the tariff penalties for excessive consumption of kvars

■ Reduces the apparent power kVA demand, on which standing charges are usually based

■ Relieves the supply transformer, which is then able to accept more load if necessary

■ The size of the cables supplying the local distribution boards may be reduced, or will have additional capacity for possible load increases

■ Losses in the same cables will be reduced

Comments

■ Reactive current still flows in all cables downstream of the local distribution boards

■ For the above reason, the sizing of these cables, and the power losses in them, are not improved by compensation by sector

■ Where large changes in loads occur, there is always a risk of overcompensation and consequent overvoltage problems

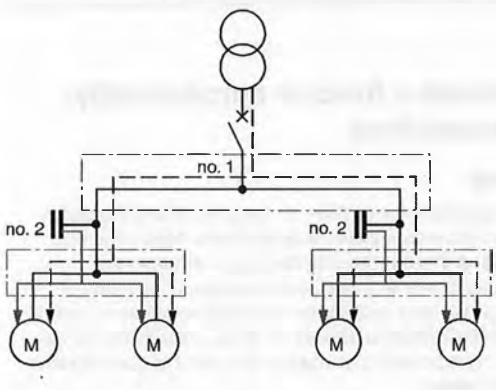


Fig. L14 : Compensation by sector

4 Where to install correction capacitors?

Individual compensation should be considered when the power of motor is significant with respect to power of the installation

4.3 Individual compensation

Principle

Capacitors are connected directly to the terminals of inductive circuit (notably motors, see further in Clause 7). Individual compensation should be considered when the power of the motor is significant with respect to the declared power requirement (kVA) of the installation.
The kvar rating of the capacitor bank is in the order of 25% of the kW rating of the motor. Complementary compensation at the origin of the installation (transformer) may also be beneficial.

Advantages

Individual compensation:

- Reduces the tariff penalties for excessive consumption of kvars
- Reduces the apparent power kVA demand
- Reduces the size of all cables as well as the cable losses

Comments

- Significant reactive currents no longer exist in the installation

5 How to decide the optimum level of compensation?

5.1 General method

Listing of reactive power demands at the design stage

This listing can be made in the same way (and at the same time) as that for the power loading described in chapter A. The levels of active and reactive power loading, at each level of the installation (generally at points of distribution and sub-distribution of circuits) can then be determined.

Technical-economic optimization for an existing installation

The optimum rating of compensation capacitors for an existing installation can be determined from the following principal considerations:

- Electricity bills prior to the installation of capacitors
- Future electricity bills anticipated following the installation of capacitors
- Costs of:
  - Purchase of capacitors and control equipment (contactors, relaying, cabinets, etc.)
  - Installation and maintenance costs
  - Cost of dielectric heating losses in the capacitors, versus reduced losses in cables, transformer, etc., following the installation of capacitors

Several simplified methods applied to typical tariffs (common in Europe) are shown in sub-clauses 5.3 and 5.4.

5.2 Simplified method

General principle

An approximate calculation is generally adequate for most practical cases, and may be based on the assumption of a power factor of 0.8 (lagging) before compensation. In order to improve the power factor to a value sufficient to avoid tariff penalties (this depends on local tariff structures, but is assumed here to be 0.93) and to reduce losses, volt-drops, etc. in the installation, reference can be made to **Figure L15** next page.

From the figure, it can be seen that, to raise the power factor of the installation from 0.8 to 0.93 will require 0.355 kvar per kW of load. The rating of a bank of capacitors at the busbars of the main distribution board of the installation would be

Q (kvar) = 0.355 x P (kW).

This simple approach allows a rapid determination of the compensation capacitors required, albeit in the global, partial or independent mode.

Example

It is required to improve the power factor of a 666 kVA installation from 0.75 to 0.928. The active power demand is 666 x 0.75 = 500 kW.
In Figure L15, the intersection of the row cos φ = 0.75 (before correction) with the column cos φ = 0.93 (after correction) indicates a value of 0.487 kvar of compensation per kW of load.
For a load of 500 kW, therefore, 500 x 0.487 = 244 kvar of capacitive compensation is required.

Note: this method is valid for any voltage level, i.e. is independent of voltage.

5 How to decide the optimum level of compensation?

Before compensation		kvar rating of capacitor bank to install per kW of load, to improve cos φ (the power factor) or tan φ, to a given value												
		tan φ	0.75	0.59	0.48	0.46	0.43	0.40	0.36	0.33	0.29	0.25	0.20	0.14	0.0
tan φ	cos φ	cos φ	0.80	0.86	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
2.29	0.40		1.557	1.691	1.805	1.832	1.861	1.895	1.924	1.959	1.998	2.037	2.085	2.146	2.288
2.22	0.41		1.474	1.625	1.742	1.769	1.798	1.831	1.840	1.896	1.935	1.973	2.021	2.082	2.225
2.16	0.42		1.413	1.561	1.681	1.709	1.738	1.771	1.800	1.836	1.874	1.913	1.961	2.022	2.164
2.10	0.43		1.356	1.499	1.624	1.651	1.680	1.713	1.742	1.778	1.816	1.855	1.903	1.964	2.107
2.04	0.44		1.290	1.441	1.558	1.585	1.614	1.647	1.677	1.712	1.751	1.790	1.837	1.899	2.041
1.98	0.45		1.230	1.384	1.501	1.532	1.561	1.592	1.628	1.659	1.695	1.737	1.784	1.846	1.988
1.93	0.46		1.179	1.330	1.446	1.473	1.502	1.533	1.567	1.600	1.636	1.677	1.725	1.786	1.929
1.88	0.47		1.130	1.278	1.397	1.425	1.454	1.485	1.519	1.532	1.588	1.629	1.677	1.758	1.881
1.83	0.48		1.076	1.228	1.343	1.370	1.400	1.430	1.464	1.497	1.534	1.575	1.623	1.684	1.826
1.78	0.49		1.030	1.179	1.297	1.326	1.355	1.386	1.420	1.453	1.489	1.530	1.578	1.639	1.782
1.73	0.50		0.982	1.232	1.248	1.276	1.303	1.337	1.369	1.403	1.441	1.481	1.529	1.590	1.732
1.69	0.51		0.936	1.087	1.202	1.230	1.257	1.291	1.323	1.357	1.395	1.435	1.483	1.544	1.686
1.64	0.52		0.894	1.043	1.160	1.188	1.215	1.249	1.281	1.315	1.353	1.393	1.441	1.502	1.644
1.60	0.53		0.850	1.000	1.116	1.144	1.171	1.205	1.237	1.271	1.309	1.349	1.397	1.458	1.600
1.56	0.54		0.809	0.959	1.075	1.103	1.130	1.164	1.196	1.230	1.268	1.308	1.356	1.417	1.559
1.52	0.55		0.769	0.918	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316	1.377	1.519
1.48	0.56		0.730	0.879	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1.338	1.480
1.44	0.57		0.692	0.841	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1.300	1.442
1.40	0.58		0.665	0.805	0.921	0.949	0.976	1.010	1.042	1.076	1.114	1.154	1.202	1.263	1.405
1.37	0.59		0.618	0.768	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165	1.226	1.368
1.33	0.60		0.584	0.733	0.849	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131	1.192	1.334
1.30	0.61		0.549	0.699	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.048	1.096	1.157	1.299
1.27	0.62		0.515	0.665	0.781	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062	1.123	1.265
1.23	0.63		0.483	0.633	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.030	1.091	1.233
1.20	0.64		0.450	0.601	0.716	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997	1.058	1.200
1.17	0.65		0.419	0.569	0.685	0.713	0.740	0.774	0.806	0.840	0.878	0.918	0.966	1.007	1.169
1.14	0.66		0.388	0.538	0.654	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935	0.996	1.138
1.11	0.67		0.358	0.508	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905	0.966	1.108
1.08	0.68		0.329	0.478	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876	0.937	1.079
1.05	0.69		0.299	0.449	0.565	0.593	0.620	0.654	0.686	0.720	0.758	0.798	0.840	0.907	1.049
1.02	0.70		0.270	0.420	0.536	0.564	0.591	0.625	0.657	0.691	0.729	0.769	0.811	0.878	1.020
0.99	0.71		0.242	0.392	0.508	0.536	0.563	0.597	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.96	0.72		0.213	0.364	0.479	0.507	0.534	0.568	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.94	0.73		0.186	0.336	0.452	0.480	0.507	0.541	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.91	0.74		0.159	0.309	0.425	0.453	0.480	0.514	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.88	0.75		0.132	0.82	0.398	0.426	0.453	0.487	0.519	0.553	0.591	0.631	0.673	0.740	0.882
0.86	0.76		0.105	0.255	0.371	0.399	0.426	0.460	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.83	0.77		0.079	0.229	0.345	0.373	0.400	0.434	0.466	0.500	0.538	0.578	0.620	0.687	0.829
0.80	0.78		0.053	0.202	0.319	0.347	0.374	0.408	0.440	0.474	0.512	0.552	0.594	0.661	0.803
0.78	0.79		0.026	0.176	0.292	0.320	0.347	0.381	0.413	0.447	0.485	0.525	0.567	0.634	0.776
0.75	0.80			0.150	0.266	0.294	0.321	0.355	0.387	0.421	0.459	0.499	0.541	0.608	0.750
0.72	0.81			0.124	0.240	0.268	0.295	0.329	0.361	0.395	0.433	0.473	0.515	0.582	0.724
0.70	0.82			0.098	0.214	0.242	0.269	0.303	0.335	0.369	0.407	0.447	0.489	0.556	0.698
0.67	0.83			0.072	0.188	0.216	0.243	0.277	0.309	0.343	0.381	0.421	0.463	0.530	0.672
0.65	0.84			0.046	0.162	0.190	0.217	0.251	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.62	0.85			0.020	0.136	0.164	0.191	0.225	0.257	0.291	0.329	0.369	0.417	0.478	0.620
0.59	0.86				0.109	0.140	0.167	0.198	0.230	0.264	0.301	0.343	0.390	0.450	0.593
0.57	0.87				0.083	0.114	0.141	0.172	0.204	0.238	0.275	0.317	0.364	0.424	0.567
0.54	0.88				0.054	0.085	0.112	0.143	0.175	0.209	0.246	0.288	0.335	0.395	0.538
0.51	0.89				0.028	0.059	0.086	0.117	0.149	0.183	0.230	0.262	0.309	0.369	0.512
0.48	0.90					0.031	0.058	0.089	0.121	0.155	0.192	0.234	0.281	0.341	0.484

Value selected as an example on section 5.2

Value selected as an example on section 5.4

Fig. L15 : kvar to be installed per kW of load, to improve the power factor of an installation

9 The effects of harmonics

For example: $h_o = \sqrt{\frac{Ssc}{Q}}$ may give a value for h_o of 2.93 which shows that the natural frequency of the capacitor/system-inductance combination is close to the 3rd harmonic frequency of the system.

From $h_o = \frac{f_o}{50}$ it can be seen that $f_o = 50\ h_o = 50 \times 2.93 = 146.5$ Hz

The closer a natural frequency approaches one of the harmonics present on the system, the greater will be the (undesirable) effect. In the above example, strong resonant conditions with the 3rd harmonic component of a distorted wave would certainly occur.

In such cases, steps are taken to change the natural frequency to a value which will not resonate with any of the harmonics known to be present. This is achieved by the addition of a harmonic-suppression inductor connected in series with the capacitor bank.

On 50 Hz systems, these reactors are often adjusted to bring the resonant frequency of the combination, i.e. the capacitor bank + reactors to 190 Hz. The reactors are adjusted to 228 Hz for a 60 Hz system. These frequencies correspond to a value for h_o of 3.8 for a 50 Hz system, i.e. approximately mid-way between the 3rd and 5th harmonics.

In this arrangement, the presence of the reactor increases the fundamental frequency (50 Hz or 60 Hz) current by a small amount (7-8%) and therefore the voltage across the capacitor in the same proportion.

This feature is taken into account, for example, by using capacitors which are designed for 440 V operation on 400 V systems.

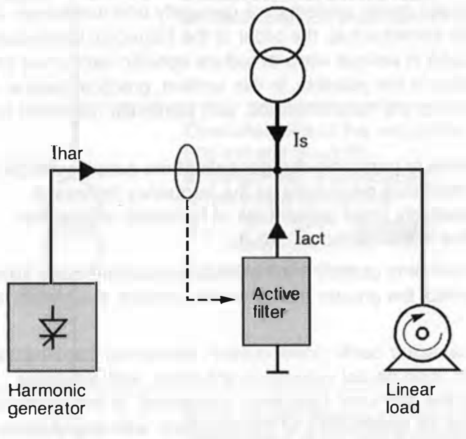


Fig. L29 : Operation principle of active filter

Active filter (see Fig. L29)

Active filters are based on power electronic technology. They are generally installed in parallel with the non linear load.

Active filters analyse the harmonics drawn by the load and then inject the same harmonic current to the load with the appropriate phase. As a result, the harmonic currents are totally neutralised at the point considered. This means they no longer flow upstream and are no longer supplied by the source.

A main advantage of active conditioners is that they continue to guarantee efficient harmonic compensation even when changes are made to the installation. They are also exceptionally easy to use as they feature:

- Auto-configuration to harmonic loads whatever their order of magnitude
- Elimination of overload risks
- Compatibility with electrical generator sets
- Connection to any point of the electrical network
- Several conditioners can be used in the same installation to increase depollution efficiency (for example when a new machine is installed)

Active filters may provide also power factor correction.

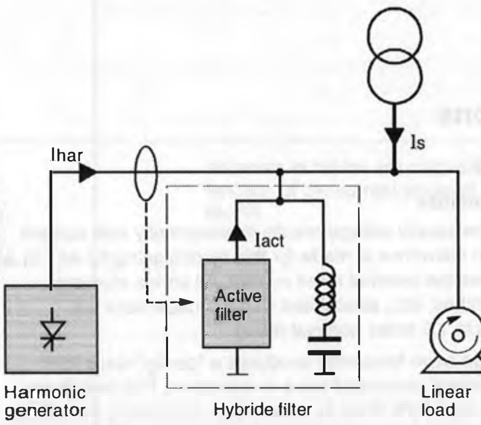


Fig. L30 : Operation principle of hybrid filter

Hybrid filter (see Fig. L30)

This type of filter combines advantages of passive and active filter. One frequency can be filtered by passive filter and all the other frequencies are filtered by active filter.

9.3 Choosing the optimum solution

Figure L31 below shows the criteria that can be taken into account to select the most suitable technology depending on the application.

	Passive filter	Active filter	Hybrid filter
Applications	Industrial	Tertiary	Industrial
... with total power of non linear loads (variable speed drive, UPS, rectifier...)	greater than 200 kVA	lower than 200 kVA	greater than 200 kVA
Power factor correction		No	
Necessity of reducing the harmonic distorsion in voltage for sensitive loads			
Necessity of reducing the harmonic distorsion in current to avoid cable overload			
Necessity of being in accordance with strict limits of harmonic rejected	No		

Fig. L31 : Selection of the most suitable technology depending on the application

For passive filter, a choice is made from the following parameters:

- Gh = the sum of the kVA ratings of all harmonic-generating devices (static converters, inverters, speed controllers, etc.) connected to the busbars from which the capacitor bank is supplied. If the ratings of some of these devices are quoted in kW only, assume an average power factor of 0.7 to obtain the kVA ratings
- Ssc = the 3-phase short-circuit level in kVA at the terminals of the capacitor bank
- Sn = the sum of the kVA ratings of all transformers supplying (i.e. directly connected to) the system level of which the busbars form a part

If a number of transformers are operating in parallel, the removal from service of one or more, will significantly change the values of Ssc and Sn. From these parameters, a choice of capacitor specification which will ensure an acceptable level of operation with the system harmonic voltages and currents, can be made, by reference to **Figure L32**.

- General rule valid for any size of transformer

$Gh \leqslant \frac{Ssc}{120}$	$\frac{Ssc}{120} \leqslant Gh \leqslant \frac{Ssc}{70}$	$Gh > \frac{Ssc}{70}$
Standard capacitors	Capacitor voltage rating increased by 10% (except 230 V units)	Capacitor voltage rating increased by 10% + harmonic-suppression reactor

- Simplified rule if transformer(s) rating $Sn \leqslant 2$ MVA

$Gh \leqslant 0.15\ Sn$	$0.15\ Sn < Gh \leqslant 0.25\ Sn$	$0.25\ Sn < Gh \leqslant 0.60\ Sn$	$Gh > 0.60\ Sn$
Standard capacitors	Capacitor voltage rating increased by 10% (except 230 V units)	Capacitor voltage rating increased by 10% + harmonic suppression reactor	Filters

Fig. L32 : Choice of solutions for limiting harmonics associated with a LV capacitor bank supplied via transformer(s)

10 Implementation of capacitor banks

10.1 Capacitor elements

Technology

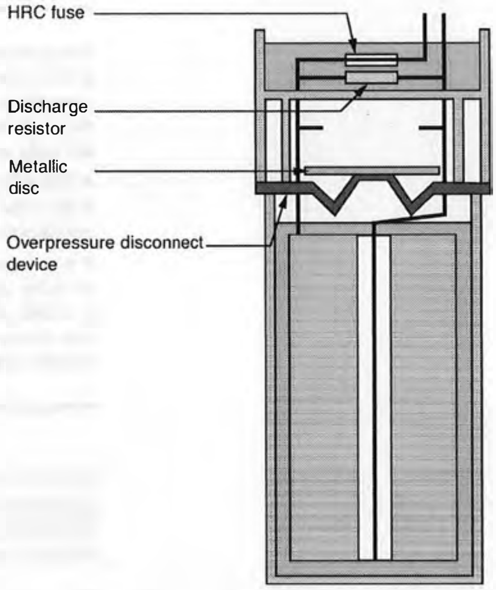
The capacitors are dry-type units (i.e. are not impregnated by liquid dielectric) comprising metallized polypropylene self-healing film in the form of a two-film roll. They are protected by a high-quality system (overpressure disconnector used with a high breaking capacity fuse) which switches off the capacitor if an internal fault occurs.

The protection scheme operates as follows:

- A short-circuit through the dielectric will blow the fuse
- Current levels greater than normal, but insufficient to blow the fuse sometimes occur, e.g. due to a microscopic flow in the dielectric film. Such "faults" often re-seal due to local heating caused by the leakage current, i.e. the units are said to be "self-healing"
- If the leakage current persists, the defect may develop into a short-circuit, and the fuse will blow
- Gas produced by vaporizing of the metallisation at the faulty location will gradually build up a pressure within the plastic container, and will eventually operate a pressure-sensitive device to short-circuit the unit, thereby causing the fuse to blow

Capacitors are made of insulating material providing them with double insulation and avoiding the need for a ground connection (see **Fig. L33**).

a)



b)

Electrical characteristics			
Standard		IEC 60439-1, NFC 54-104, VDE 0560 CSA Standards, UL tests	
Operating range	Rated voltage	400 V	
	Rated frequency	50 Hz	
Capacitance tolerance		- 5% to + 10%	
Temperature range (up to 65 kvar)	Maximum temperature	55 °C	
	Average temperature over 24 h	45 °C	
	Average annual temperature	35 °C	
	Minimum temperature	- 25 °C	
Insulation level		50 Hz 1 min withstand voltage : 6 kV 1.2/50 μs impulse withstand voltage : 25 kV	
Permissible current overload		Classic range(1)	Comfort range(1)
		30%	50%
Permissible voltage overload		10%	20%

Fig. L33 : Capacitor element, (a) cross-section, (b) electrical characteristics

(1) Merlin-Gerin designation

10.2 Choice of protection, control devices and connecting cables

The choice of upstream cables and protection and control devices depends on the current loading.

For capacitors, the current is a function of:
- The applied voltage and its harmonics
- The capacitance value

The nominal current In of a 3-phase capacitor bank is equal to:

$$In = \frac{Q}{Un\sqrt{3}}$$ with:

- Q: kvar rating
- Un: Phase-to-phase voltage (kV)

The permitted range of applied voltage at fundamental frequency, plus harmonic components, together with manufacturing tolerances of actual capacitance (for a declared nominal value) can result in a 50% increase above the calculated value of current. Approximately 30% of this increase is due to the voltage increases, while a further 15% is due to the range of manufacturing tolerances, so that
1.3 x 1.15 = 1.5

All components carrying the capacitor current therefore, must be adequate to cover this "worst-case" condition, in an ambient temperature of 50 °C maximum. In the case where temperatures higher than 50 °C occur in enclosures, etc. derating of the components will be necessary.

Protection

The size of the circuit-breaker can be chosen in order to allow the setting of long time delay at:
- 1.36 x In for Classic range(1)
- 1.50 x In for Comfort range(1)
- 1.12 x In for Harmony range(1) (tuned at 2.7 f)(2)
- 1.19 x In for Harmony range(1) (tuned at 3.8 f)
- 1.31 x In for Harmony range(1) (tuned at 4.3 f)

Short time delay setting (short-circuit protection) must be insensitive to inrush current. The setting will be 10 x In for Classic, Comfort and Harmony range(1).

Example 1

50 kvar – 400V – 50 Hz – Classic range

$$In = \frac{50,000}{(400 \times 1.732)} = 72 \text{ A}$$

Long time delay setting: 1.36 x 72 = 98 A

Short time delay setting: 10 x In = 720 A

Example 2

50 kvar – 400V – 50 Hz – Harmony range (tuned at 4.3 f)

In = 72 A

Long time delay setting: 1.31 x 72 = 94 A

Short time delay setting: 10 x In = 720 A

Upstream cables

Figure L34 next page gives the minimum cross section area of the upstream cable for Rectiphase capacitors.

Cables for control

The minimum cross section area of these cables will be 1.5 mm^2 for 230 V.

For the secondary side of the transformer, the recommended cross section area is ≥ 2.5 mm^2.

(1) Merlin-Gerin designation

(2) Harmony capacitor banks are equipped with a harmonic suppression reactor.

10 Implementation of capacitor banks

Bank power (kvar)		Copper cross- section (mm²)	Aluminium cross- section (mm²)
230 V	400 V		
5	10	2.5	16
10	20	4	16
15	30	6	16
20	40	10	16
25	50	16	25
30	60	25	35
40	80	35	50
50	100	50	70
60	120	70	95
70	140	95	120
90-100	180	120	185
	200	150	240
120	240	185	2 x 95
150	250	240	2 x 120
	300	2 x 95	2 x 150
180-210	360	2 x 120	2 x 185
245	420	2 x 150	2 x 240
280	480	2 x 185	2 x 300
315	540	2 x 240	3 x 185
350	600	2 x 300	3 x 240
385	660	3 x 150	3 x 240
420	720	3 x 185	3 x 300

Fig L34 : Cross-section of cables connecting medium and high power capacitor banks(1)

Voltage transients

High-frequency voltage and current transients occur when switching a capacitor bank into service. The maximum voltage peak does not exceed (in the absence of harmonics) twice the peak value of the rated voltage when switching uncharged capacitors.

In the case of a capacitor being already charged at the instant of switch closure, however, the voltage transient can reach a maximum value approaching 3 times the normal rated peak value.

This maximum condition occurs only if:

■ The existing voltage at the capacitor is equal to the peak value of rated voltage, and

■ The switch contacts close at the instant of peak supply voltage, and

■ The polarity of the power-supply voltage is opposite to that of the charged capacitor

In such a situation, the current transient will be at its maximum possible value, viz: Twice that of its maximum when closing on to an initially uncharged capacitor, as previously noted.

For any other values of voltage and polarity on the pre-charged capacitor, the transient peaks of voltage and current will be less than those mentioned above.
In the particular case of peak rated voltage on the capacitor having the same polarity as that of the supply voltage, and closing the switch at the instant of supply-voltage peak, there would be no voltage or current transients.

Where automatic switching of stepped banks of capacitors is considered, therefore, care must be taken to ensure that a section of capacitors about to be energized is fully discharged.

The discharge delay time may be shortened, if necessary, by using discharge resistors of a lower resistance value.

(1) Minimum cross-section not allowing for any correction factors (installation mode, temperature, etc.). The calculations were made for single-pole cables laid in open air at 30 °C.