Part IV

Power Capacitors and Reactive Power Controls

23 Power capacitors: behaviour, switching phenomena and improvement of power factor

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SECTION I Power capacitors

23.1 Introduction

In view of the considerable increase in power distribution networks and their over-utilization to meet increasing consumer and industrial demands it has become imperative to optimize the use of available power through efficient transmission and distribution.

Voltage and power factor (p.f.) are the two most important parameters in a power system that influence its utilization. The element of voltage is optimized by raising the transmission and distribution voltages as much as feasible. The more prevalent of these are 400 kV a.c. for long-distance transmissions and 33–132 kV or even higher for secondary transmissions. Figure 23.1 illustrates a typical transmission and distribution network. Continued efforts are being made to raise the transmission voltage to 765 kV a.c. or 500 kV d.c., or higher. Some countries such as the USA, Russia and Canada have already adopted such systems. A d.c. system, we recall, has no skin effect (Section 28.7) and can transmit power at unity p.f.

The element of p.f. mainly affects the secondary distribution system which serves industries, agriculture, public utilities and domestic loads. Most of them are highly inductive and result in lowering the system p.f. These loads are largely responsible for most of the distribution losses and voltage fluctuations at the consumer end. In developing countries it is estimated that useful power is lost mainly due to transmission and distribution losses. In India, for instance, it is estimated to result in a loss of about 18–20% of the total useful power, most of which occurs at the secondary distribution attributable to low p.fs.

The application of power capacitors, can tackle problems of both low p.f. and voltage fluctuations and these aspects are discussed here.

23.2 Applications of power capacitors

A capacitor draws leading current. When connected to an inductive circuit, it offsets its inductive (reactive) component and improves the p.f. of the circuit. It can be applied in two ways and is accordingly classified as follows:

1 Shunt capacitor – connected across the inductive circuit to improve its p.f.
2 Series capacitor – connected in series at the far end of a long transmission or HV* distribution line to offset the reactive component of the line impedance, contain the voltage drop and enhance the receiving-end voltage. It can support a transmission or distribution system in the following ways:

   - Improving the regulation of the system at the receiving end
   - Limiting the system voltage swing during a load rejection or off-peak periods, and protect it from over-voltages
   - Enhancing the dynamic stability of the system by minimizing the voltage fluctuations caused by load variations and
   - Enhancing the power-carrying capacity of the system by reducing the I^2R losses.

This subject is dealt with in more detail in Chapter 24.

23.3 Effect of low PF

A low p.f. means a higher load current than necessary and accompanying higher line losses. Inductive loads are the main cause of a low p.f., with induction motors the major contributors. Under operating conditions a motor may often be operating under-loaded due to one or more of the following reasons:

- While making selection of even for a standard motor, it is generally not possible to exactly match the rating of the machine with the load. The motor may have some reserve capacity.
- Users may select a slightly larger machine to ensure safety.
- When selecting a machine for more critical installations, as discussed in Section 7.20 the number

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* HV means all voltages 3.3 kV and above.

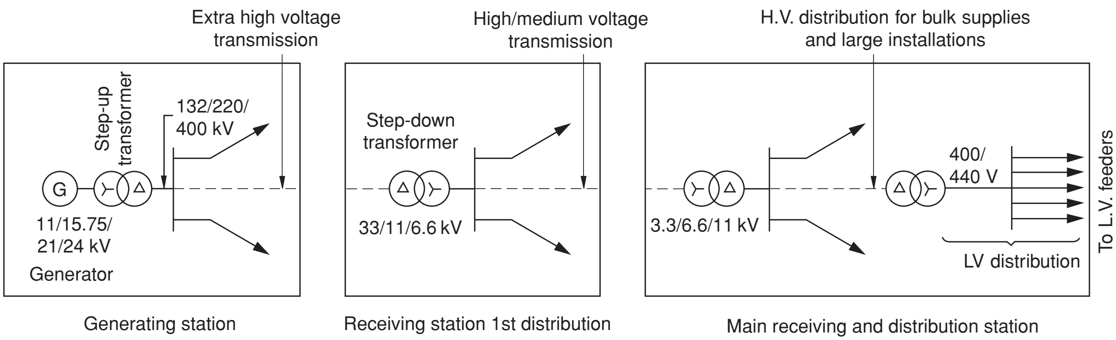


Figure 23.1 A typical transmission and distribution network

of deratings for all unfavourable operating conditions are assumed to be occurring at the same time. This results in the selection of an oversized machine as all the unfavourable conditions may not be occurring simultaneously.

- Wide voltage fluctuations may be prevalent in a rural distribution system, particularly in developing countries. In such cases it is common practice for users to select an oversized machine for their needs. Accordingly, the motors employed for loads such as pumps, thrashers and winnowers are normally over-rated and remain under-utilized. Also the same motor may have to cater for different types of loads, at different times, and these loads may be much less than the motor rating.

The power factor of a motor decreases sharply at loads lower than rated as discussed in Section 1.8. All the above factors, contribute to reducing the overall system power factor, which is sometimes seen to reach a low of 0.6 or even less on an LV distribution network.

Higher line losses result in higher voltage fluctuations due to the greater line drop (IZ). In an HV system, the voltage at the receiving end is not as much affected as in an LV system due to the lower voltage drop on an HV system as a percentage of the system voltage. An LV system experiences a much higher fluctuation, as a percentage of the supply voltage, due to excessive voltage drops. A higher current for a smaller load, due to a low power factor, reduces the capacity of the distribution network. In other words, it decreases the generating capacity of the power plant, feeding such a system. For instance, for the same power generated or distributed 'P'

$$P = \sqrt{3} \cdot V \cdot I \cdot \cos \phi$$

Therefore, for a given load current I,

$$P \propto \cos \phi$$

Thus, at 0.70 p.f., the generating or the distributing capacity of the system, compared to a system having a p.f. of 0.90, will reduce to approximately 77.8% (0.7/0.9 × 100%). In other words, if we consider a distribution p.f. 0.70 to be improved to 0.9, then the useful power can be enhanced by

$$\frac{0.90 - 0.70}{0.70} \times 100\%$$

i.e. 28.6% of the existing system (see Figure 23.2). For the same generation or distribution current I, at a p.f. $\cos \phi_1$, utilization of the system will be

$$P_1 \propto I \times \cos \phi_1$$

whereas at an improved p.f. $\cos \phi_2$, it will be

$$P_2 \propto I \times \cos \phi_2$$

Thus while the I^2R loss will remain the same in both cases, at a lower power factor the utilization capacity of the system will reduce in the same proportion as the power factors, i.e.

$$\frac{\cos \phi_1}{\cos \phi_2}$$

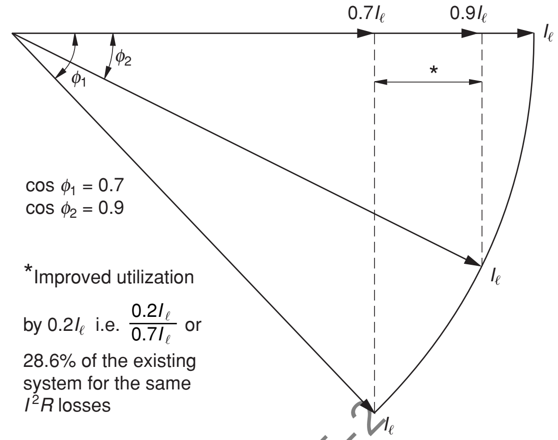


Figure 23.2 Better utilization of power with improved power factor

As a result of higher voltage drops, the receiving-end voltage may sometimes fall below the required limit which, in electric motors, is –6% (Section 1.6.2). Motors for such locations may be required to be suitable for voltages lower than the standard system voltages such as 400 V, 380 V or even less, as against the standard 415 V. A motor designed especially for a lower voltage than standard may sometimes require a larger frame size at a higher cost.

Note
Old system voltages are retained for illustration. See introduction for new voltages as per IEC 60038.

23.4 Other benefits of an improved power factor

- Reduced kVA demand will result in lower tariffs since the electricity companies usually charge users on the basis of their maximum kVA demand.
- In certain countries the consumer may even be entitled to a rebate for maintaining a high power factor, instead of paying a higher tariff.
- Lower kVA demand will reduce the load current (due to reduced I^2R losses) and result in an economical selection of switchgear components and cables.
- Lower voltage drops in the lines and cables and thus lesser voltage fluctuations.
- The electricity companies would also benefit due to better utilization of their distribution system and make more power available to consumers.

23.5 Behaviour of a power capacitor in operation

Before we discuss the application of this device, it is important that we study its behaviour during operation. A capacitor unit behaves like a short-circuit on being energized and retains its charge for a brief period even when the source of supply is removed. This behaviour gives rise to the following:

- Switching over-voltages
- Harmonic effects and inductive interferences and
- Excessive charging currents.

These aspects are discussed briefly below.

23.5.1 Switching over-voltages (surges)

This phenomenon is generally associated with an HV system. We have discussed in Section 17.7 the subject of switching surges as related to an inductive circuit. Switching phenomenon in a capacitive circuit is equally important, and a little more complex. It therefore requires more careful handling of this device. Although the switching behaviour of a capacitor circuit is almost a replica of an inductive switching, its current leading the applied voltage by 90° results in more complex behaviour than an inductive circuit during a switching operation.

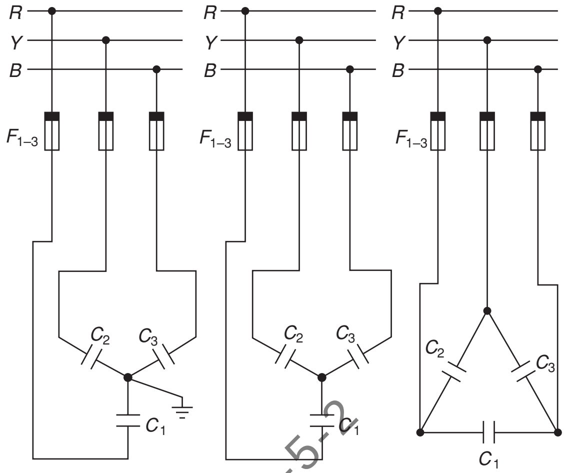
The phasor displacement between the voltage and the current in an inductive circuit, particularly an induction motor or a transformer, is much less than 90° during normal operation. At a p.f. of 0.65, for instance, the current will lag the voltage by 49° and at a p.f. of 0.9 by 25°. During the most severe conditions, such as on a fault, at near a p.f. of 0.1, the current will lag the voltage by 84° and at a p.f. of 0.3 by 72°. In capacitor switching, in addition to 90° phasor displacement between the applied voltage and the current, under all conditions of switching there will also appear an over-voltage across the parting contacts, depending upon the grounding method of the capacitor units, their configuration and the applied voltage. All such over-voltages must be limited within the impulse withstand level of the capacitors, as noted in Section 26.3.2. We have analysed these aspects for the following capacitor configurations:

- Grounded star (a widely adopted practice in LV systems)
- Ungrounded star
- Delta connections and
- Parallel switching of capacitor units.

(i) Grounded star capacitor units

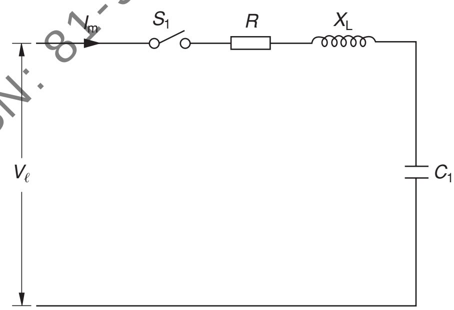
See the arrangement shown in Figure 23.3(a) and its equivalent single-phase circuit in Figure 23.4. We are discussing the phenomenon of switching over-voltages associated with an HV system. An LV system, although not immune to over-voltages, causes no restriking between the parting contacts of the interrupting device as a result of inadequate transient recovery voltage (TRV; Section 17.6.2) and generates no switching surges.

Consider the opening of a switch on one pole (Section 19.7) at the instant of contact interruption, say at point a' on the current wave (Figure 23.5). The current will lead the voltage by 90° and the parting contacts will be subjected to a full system voltage of 1 p.u. Refer to point 'a' on the voltage wave. In addition, the contacts will also be subjected to the trapped charge of 1 p.u. within the capacitor unit, which it will retain for a while. If the



(a) Grounded star (b) Ungrounded star (c) Delta connection

Figure 23.3 Configurations and grounding methods of capacitor banks



R and X_L are voltage damping impedances

Figure 23.4 A single capacitor switching

contacts fail to interrupt at point a' the arc will strike again (re-ignition of the arc plasma, Section 19.4). By the next current zero (point b' on the current wave), when the arc ceases again and the contacts try to interrupt, they will be subjected to a TRV of 3 p.u., the capacitor unit still retaining the charge. Refer to point bb'' on the voltage wave. It is possible that the contacts are not able to travel sufficiently apart to build up the required dielectric strength, and the arc may strike again. At the next current zero (point c' on the current wave), when the contacts have travelled by another one half of a cycle, they will be subjected to four times the system voltage cc'' on the voltage wave, considering that the capacitor unit may still be retaining its charge. The arc may now be extinguished as a result of self-attenuation, as the contacts will have travelled sufficiently far apart to withstand the TRV and interrupt the circuit. The process may be repeated if the dielectric strength or the travel of the contacts is not sufficient to withstand a TRV of four times the rated voltage. It will continue to do so until the process attenuates on its own due to circuit parameters L and C, the decreasing capacitor charge and adequate travel of the moving contact of the interrupting device and extinguish the arc to finally

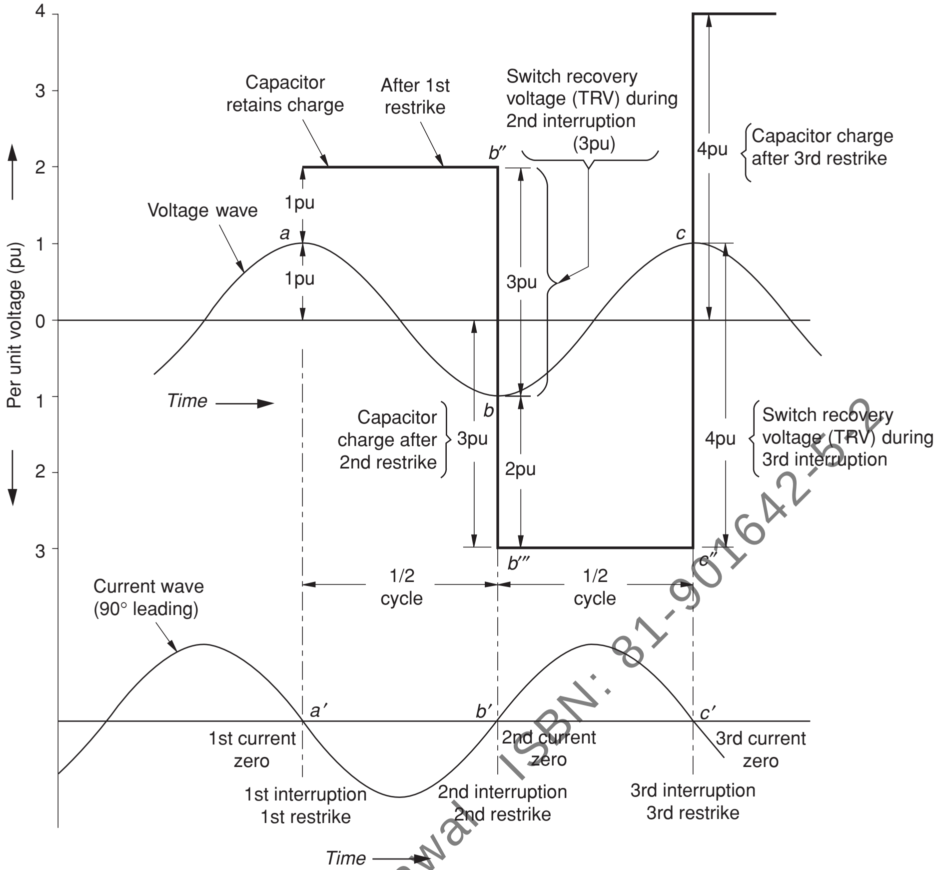


Figure 23.5 Build-up of capacitive voltage (TRV) on restrike during contact interruption in a grounded star HV capacitor unit

interrupt the circuit. Field experiments have revealed that over-voltages due to such repeated restrikes during the interruption of a grounded capacitor unit seldom exceed 2.6 p.u. as a result of self-attenuation and high-speed modern interrupters.

(ii) Ungrounded capacitor units (both star- and delta-connected units)

Consider the arrangements shown in Figures 23.3(b) and (c). Now the opening of the switch in one phase will not isolate the capacitor in that phase from the system, as in the grounded system as a result of a feedback through the lumped (leakage) capacitances of the other two phases (Section 20.1 and Figure 20.2). Assume the initiation of interruption in one of the phases at a current zero. Refer to point a' on the current wave (Figure 23.6(a)). The parting contacts will now be subjected to an additional voltage equal to the system voltage of 1 p.u., because of the other two phases, which would also be conducting, besides 2 p.u. at point 'a' as discussed in the previous case. The other two phases which are now conducting will each retain a charge of 0.5 p.u. at every voltage peak in the first phase, as illustrated in Figure 23.6(b). This charge will be redistributed in the first phase as soon as its contacts open. The unswitched phases, however, will retain a charge of

0.5 p.u. + 0.866 p.u. or 1.366 p.u. (max.)

where 0.5 p.u. = trapped charge and

0.866 p.u. $= \frac{\sqrt{3}}{2}$ p.u. is the excitation due to lumped capacitances of the ungrounded unswitched phases.

The parting contacts will therefore now be subjected to a TRV of 3 p.u. at the first interruption. If the contacts fail to interrupt at point a', the arc will strike again, and by the next current zero (point b' on the current wave), when they will try to interrupt again, will be subjected to a TRV of 4 p.u. Refer to point bb'' on the voltage wave, assuming that the capacitor unit is still retaining its charge. If the contacts fail to interrupt again the cycle of an arc restrike will be repeated at the next current zero c', at 5 p.u., point cc'' on the voltage wave. The process will continue until the circuit will finally interrupt by virtue of the interrupter's ability to interrupt or attenuation of the TRV, whichever occurs first. Field experiments have revealed that over-voltages due to repeated restrikes during the interruption of an ungrounded capacitor unit, connected in star or delta, will seldom exceed 3 p.u. due to self-attenuation and high-speed modern interrupters. The system grounding has no effect on such ungrounded capacitor units. The interruption of ungrounded capacitor units is thus more severe than of grounded units.

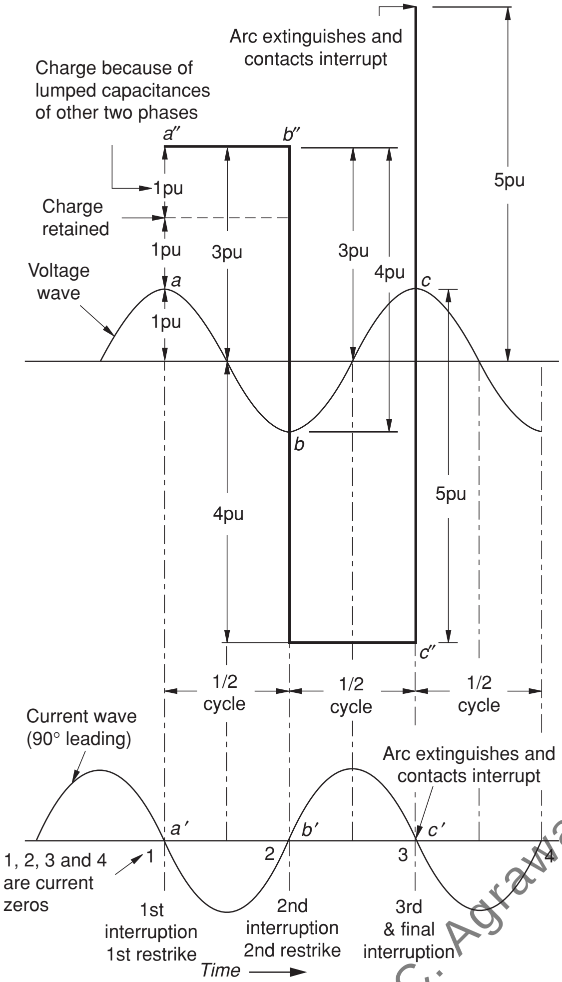


Figure 23.6(a) Build up of capacitive voltage (TRV) on restrike during a contact interruption in an ungrounded star HV capacitor unit

(iii) Parallel switching of capacitor units

The amplitudes of over-voltages (TRVs) caused by a single capacitor switching, as discussed above, will diminish when the capacitor interrupts into a circuit that already has energized capacitor units of comparable sizes in the same system. At the instant of contact separation, the two units, which may be charged at different potentials, will get discharged into each other and their cumulative voltage will tend to settle at an intermediate value that will depend upon the size of the capacitors being switched. The larger the line banks (already charged capacitors), the lower will be the amplitude of the TRV of the combined units.

Summary of over-voltages (on HV capacitor switchings)

1 Switching over-voltages is generally a phenomenon of HV circuits.
2 The choice of the type of capacitor connections will largely depend upon the system, its fault level and the presence of a communication system in the vicinity (harmonic effects and inductive interferences). Different electricity companies may adopt to different practices of capacitor connections and their switchings, depending upon these factors. A more detailed study on this subject (harmonics and inductive interferences) is beyond the scope of this handbook, nevertheless these effects are discussed briefly in Section 23.5.2 and their EMC (electromagnetic compatibility) and EMI (electromagnetic interferences) effects in Section 23.18. The text provided shall be adequate to provide necessary guidelines to tackle these effects in actual practice. Various papers written on the subject and a study of existing systems and the normal practices to deal with these effects and interferences are available and may be referred to for more details. See Further Reading at the end of this chapter. Over-voltages, as developed on different grounding systems, are discussed in more detail in Section 20.2.
3 When interrupting a capacitive circuit while the capacitor is fully charged, the system will experience

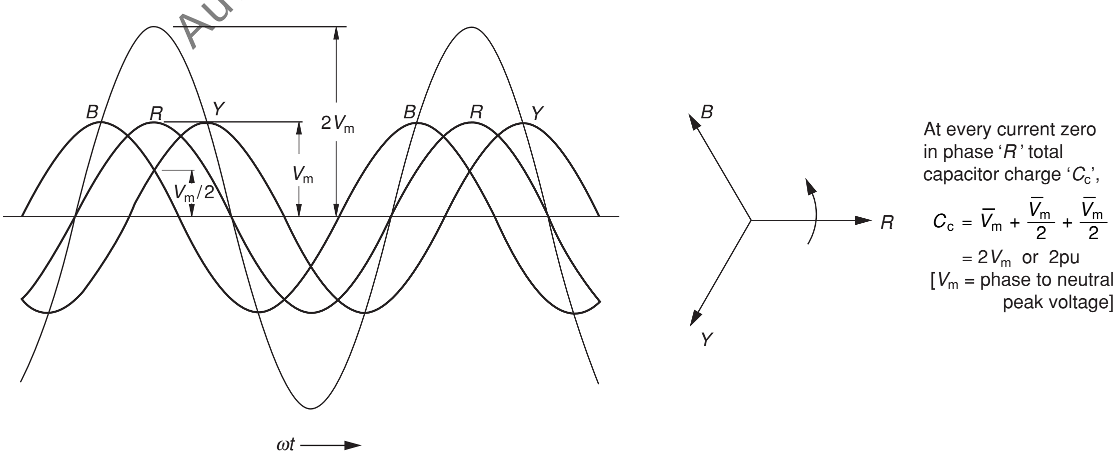


Figure 23.6(b) Capacitor charge in an ungrounded system

an over-voltage and the arc between the parting contacts of an interrupting device (a breaker or a contactor) may restrike even more severely than an inductive circuit, due to higher restriking voltages (TRVs).

4 Some resistance and/or inductance is recommended to be introduced into the switching circuit to damp the restriking voltage by altering the p.f. of the switching circuit during a make or a break, by helping the voltage and the current phasors to move closer so that at a current zero, the TRV is much less than V_m. See also Figures 17.11(a) and (b) for an inductive circuit. The situation will be almost the same for a capacitive switching except that the current will now be leading the voltage by 90° instead of lagging at much less than 90°.

5 The impedance of the capacitor switching circuit will determine the attenuation of the striking voltage and the time of arc extinction.

6 Frequent switching operations must be avoided as far as possible. In an HV system, they are as such low. However, where automatic switching devices have been installed, frequent switching operations may be likely. As standard practice, therefore, precautions should be taken to allow a pause before the next switching, or introducing a rapid discharge device across each capacitor unit to allow the last disconnected unit discharge to a safer value before reswitching (Section 25.7). Nevertheless, switching surges must be damped as much as possible by introducing some resistance or inductance into the switching circuit, as noted above.

7 The following are the recommended values of the switching transient voltages that may be considered to select the switching device:
   (a) Grounded capacitor units – peak recovery voltage (TRV) on a healthy switching up to 2.6 p.u.
   (b) Ungrounded star- and delta-connected capacitor units – peak recovery voltage (TRV) up to 3 p.u.

8 Where necessary, surge arresters may be used to damp the high transient switching voltages. Refer to Section 17.11.

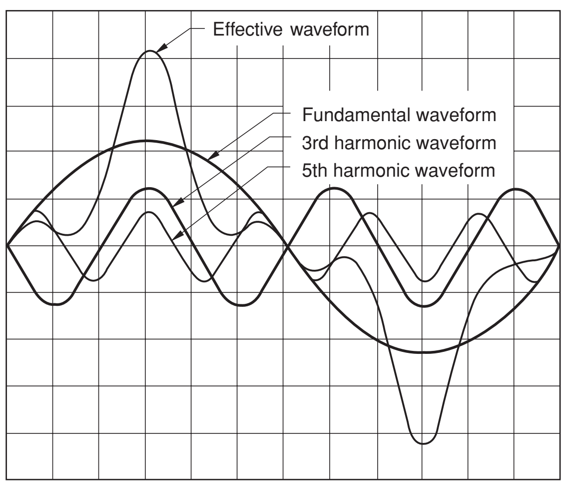
9 A capacitor will retain its charge, even after disconnection, as it takes time to decay. If it is connected across a motor it is possible that the capacitor electrostatic kVAr may excite the motor during an idle period, and make it act like an induction generator and result in an over-voltage (Section 23.13). This over-voltage may pose yet another switching problem in the inductive circuit, as discussed in Section 17.7. The capacitor manufacturers, as standard practice, provide a discharge resistance across each capacitor unit to discharge the trapped charge as soon as the capacitor is disconnected. For rate of discharge see Section 26.3.1(5).

10 As an energized capacitor retains its charge, even after a disconnection and causes a voltage transient on a reswitching, it is recommended that its circuit be closed only through a contactor or a breaker, with an undervoltage release. So that in the event of a power failure, the circuit will interrupt automatically and can be reclosed either manually or through a power factor correction relay to allow a pause before reclosing.

23.5.2 Harmonic effects and inductive interferences (an EMI effect)

Distortions in voltage and current waveforms, from their sinusoidal waveforms, are termed harmonic disorders. They are caused by equipment whose impedance varies with the voltage or current change (non-linear loads). This includes induction motors, fluorescent lamps, battery chargers, silicon-controlled rectifiers (SCRs), PWM based inverter circuits, induction and arc-furnaces and welding equipment as well as any magnetic core that saturates at varying degrees of applied voltage. A sinusoidal (a.c.) voltage that rises and falls with each one half of a cycle causes such an effect. Such loads are saturable reactors and power transformers (Section 1.2.1). The amplitudes of such distortions (harmonics) magnify with resonance effects between the system and the load impedances. The amplitude of the thus distorted sinusoidal waveform of the voltage or the current quantities is the phasor sum of all the individual sinusoidal waveforms of each harmonic present in the system, as if all the harmonics are superimposed on each other (Figure 23.7). A harmonic is the integral multiple of the fundamental frequency, such as the third, fifth, seventh and eleventh having a frequency of $3f$, $5f$, $7f$, and $11f$ respectively (f being the fundamental frequency of the system).

Generally, a few harmonic quantities are always present in an a.c. system, as normally some non-linear loads always constitute a power system. These harmonics may influence different electrical and electronic equipment and devices in different proportions. For instance they may not affect the operation of the inductive loads connected on the system as much as a capacitive load, electronic appliance or a communication network that may be running in parallel or in the vicinity of long-distance HV distribution power lines. Sometimes the communication lines may be running through the same structures on which the power lines are running.



3rd harmonic in phase opposition with the fundamental wave
5th harmonic in phase with the fundamental wave

Figure 23.7 Effective amplitude of a particular waveform with third and fifth harmonics

Below we briefly discuss the sources of generation of harmonics of different orders, their likely magnitudes and possible influence on different electrical and electronic equipment and devices connected on the system. We also study their influence on a communication network. We then provide brief guidelines to the manufacturers and the users of such electrical and electronic equipment and devices to take account of the harmonics present in the system and mitigate their effects as much as possible at the source itself in consonance with the requirements and directives of EMC and EMI regulations noted in Section 23.18.

A Effects of harmonics on the performance of a capacitor unit

Capacitors themselves do not generate harmonics but they do magnify their amplitudes, when connected in the system. If the capacitors are grounded star, they will provide a return path for the third harmonic quantity through their grounded neutral and help the system to generate third harmonic disorders. The harmonic components affect a capacitive circuit more than any other equipment connected in the system. They may also disturb a communications network as a result of capacitive coupling, whose effects are magnified in the presence of capacitor units in the power system. It is therefore considered relevant to discuss this subject in more detail to make the harmonic study more informative.

By the harmonic voltages

The effective harmonic voltage can be expressed by

$$V_h = \sqrt{(V_1^2 + V_{h3}^2 + V_{h5}^2 + V_{h7}^2 + \ldots V_{hn}^2)} \qquad (23.1)$$

where

V_h = effective harmonic voltage
V_1 = system voltage and
V_{h3}, V_{h5}, V_{h7} and V_{hn} etc. = magnitudes of the harmonic voltage components in terms of fundamental voltage at different harmonic orders.

Referring to the data available from experiments, as shown in Table 23.1, it has been estimated that a V_h of $1.1 V_1$ should be sufficient to account for the harmonic effects. For this dielectric strength is designed a capacitor unit and selected a switching or protective device.

By the harmonic currents

A harmonic component affects the performance of a capacitor unit significantly due to diminishing reactance at higher frequencies, which adds to its loading substantially and can be analyzed as follows:

$$Xc = \frac{1}{2\pi fc} \text{ or } \propto \frac{1}{f}$$

If n is the harmonic order, such as 3, 5, 7 and 9 etc., then the harmonic frequency

$$f_{hn} = n \cdot f$$

and harmonic reactance

$$X_{ch} \propto \frac{I}{n \cdot f}$$

This means that the capacitor will offer a low reactance to the higher harmonics and will tend to magnify the harmonic effect due to higher harmonic currents on account of this. In fact, harmonic currents have a greater heating effect too compared to the fundamental component due to the skin effect (Section 28.7).

$$\because\ I_{ch} = \frac{V}{X_{ch}} \qquad \therefore\ I_{ch} \propto n \cdot f$$

where

I_{ch} and X_{ch} have been considered as the capacitive current and the reactance of the capacitor respectively, at a particular harmonic frequency, $f_h = n \cdot f$. The effective current caused by all the harmonics present in the system can be expressed by

$$I_{ch} = \sqrt{(I_c^2 + 9\, I_{ch3}^2 + 25\, I_{ch5}^2 + 49\, I_{ch7}^2 + \ldots n^2\, I_{chn}^2)} \qquad (23.2)$$

where

I_c = rated current of the capacitor, and
I_{ch3}, I_{ch5}, I_{ch7} and I_{chn} etc = magnitude of the harmonic current components at different harmonic orders.

Based on the system studies carried out and Table 23.1, it has been assessed that in actual operation, effective current through a capacitor circuit may increase up to 1.3 times its rated current, I_c, i.e. $I_{ch} \simeq 1.3\, I_c$ to account for all the harmonic effects ($V_h^2 \cdot f_h$; Equation (23.4)). A capacitor unit is thus designed for at least 30% continuous overload capacity (Section 25.6). Its switching and protective devices are selected along similar lines.

Summarizing the above, the harmonic quantities when present in a system on which are connected a few capacitor banks affect the capacitors as follows:

- Over-current will mean higher losses ($I_{ch}^2 \cdot R$).
- Over-current will also mean an over-voltage across the capacitor units, which would inflict greater dielectric stresses on the capacitor elements.
- Since the harmonic disorders occur at higher frequencies than the fundamental ($f_h > f$), they cause higher dielectric losses due to a higher skin effect.

Harmonic output of a capacitor unit

The rating of a shunt capacitor unit

$$\text{kVAr} = \frac{\sqrt{3} \cdot V \cdot I_c}{1000} \quad (V \text{ in volts and } I_c \text{ in amperes})$$

and $\quad I_c = \dfrac{V}{X_c}$

$$\therefore \text{kVAr} = \frac{\sqrt{3} \cdot V^2}{1000 \cdot X_c} \qquad (23.3)$$

$$\text{or kVAr} = \frac{\sqrt{3} \cdot V^2 \cdot 2\pi\, \text{f.c.}}{1000} \qquad (23.4)$$

Generalizing, $\text{kVAr}_h \propto V_h^2 \cdot f_h$

or

$$\text{kVAr}_h \propto \sqrt{V_1^2 + 3 \cdot V_{h3}^2 + 5 \cdot V_{h5}^2 + 7 \cdot V_{h7}^2 + \ldots n \cdot V_{hn}^2)} \qquad (23.5)$$

The rating of a capacitor unit will thus vary in a square proportion of the effective harmonic voltage and in a direct proportion to the harmonic frequency. This rise in kVAr, however, will not contribute to improvement of the system p.f. but only of the over-loading of the capacitors themselves.

Note

1 When determining the actual load current of a capacitor unit in operation, a factor of 1.15 is additionally considered to account for the allowable tolerance in the capacitance value of the capacitor unit (Section 26.3.1(1)):

$$\therefore \text{ Effective kVAr}_h = 1.3 \times 1.15$$

$$\simeq 1.5 \text{ times the rated kVAr}$$

and for which all the switching and protective devices must be selected. It may, however, sometimes be desirable to further enhance the over-loading capacity of the capacitor and so also the rating of the current-carrying components if the circuit conditions and type of loads connected on the system are prone to generate excessive harmonics. Examples are when they are connected on a system on which are operating non-linear drives like, static drives and arc furnaces.

2 It is desirable to contain the harmonic effects as far as practicable at the installation of capacitors itself, to protect the capacitors as well as inductive loads and all electronic equipment and devices connected on the system and the communication network, if running in the vicinity.

B Influence of harmonics on the performance of an inductive load

In an inductive circuit the presence of harmonics is not felt so much as the higher harmonics tend to enhance the harmonic reactance, which causes a damping effect:

$X_L = 2\pi \cdot f \cdot L$

For a harmonic order n and harmonic frequency $n \cdot f$, the harmonic reactance will become

$X_{Lh} = 2\pi \cdot n \cdot f \cdot L$, i.e. $\propto n \cdot f$

- At higher harmonic frequencies, X_{Lh} will rise proportionately and reduce the harmonic currents and provide a damping effect. The harmonic quantities present in the system thus do not have any significant effect on the performance of an inductive load, which can be a generator, transformer, motor, cables and overhead lines etc. In an LV system, such effects are highly damped due to high system impedance. No special efforts are therefore generally made to suppress the harmonic effects in an LV system.
- The magnetic core of an electromagnetic equipment (generator, transformer, reactor and motor etc.) will, however, generate additional no-load iron losses at higher harmonic frequencies (Equations (1.12) and (1.13)). The content of iron losses, being low, will rise only marginally and can be ignored for all general applications.

C Influence of harmonics on electronic equipment and devices

The influence of harmonics in such cases would be in the form of some kind of distortion or disturbance. For instance in case of measuring and calibrating instruments or health monitoring apparatus it may be in the form of erroneous readings and calibrations or misleading diagnosis (in case of medical instruments). In case of protective relays it may be by way of wrong signals and erratic indications and in case of audio or visual devices and household appliances it may be by way of noise disturbance and poor quality of video viewing.

- Electronic appliances that are highly susceptible to such effects are, however, provided as standard practice with harmonic filters in their incoming circuits, see Section 23.18.

D Effects of harmonics on telephone lines

In earlier years, to reach a remote area, where separate telephone lines had not been laid it was normal practice to run them through the same poles as the HV power distribution lines (generally 11–33 kV). This was particularly true of internal communications of the electricity companies for ease of operation and to save costs and time. This communication was known as the magneto-telephone system. But the proximity of telephone lines to power lines adversely affected the performance of the telephone lines due to generation of over-voltages (Chapter 20) and electrical interferences (conductive and inductive interferences, discussed later) on the telephone lines by the power lines. Some of these interferences, particularly system harmonics, had the same frequency as the audio frequency of the telephone lines and affected their audio quality severely.

The running of telephone lines through power lines is long discontinued. They are now run on separate structures within a city and nearby areas at audio frequency ($\simeq$ 0.3–3.4 kHz), and maintain enough distance from HV power distribution lines. They are therefore almost unaffected from such disturbances. Nevertheless, interferences must be kept in mind when installing these lines so that they are out of the inductive interference zone of the power lines. The latest method in the field of communications to avoid disturbances is to use undergrounded optical fibre cables, where possible, as discussed later. Optical fibre cables are totally immune to such disturbances.

Remedies for electrical interferences

The following measures are recommended to mitigate these problems:

1 Use of screened cables in the communication network and grounding the screen effectively. Metallic-sheath or armoured cables are not recommended.
2 Transposing the overhead communication lines, i.e. reversing the respective positions of the two sides of the lines every 1 km or so, to avoid continuous parallelism (due to electrostatic and electromagnetic inductions), as illustrated in Figure 23.8. See also Section 28.8.4(3) on phase transposition.
3 It is common practice to leave the star-connected capacitor banks ungrounded when used in the system

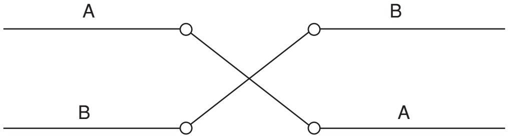


Figure 23.8 Transposition of overhead communication lines

or use delta-connected banks to prevent the flow of third harmonic currents into the power system through the grounded neutral. Similarly a filter circuit can be provided in their neutral circuit to drain out the third harmonics.

4 Use of filter circuits in the power lines at suitable locations, to drain the excessive harmonic quantities of the system into the filter circuits.

Filter circuits

A filter circuit is a combination of capacitor and series reactance, tuned to a particular harmonic frequency (series resonance), to offer it the least impedance at that frequency and hence, filter it out. Say, for the fifth harmonic, $X_{C5} = X_{L5}$,

Since $f_{h5} = 5 \cdot f$

$$\therefore \quad \frac{1}{2\pi \cdot 5f \cdot C} = 2\pi \cdot 5\,\mathrm{f} \cdot \mathrm{L}$$

$$\text{or} \qquad \frac{X_c}{5} = 5X_L$$

$$\text{or} \qquad X_c = 5^2 \cdot X_L$$

Generalizing, $X_c = N_h^2 \cdot X_L$ for the N_hth ordinal number of the harmonic disorder.

A capacitor is susceptible to variations in the system voltage, frequency and operating temperature. Failure of capacitor elements may also cause a variation in capacitive values in the three phases of the filter circuit. Under these conditions, it is possible that a filter circuit may fall out of tune during normal service and cause excessive currents in one or more phases due to sub-synchronous or ferro-resonance effects with the impedance of the main system. If we consider the reactance of the detuned circuit as X_c (considering it to be capacitive after detuning, as X_c will rise when C of the capacitor units decreases), which may fall in phase opposition to the system reactance X_L (considering it to be inductive), as shown in Figure 23.15(b) then it will lead to such a situation and cause excessive harmonic currents through the filter circuit, due to its low effective impedance, Z, since

$Z = R_o + X_L - X_C$ (R_o is the resistance of the main system)

= very low

It is therefore recommended that a small resistance of a low $I^2 \cdot R$ loss be introduced into the filter circuits as shown in Figure 23.15(a) to limit such an excessive flow of currents through them. Knowledge of the system parameters (resistance and reactance) is also essential to design an appropriate filter circuit to avoid a possible resonance in the first instance. If this occurs the resistance thus introduced will limit the excessive flow of current.

5 Another remedial measure is the use of blocking circuits by providing a high-impedance path in the ground circuit when a phase-to-ground circuit is used for the communication network, to block the entry of the third harmonic quantities into the system from other systems.

Blocking circuits

These are parallel resonant L-C circuits, and are tuned to offer a high impedance to a particular harmonic frequency to block its entry into the system through its neutral from another system. For other frequencies, particularly at power frequency, it will offer a very low impedance and permit them to flow into the system. The filter circuit may now be designed for a notch frequency of

$$f_h = \frac{1}{2\pi \cdot \sqrt{LC}} \tag{23.6}$$

At this frequency, the filter circuit will offer a very high impedance and block the entry of that harmonic to flow into the circuit through its neutral. For other frequencies, it will provide a very low impedance and permit them to flow into the circuit. Thus for any value of f_h the product of LC can be determined, and the blocking circuit can be designed. To achieve a narrow bandwidth of attenuation, at near f_h, the blocking circuit may be designed separately for each major harmonic frequency (f_h). To ensure a high X_{ch}, it is advisable to keep the value of L low and hence limit the inflow of charging currents.

Application of such circuits is also provided in the form of a line trap, which is a blocking circuit and is used at each end of the line to which the carrier relaying is connected as discussed later. A bypass or filter circuit is also provided to drain the power frequency component of the current when present in the communication network. One end is connected to the main line through a coupling capacitor or CVT and the other to the ground through the PLCC (Power Line Carrier Communication), as illustrated in Figure 23.9(b). Leading manufacturers combine the coupling equipment and PLCC coupling device into one unit for ease of application and installation.

6 Use of tertiary (auxiliary) winding

When a power transformer is Y/Y or Y/Y connected and is feeding a system on which harmonics are not desirable, it is generally provided with a tertiary winding. A tertiary winding, which is also called an auxiliary winding, is an additional winding connected in Δ, and sandwiched between the main primary and the secondary windings of the transformer. It thus has the same magnetic circuit. This winding provides a closed path for the third harmonic quantities to circulate and prevents them from appearing on the load side. It may also be used for the purpose of metering, indication and protection of ground fault currents.

Other than the system harmonics, electrical interferences are also caused by line disturbances, which may be caused by lightning, switching, sparking or a fault. As discussed in Chapter 17, line disturbances occur at very high frequencies but some may coincide with the audio frequency of telephone lines, and cause disturbance in the audio quality of the telephone system. All these disturbances are referred to as inductive interferences.

We provide below more details on inductive interferences to make the subject of electrical interferences more informative. We also provide a passing reference to communication systems being adopted worldwide, at sub-section (F).

E Influence of harmonics on other electrical and electronic circuits

By the harmonic voltages

1 All electrical equipment and devices connected on the system are subject to higher dielectric stresses due to a higher effective voltage (Equation (23.1)).
2 High harmonic voltages may give rise to pulsating and transient torques in a motor or a generator, in square proportion to the voltage ($T_h \propto V_h^2$). At higher amplitudes of such harmonics, it is possible that the driving or the driven shafts may even shear off as a consequence of transient torques. Transient torques, up to 20 times the rated torque, have been experienced with oversized capacitor units connected on the system, causing wide voltage fluctuations.
3 Additional noise from inductive equipment such as motors, generators and transformers and even overhead lines.
4 Flickering of GLS lamps in homes and offices.

By the harmonic currents

1 Over-heating of the windings of an inductive load, such as a transformer and rotating machines, cables and overhead lines etc., connected on the system due to the higher effective current (Equation (23.2)).
2 The electromagnetic relays, having a magnetic core and are matched to the fundamental frequency, may be sensitive to such disturbances and malfunction, sending erroneous signals leading to malfunctioning of control systems (see Table 13.17).
3 They may cause magnetic disturbances and noise in communication networks in the vicinity as discussed above.
4 They may also affect the performance of electronic equipment operating on the same system, such as a computer or a static power factor correction relay.
5 Increased errors in all types of measuring instruments, which are calibrated at a fundamental frequency.
6 Interference with the communication network.
7 Possible resonance and ferro-resonance effects (Section 20.2.1(2)) between the reactances of the generator and the transformer windings and the line capacitances. In addition to the line capacitors, it is possible that the circuit gets completed through the ground coupling capacitances (Section 20.1 and Figure 20.2) and give rise to high to very high system voltages. The effect will be the same, whether the system is grounded or not. The ground coupling capacitances providing the return path, as through a grounded neutral. This phenomenon would normally apply to an EHV system.

By the harmonic flux and frequencies

Increased iron losses in the inductive machines, operating on such a system, due to saturation effects (Equations (1.12) and (1.13).

F Influence of HV and EHV system disturbances on communication services

(an EMI effect (Section 23.18))
[For serial data transmission see Section 24.11.5]

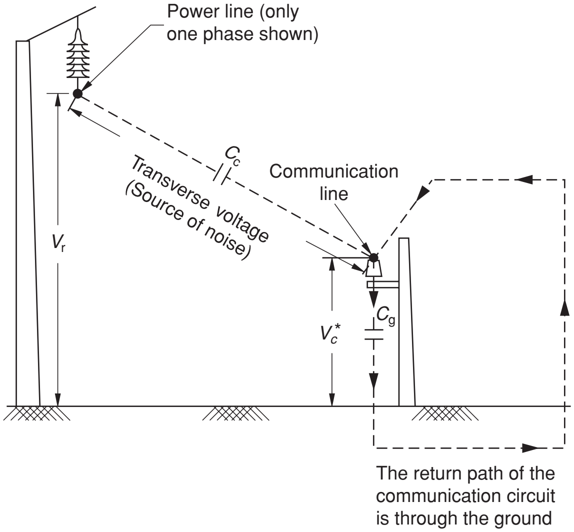
Power and communication lines are not run through the same structures due to very high transmission and distribution voltages. Referring to long HV* or EHV* power lines, electrical interferences are caused whenever these lines and the communication lines run in parallel in close vicinity to each other and the distance between them falls short of the inductive zone of the power lines. To protect the communication lines from inductive (due to induction) interferences their distance from the power lines is maintained such as to contain the maximum radio influence voltage (RIV) of the power lines on the communication lines within 100 μV at 1000 kHz, as in **NEMA-107. The main causes of inductive interferences in an overhead communication network are electrostatic (electric) and electromagnetic (EMI) interferences, which magnify on a line disturbance as discussed below.

1 Electrostatic induction (a voltage effect)

This is the prime cause of noise and distortion in an audio system. The capacitive coupling (conduction) between the power and the communication lines gives rise to such an effect. It is associated more with the voltage of the system and particularly when it is capacitor compensated. Even without the power capacitors, the leakage (coupling) capacitances between the HV or EHV power lines, particularly 132 kV and above, and the overhead communication lines play an important role and give rise to this phenomenon. Systems lower than 132 kV do not cause such a situation as a result of the insignificant capacitive effect.

Normally small charging currents will flow from the main power lines to the communication lines through their coupling capacitances C_c (Figure 23.9(a)). The charging currents find their return path through the grounded communication lines (when the communication lines have their return path through the ground), having a ground capacitance C_g. These capacitances form a sort of voltage divider and induce an electrostatic voltage into the communication lines which can be expressed by

* For classification of voltages as per IEC 60038 see Introduction.
**NEMA – National Environmental Management Act (South Africa).



* Longitudinal voltage (Source of danger to the telephone equipment and operating personnel)

Figure 23.9(a) Electrostatic influence on a communication line

$$V_c = \frac{C_c}{C_c + C_g} \cdot \frac{V_r}{\sqrt{3}} \tag{23.7}$$

where

V_c = induced electrostatic voltage in the communication lines

C_c = coupling capacitance between the power and the communication lines and

C_g = ground circuit capacitance of the grounded communication lines.

Both C_c and C_g, are related to the system voltage, as can be inferred from Table 24.1(b). The field induced by them is termed an electric field (non-magnetic). This field, i.e. content of C_c and C_g, rises with an increase in the system voltage.

V_r = nominal voltage of the power system.

The voltage, V_c, is the main source of distortion in the audio quality of speech and the carrier waves. In normal conditions (at power frequency) the electrostatic effect may be feeble but during a line disturbance, the charging currents (V_h/X_{ch}) magnify due to higher system frequencies (high f_h) and the diminishing value of coupling impedance, $X_{ch} = \dfrac{1}{2\pi f_h C_c}$ and cause severe distortions in the audio and carrier waves. The higher the system frequency on a disturbance, the higher will be the distortion level, even for their (harmonics) small contents (Table 23.1). During a phase-to-ground fault, for instance, the ground potential may rise (Section 20.1) and cause much higher inductive interferences (electrostatic induction), that may jeopardize the communication systems particularly those serving essential services such as railways, aviation, defence installations, power generation and transmission. The ground conductor now acts like a large-diameter solenoid producing high induced currents in the grounded communication network and raises its ground potential. It gives rise to noise disturbances and affects its audio quality. It may also distort the carrier waves ($\simeq$ 30–500 kHz) such as those used in a power line carrier communication (PLCC) network, and mutilate the transfer of vital data or send out wrong signals. To achieve better reliability, such as on a critical power network, coupling between phase to phase is used. We provide the layout of such a system in Figure 23.9(b).

2 Electromagnetic induction (EMI) (a current effect)

This may occur as a result of electromagnetic induction between the power and the communication lines due to their proximity. The magnetic field produced by the main power conductors may infringe upon nearby existing communication lines. As such, it may not cause serious disturbance due to adequate spacing (>305 mm, Section 28.8) between the power and the communication lines. But in a grounded communication network the situation may deteriorate, during a single phase-to-ground fault in the power lines. The grounded conductor which will carry the ground fault current will now act as a very large-diameter solenoid and produce high magnetic fields, inducing heavy over-voltages in the communication lines significantly affecting audio quality. Where a more reliable communication network is imperative, this is achieved by connecting the network between phase to phase than phase to ground.

All effects caused by electrostatic or electromagnetic inductions are termed Inductive Interferences. With the use of glass optical fibre cables in new installations, this effect is overcome automatically. Optical fibre cables, as discussed later, have no metal content and carry no electrical signals. Therefore the above discussion is more appropriate for existing installations not using latest technology or optical fibre cables and also to provide a theoretical aspect and more clarity to the phenomena of inductive interferences.

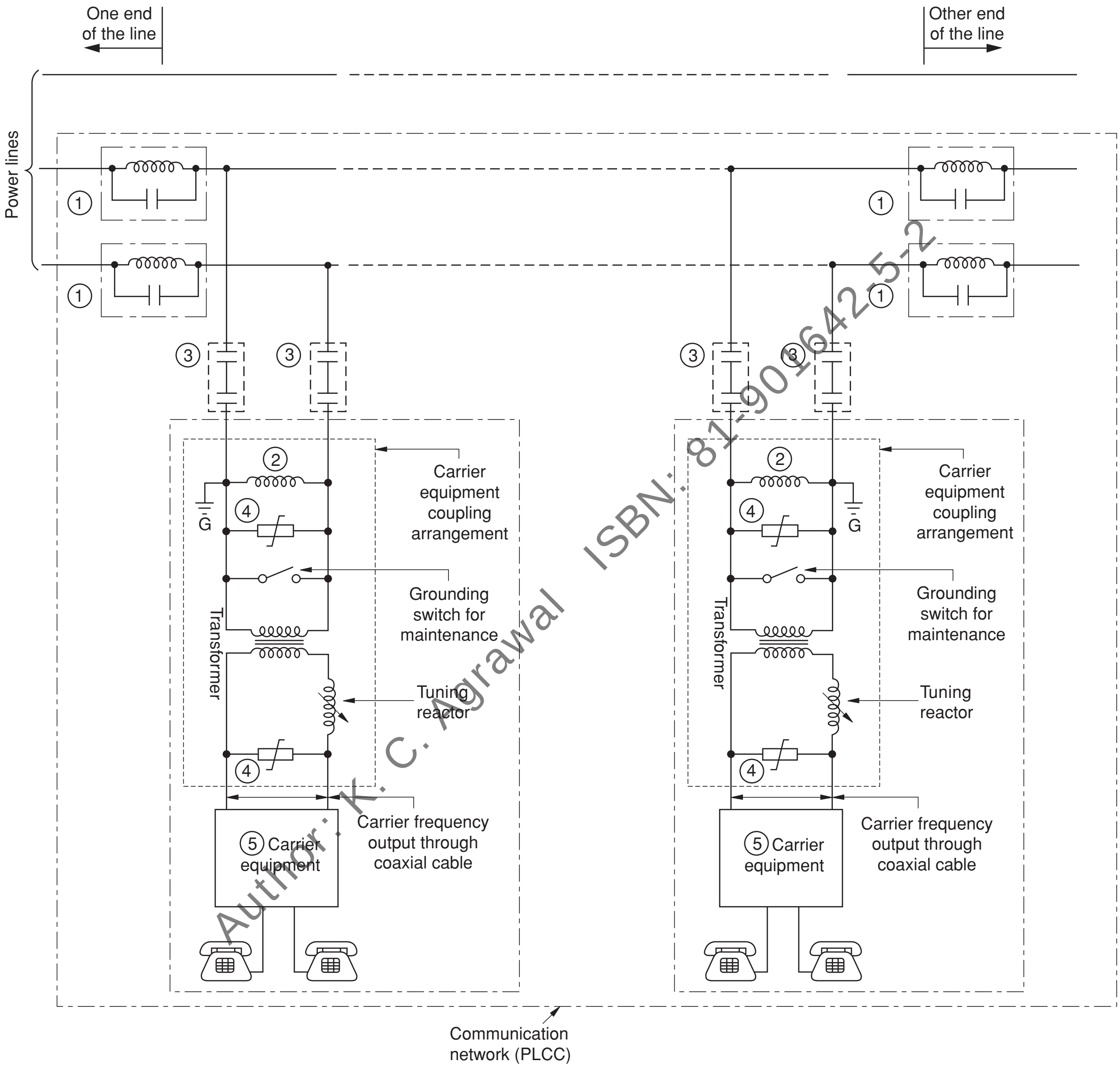
In the earlier installations sensitive to such interferences the normal practice was co-ordination between the generating and power transmission agencies and the authorities of essential services (such as public telephones, defence services, civil aviation and railways), who provide their own communication systems, to relocate their telephone network to mitigate this problem at the planning stage itself. The practice continues to ensure a sound communication network free from all disturbances as far as feasible.

3 Poor joints and arcing grounds

In addition to the above, sparking in the main lines due to poor joints or old and dirty insulators, flashovers and arcings during making and breaking of contacts of a switching device or arcing grounds also may generate high-frequency radio waves 10 kHz to some MHz and distort the carrier and radio frequency waves.

4 Corona discharge

Similar distortions in carrier and radio frequency waves are also caused by corona discharges. Corona discharge is a phenomenon of HV and EHV overhead lines and is a result of ionisation of atmospheric air in the close vicinity of conductor under certain electrostatic field intensity (as caused by electrostatic induction noted above) and adverse weather conditions such as during rainy season or when the surrounding air is damp and humid. Damp and humid air possessing a reduced dielectric strength breaks down and becomes conducting. Breakdown strength of air, under normal temperature of 25°C and pressure 76 cm of Hg is about 3.1 kV/mm peak. Its



1. Line Trap:
   To block carrier frequencies to travel beyond the communication network and weaken the vital signals.
2. Drain Coil:
   It has low impedance at power frequency and high impedance at carrier frequency
   (a) To drain out power frequency component of the current when present in the communication network
   (b) It also protects the CVT from overvoltages.
3. Coupling capacitor or CVT is used when it is required for measurement and protection. For details on CVT refer to Section 15.4.4.
4. Surge Arrester:
   To drain out the excessive voltages transferred to the communication network through the CVT, caused by lightning, switching or a fault.
5. The carrier equipment generally comprises the following:
   (a) Carrier wave instruments and devices,
   (b) Protection signalling equipment and devices, and
   (c) Telephone, Telex, Fax and Data transmission equipment.

Figure 23.9(b) Typical layout of a line coupling device and carrier equipment (PLCC) showing phase-to-phase coupling breakdown causes a leakage current between the phase conductors or phase to ground through the leakage capacitances, rich in harmonics (Section 18.10), similar to the leakage current of a surge arrester (Section 18.2) and results into a power loss.

It occurs in the form of a pale violet glow shining ball on the surface of the conductor and is associated with a hissing noise and odour of ozone. Besides the power loss, being rich in harmonics, it also causes radio interference and distorts the line communication network. Nevertheless in the event of a voltage surge it provides a conducting path to the ground and damps the magnitude of surges and supports the arrester. The severity of corona is influenced by irregularities of the conductor like bends, curvatures and roughness of surface, deposits of dirt and silt etc. as noted above. The ionisation takes place where the maximum electrostatic field exists. These irregularities are spots prone to having the maximum field and consequently become prominent spots for corona discharges. To minimise this effect, precautions are necessary to avoid or at least keep irregularities and projections as low as possible like by avoiding jagged bolt heads or shield them adequately by providing a sleeve or tube over such joints and maintaining conductor surface clean and smooth as far as possible.

Reliable communication services

A reliable telephone system for public communication, a defence installation, railways, civil aviation or a power generating and transmitting network is an essential requirement between any two stations, and must be free of such disturbances. The proximity of HV and EHV power lines influences their performance. Some interference may be due to lightning and switching surges or corona discharges at very high frequencies. All these may cause disturbances when their frequencies coincide with those of the carrier waves ($\simeq$ 30–500 kHz) and radio waves (in MHz). These disturbances may also distort the transmittal of vital data and information, when such services are also employed for transmitting of information such as through a power line carrier communication (PLCC) and signalling network or a SCADA system (Section 24.9).

We give below for a general reference brief details of a PLCC network as used for power generating and transmitting communication services. A PLCC uses coupling equipment, filter and blocking circuits, which have also been discussed in this chapter.

Power system communication through a PLCC

Power system communication is a complex subject. As power generation and transmission capacity grows, so does the necessity for exchange of information at high speed, between the generating stations, local dispatch centres and the load control centres. Powerhouse communication services are different from normal telephone services. These are dedicated networks regarded as highly essential and require far more reliability to maintain continuity. They should remain free of disturbances, particularly during fault conditions or line disturbances. Reliable communication helps in monitoring all the feeding stations and generating units that are operating in tandem on that network for their operating conditions and load balancing and then taking prompt remedial action, when required, by load balancing or load shedding as may be necessary. It also provides protection signalling to isolate the faulty section from the system and enhance the security or dynamic stability level of the system. All this is achieved with the use of a PLCC network, which is connected at both ends of the lines as illustrated in Figure 23.9(b). It can carry out a number of important functions for a power generating and transmitting network, besides monitoring its health. The main functions of a PLCC can be

- Voice communication (telephone services) between the generating stations, substations and the load dispatching centres.
- Fax and telex services
- Telemetering:
  - (a) To transmit messages and data between two stations and to monitor and take preventive measures in the operating conditions of the entire power network, to achieve a more efficient and reliable power system.
  - (b) To transmit data records of voltage, frequency, kW, kWh and kVAr or any other relevant information on the system's operating condition. These data are generally superposed on the speech channels.

Note
There can be separate dedicated channels for data transmission and voice communication. The data channel can also be superposed over a voice on the same channel.

- Remote supervision and automatic load-control of generating units, load dispatch centres and substations to maintain the desired operating parameters, including load sharing.
- Protection signalling between two ends of the line. This accelerates operation of the protective relays either by isolating the faulty line from the system or by preventing tripping of a healthy line through blocking signals during a system disturbance, hence retaining continuity of supply of the healthy lines on a system disturbance as far as possible.
- Carrier relaying permits high-speed clearing of faults.
- For protection where the direction of the current or the phase angle of the two ends of the line are compared to decide whether there is a fault on a particular line.

The transmission of data to the load dispatch centres is conducted at different frequencies. The carrier frequency is decided by the user and may fall in the range of 30–500 kHz. A typical communication and relaying scheme is illustrated in Figure 23.9(b). For more details on PLCC refer to Further Reading at the end of the chapter.

A PLCC should ensure a good quality of speech and transmission of vital data at a carrier frequency for clear and unambiguous communication between two stations. It should also avoid false signalling so that

- High-frequency disturbances are not transferred to the carrier equipment through the coupling equipment.
- Disturbances do not mutilate the transfer of vital data or send out erroneous signals that may lead to

malfunctioning of some vital relays or prevent them from taking timely corrective action.

- The coupling of a PLCC with the main lines is carried out through line traps, and coupling capacitors or a CVT. A CVT is used when it is also required for measurement and protection. For details on a CVT refer to Section 15.4.4.

The PLCC can be connected between a phase and the ground of the transmission line itself, the ground forming the return path. Use of only one conductor saves on cost and makes the whole system economical. But this arrangement is not reliable due to dependence on a single conductor which during a problem or fault on this phase may render the whole communication system inoperative. Good practice is therefore to connect the PLCC between any two phases. A typical network is shown in Figure 23.9(b). Use of digital PLCC equipment can provide a more reliable communication system and more speech and data communication channels. The latest in the field of primary system communication is using optical fibre cables noted briefly below. For high speed data transmission through serial data transmission system see Section 24.11.5.

Optical fibre cables (OFCs)

The optical fibre communication system employs the latest technology in the field of communication and data transmission and replaces the use of conventional copper cables and overhead lines to underground fibre optical communication systems. The principle of this technique is that the transmission of light signals by internal reflections through transparent fibres of glass, can be carried over long distances without losing clarity or strength.

The optical fibre is an extremely pure core of glass fibre, surrounded by a cladding to contain the light beams within the core. Metallic shielding of non-magnetic material is also provided over the glass fibre to protect the cable from damage during transportation and handling. These cables are totally immune to electromagnetic interferences (EMIs) (Section 23.18).

The electrical signals (pulses) of the audio waves are converted into light pulses optical energy through transducers. This optical energy is then aimed at one end of the thin and transparent optical fibre. The thickness of the fibre is even less than a human hair, say, up to 25 μm. The core of fibre glass transforms the optical (light) energy into a single wave (1330×10^6 or 1550×10^6 km wavelength) of intense light. This wave possesses much more capacity for carrying information than copper cables. At the receiving end a decoder is used to convert the optical energy back to the original audio waves. A bunch of optical fibre cables can transmit millions of audio signals at the same time, each fibre being capable of transmitting as much information as a thick copper cable with a number of cores.

This technique has completely transformed traditional overhead communication systems. As there is no use of copper or electricity in the optical fibre the optical waves are not subject to any electrical interference as discussed above. Corning Glass Works, USA, were the first to produce such cables in 1970.

23.6a Generation of triple harmonics in an inductive circuit

A hysteresis loss in an electromagnetic circuit will occur due to molecular magnetic friction (magnetostriction), as discussed in Section 1.6.2(A-iv). This causes a distortion in voltage and current by distorting their natural sinusoidal waveforms. This distortion in the natural waveforms, in terms of magnetizing current I_m, induced e.m.f. e and magnetic flux ϕ of the magnetic circuit is the source of generating triple harmonic quantities, the magnitude of which will depend upon the shape of the hysteresis loop, which is a function of the core material. A fluctuation in the system voltage which causes a change in the flux density B (Equation (1.5)) also adds to the triple harmonic quantities. Permeability μ of the magnetic core is different at different flux densities B. This also results in giving rise to triple harmonics due to magnetic friction (magnetostriction). Wherever the switching of a capacitor bank is more frequent, the generation of triple harmonic voltages is more severe.

Uneven distribution of loads causes an imbalance in the supply system which also generates triple harmonic voltages. This is more pronounced in LV systems than in HV systems due generally to fewer switching operations and an almost balanced load distribution in HV systems (also refer to Table 23.1). But an HV system too is not free from third harmonics due to unequal overhead line impedances which may be caused by unequal spacings between the horizontal and vertical formation of conductors, asymmetrical conductor spacings and hence an unequal induced magnetic field. Over-excitation of transformer cores, which may be a result of voltage fluctuations or a load rejection, may also cause triple harmonic voltages. When capacitors are used to improve the system's regulation, they may cause excessive voltages during offpeak periods, resulting in an over-saturation of the transformer cores and the generation of triple harmonics.

23.6b Generation of harmonics by a power electronic circuit

Another reason for harmonic disorders is the presence of power electronic circuits in the system. The loads supplied through solid-state devices such as thyristors and PWM inverters generate non-sinusoidal waveforms. These waveforms give rise to harmonic currents and distort the supply voltage. Line-commutated converters and frequency converters employed for a.c./d.c. drives, electrolytic processes, inverters, a.c. controllers, d.c. choppers, cyclo-converters, and SCR rectifiers are examples of electronic applications that may generate harmonic quantities and influence the normal current drawn by a power capacitor (for details see Section 6.13). With advances in power electronics, modern power systems have a wider application of solid-state technology in the control of induction motors and d.c. motor drives as discussed in Chapter 6. There is therefore more likelihood of the presence of harmonics in the system that may result in high to very high harmonic currents and consequent harmonic voltages. This effect is felt more on LV and also HV systems up to 11 kV where use of static controls is more prominent. For the harmonics generated by power electronic circuits, the harmonics ordinal numbers that may be present in the system are expressed by

harmonic ordinal number $N_h = nk \pm 1$

where

n = pulse number; 3 for a three phase and 6 for a hexaphase power electronics circuit, etc.

This represents the type of converter connection and identifies the number of successive commutations (i.e. the number of discrete segments of the d.c. waveform, Figure 23.10) the rectifier unit will conduct during each cycle of a.c. power input. The higher the pulse number, the nearer will the mean and effective values of the rectified voltages approaching the peak value, as illustrated in Figure 23.10. Six pulse rectifiers are therefore considered ideal to achieve a near-peak voltage both in its mean and effective values and are more commonly used. In which case; form factor or harmonic distortion factor

$$\frac{\text{Effective value (r.m.s. value of all harmonics)}}{\text{Mean value}} \simeq 1.0009$$

and rectifier peak factor, i.e. $\dfrac{\text{Peak value}}{\text{Mean value}} \simeq 1.05$

as against the values indicated in Figure 23.11. Figure 23.10 illustrates some common types of pulse numbers, the likely shape of their waveforms and the approximate values of their 'form factors' and 'rectifier peak factors'.

k = 1st, 2nd, 3rd, and 4th etc. waveforms

For k = 1 and 2, the harmonic sequence will be

(i) for a three-phase thyristor circuit
$3 \times 1 \pm 1$, i.e. 2 and 4, and
$3 \times 2 \pm 1$, i.e. 5 and 7, etc.

(ii) for a hexaphase thyristor circuit
$6 \times 1 \pm 1 = 5$ and 7, and
$6 \times 2 \pm 1 = 11$ and 13, etc.

The plus sign indicates a positive sequence harmonic and the minus sign a negative sequence harmonic. Their effect is same as for the positive and the negative sequence components discussed in Section 12.2(v) and causes pulsation in the magnetic field (magnetostriction) and hence, in the torque of a rotating machine.

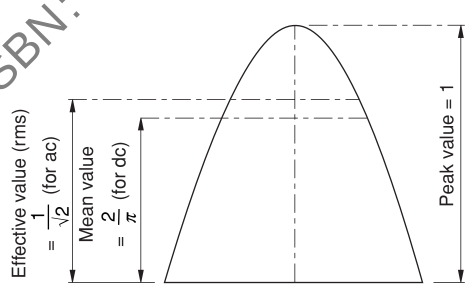
23.6c Resonance

Yet another reason for harmonic disorder in a power circuit is the occurrence of series or parallel resonance or a combination of both. Such a situation may occur at certain frequencies generated by the harmonic generating sources in the system. The capacitors installed in the system magnifying the same.

All such harmonics are undesirable for the system and the equipment connected to it. Refer to Table 23.1 for the likely magnitudes of harmonic quantities which may be present in a typical power system.

23.6.1 Theory of circulation of triple harmonic quantities in an a.c. system

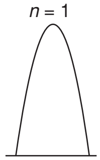
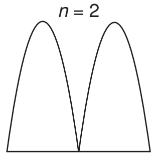
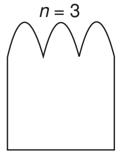
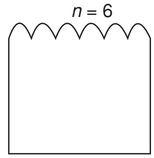
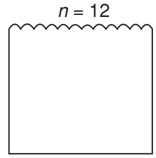
Triple harmonic quantities are unbalanced quantities and can exist only on a system, which has a grounded neutral.



Form factor $= \dfrac{1/\sqrt{2}}{2/\pi} = 1.11$ Rectifier factor $= \dfrac{1}{2/\pi} = 1.57$

Note: When referring to the d.c. side, it is the mean value and when referring to the a.c. side, it is the effective value that is more relevant

Figure 23.11 Effective and mean values in a sinusoidal waveform

Parameters	Likely waveforms generated by a rectifier unit in its output for each cycle of a.c. input, for different numbers of pulses				
	n = 1 	n = 2 	n = 3 	n = 6 	n = 12 
$\dfrac{\text{Effective value*}}{\text{Mean value}}$ [Form factor or harmonic distortion factor]	1.57	1.11	1.017	1.0009	1.00005
$\dfrac{\text{Peak value}}{\text{Mean value}}$ (Rectifier peak factor)	3.14	1.57	1.21	1.05	1.01

* – rms value of all harmonics

Figure 23.10 The content of ripples for different number of pulses (n)

The configuration of the windings of the source generating the harmonics, the system to which it is connected, and its grounding conditions, thus play a significant role in transmitting the harmonics to the whole system as discussed below:

When the system is star connected

1 **Isolated neutral** In a symmetrical three-phase three-wire star-connected system the summation of all phase quantities, voltage or current will be zero, as illustrated in Figure 21.7. When a few harmonics exist in such a system, this balance is disturbed and the sum of these quantities is not zero. The third harmonic quantities can find their outlet only through a neutral of the system. Since there is no neutral available in this system, no third harmonic quantities will flow into or out of the supply system and affect the equipment associated with it or a communication network if existing in the vicinity (Figure 23.12(a)).

2 **Ungrounded neutral (floating neutral)** However, when the neutral is provided, each phase can complete its own circuit through the neutral, provided the connections are made so that it can complete its circuit through the neutral. The supply system would contain no third harmonic now also, as it cannot drain out this through a floating neutral. The supply system, being balanced, would contain no harmonic as noted above. In each phase to neutral, however, the third harmonic may exist but of a lesser magnitude, depending upon the impedance of the system. (Figure 23.12(b).)

3 **Grounded neutral** When the neutral is grounded, the third harmonic quantities will be able to find their way through it. This system can thus be considered to contain the third harmonic quantities and will affect operation of the equipment connected on it and communication networks if existing in the vicinity (Figure 23.12(c)).

When the system is delta connected

This is a similar system to that discussed in 1 above and will contain no third harmonic quantities (Figure 23.12(d)).

23.7 Effective magnitudes of harmonic voltages and currents

A waveform containing harmonics may be considered to be a standard sinusoidal waveform superimposed with the other harmonic waveforms. Figure 23.7 illustrates a

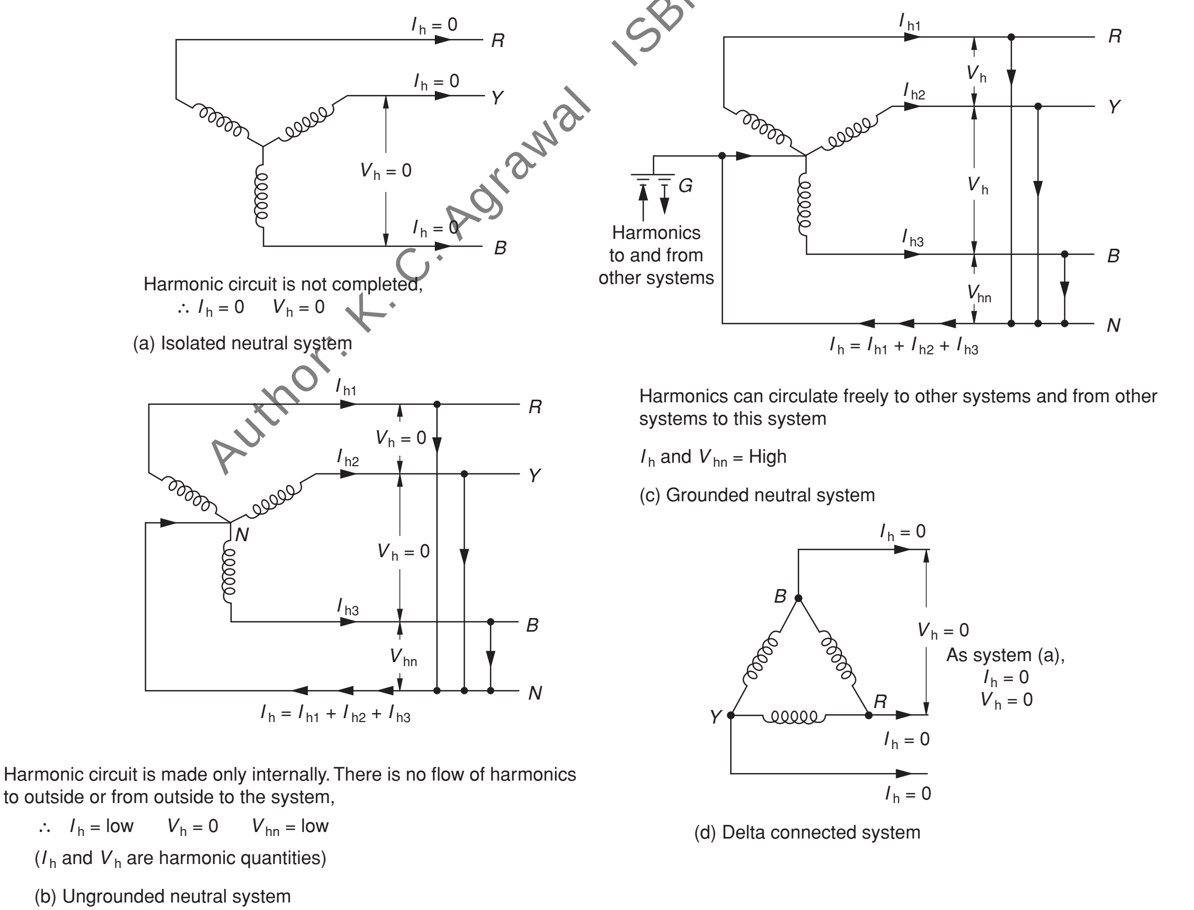


Figure 23.12 Circulation of triple harmonic quantities

standard sinusoidal waveform, superposed with third and fifth harmonic waveforms. Higher harmonics are not shown being of lower magnitudes. Harmonics tend to diminish in amplitude at higher orders, i.e. amplitude at h3 > h5 > h7 etc., where h3, h5 and h7 etc. are the harmonic quantities at the third, fifth and seventh harmonic orders respectively. The effective value under the influence of such harmonics will be the summation of all such harmonics present in the system. Each harmonic wave may have a different phase relationship with the fundamental waveform, as illustrated in the figure, and add or subtract from it to give the waveform a shape somewhat of a pulsating nature as shown in Figure 23.7.

Accurate measurement of harmonic quantities and their cumulative effect is a complex subject, and is not possible to determine theoretically with the help of algebraic equations. But it can be easily measured with the help of a harmonic analyser*. Cigre (1989) has made a comprehensive study of the likely harmonics and their amplitudes that may be present in a power system. These are briefly described in Table 23.1.

Inference
The study based on which the table is produced has revealed the following important aspects:

1 Hexaphase electronic circuits generate maximum harmonic disorders. It is therefore advisable to use 12 pulse or 18 pulse rectifier circuits where possible, Section 6.13.1.
2 Inductive equipment generates moderate amounts of harmonic disorders, except the third harmonics on an LV system.
3 The odd harmonics (non-multiples of 3), generated by hexaphase rectifiers, are more severe than any other harmonic disorders present in the system, except LV systems, where third harmonics are too pronounced. An LV system and the devices connected on it must take cognizance of these effects and suitable measures be taken, either to diminish such effects or to select higher ratings of the devices to operate on such systems without over-loading. HV systems must take particular cognizance of odd harmonics.

 It is mandatory to religiously follow EMC and EMI directives to contain at source the inductive and harmonic pollutants to their minimum. In Tables 23.2 and 23.3 we provide the recommended magnitudes of harmonics at different system voltages as per these directives.

23.7.1 Recommended magnitudes of harmonic disorders

For safe operation of power and control equipment and devices operating in such systems it is essential to limit the amplitude of the voltage distortions to a safe value by installing filter circuits based on the system's actual operating conditions. These limits as recommended by leading Standards organizations are:

1 UK engineering recommendation – G5/3 (British Electricity Council Standard). For harmonic voltage distortions in the system as in Table 23.2.
2 IEEE-519: Guide for harmonic control and reactive compensation of static power converters, for harmonic voltage distortions of general and dedicated power system, as in Table 23.3.

23.8 When will harmonics appear in a system

There are three possible ways in which harmonics may appear in a power system:

1 When the system voltage is linear (an ideal condition that would seldom exist) but the load is non-linear: The current will be distorted and become non-sinusoidal. The actual current I_h (r.m.s.) (Equation (23.2)) will become higher than could be measured by an ammeter or any other measuring instrument (measuring instruments measure at the fundamental frequency). Figure 23.13 illustrates the difference between the apparent current, measured by an instrument, and the actual current, where

 I_a = active component of the current
 I_r = apparent or current measured by an ammeter
 I_h = actual current due to harmonic distortions
 All the above are r.m.s. quantities.
 ϕ = displacement angle between the system voltage and apparent current, defining the p.f. of the load.
 δ = actual phase displacement due to harmonic distortions. It is the actual p.f. which is less than measured for a system containing harmonic disorders.

 Quantity I_h is composed of two components:

 - One at fundamental frequency. Its displacement with the fundamental voltage is termed the displacement factor, and for a linear voltage and linear load will define the p.f. of the load, i.e.

$$\frac{I_a}{I_r} = \cos\phi$$

 - The second component is caused by the different harmonic quantities present in the system when the supply voltage is non-linear or the load is non-linear or both. This adds to the fundamental current, I_r and raises it to I_h. Since the active power component I_a remains the same, it further reduces the p.f. of the system and raises the line losses. The factor I_r/I_h is termed the distortion factor. In other words, it defines the purity of the sinusoidal wave shape.

$$\therefore \cos\delta = \text{displacement factor} \times \text{distortion factor}$$

$$= \frac{I_a}{I_r} \times \frac{I_r}{I_h}$$

 For example, if the apparent p.f. is 0.9, a distortion factor of 0.85 will reduce it to 0.9 × 0.85 or 0.765.
2 When the supply system itself contains harmonics and the voltage is already distorted: now even the

* Power or harmonic analyser is a handy tool to measure at site quality of power in terms of individual and total harmonic disorders. Also active, apparent and reactive powers and the true p.f. of a power circuit.

Table 23.1 Typical harmonic orders and their magnitudes as studied in a power system

Odd harmonics				*Triple harmonics*				*Even harmonics*			
Likely harmonic voltage (%) System voltage				*Likely harmonic voltage (%) System voltage*				*Likely harmonic voltage (%) System voltage*			
Harmonic order n	*Up to 1 kV*	*Above 1–33 kV networks and primary distribution, 33–110 kV*	*Above 33–110 kV networks and secondary transmission above 110–220 kV*	*Harmonic order n*	*Up to 1 kV*	*Above 1–33 kV networks, and primary distribution, 33–110 kV*	*Above 33–110 kV networks and secondary transmission above 110–220 kV*	*Harmonic order n*	*Up to 1 kV*	*Above 1–33 kV networks and primary distribution, 33–110 kV*	*Above 33–110 kV networks and secondary transmission above 110–220 kV*
5	4 to 6	5 to 6	1 to 2	3	4 to 5	1.5 to 2.5	0.8 to 1.5	2	1 to 2	1 to 1.5	1 to 1.5
7	4 to 5	4 to 5	1 to 2	9	0.8 to 1.5	0.8 to 1.5	0.5 to 1	4	0.5 to 1	0.5 to 1	0.5 to 1
11	2.5 to 3.5	2.5 to 3.5	0.8 to 1.5	15	≤ 0.3	≤ 0.3	≤ 0.3	6	≤ 0.5	0.2 to 0.5	0.2 to 0.5
13	2 to 3	2 to 3	0.8 to 1.5	21	≤ 0.2	≤ 0.2	≤ 0.2	8	≤ 0.5	≤ 0.2	≤ 0.2
17	1 to 2	1 to 2	0.5 to 1								

Source: IEEE 519 (Cigre 1989) for general and dedicated power systems. (Due to enormous rise in the application of power electronics in the past three decades, in handling large to very large powers, the above situation has undergone a significant change and this table has since been withdrawn. But we have retained it for general reference as overall distortions may even be lower now in view of practising EMC norms and controlling EM interferences, at source.)

Notes

1 Still higher harmonics have not been considered, as they are of even lower magnitudes.
2 The values are expressed as a percentage of the fundamental voltage.
3 The above data is for a general reference. Actual harmonic distortion on the system during operation will depend upon the types of connected loads and their operating conditions, such as variation in its loading and fluctuations in the system voltage. To ascertain accurate harmonic contents one may use oscilloscope or harmonic analyser.

Table 23.2 Permissible individual and total harmonic voltage distortions – as in G5/3*, UK engineering recommendations

Nominal system voltage	*Individual harmonic voltage distortions*		*Total harmonic distortions*
kV	*Odd (%)*	*Even (%)*	*%*
0.415	4	2	5
6.6–11	3	1.75	4
33–66	2	1	3
132	1	0.5	1.5

* This specification is a guide to good practice for the equipment supplier and the consumer in controlling harmonics at the source and also limiting EM interferences as promulgated by EMC (Electromagnetic compatibility) and EMI (Electromagnetic interferences) regulations. This specification has now undergone a change (since 2001) in view of enormous rise in the application of static power technology in the past three decades (Section 6.7.4), due to which the earlier norms to maintain a quality power supply system have fallen short of fulfilling the desired goal. The power networks were found to be ailing with higher distortions than were envisaged. Recommendation G5/4 takes account of this and now specifies limits for each harmonic current disorder being produced by a power electronic circuit besides limiting the THD (total harmonic disorders) at the point of installation. We are retaining the above table as a general reference data. For exact details one may refer to G5/4 mentioned under Relevant Standards.

Table 23.3 Premissible voltage distortions as in IEEE 519 for individual consumer and the utility (supply system)

Nominal system Voltage kV	*Individual consumer voltage distortion %*	*Total harmonic distortions (THD) %*
< 69	3.0	5.0
69–161	1.5	2.5
>161	1.0	1.5

Note
For short-term abnormalities like during start-up of a plant or during unusual operating conditions, not lasting for more than an hour, the above limits may be exceeded by 50%.

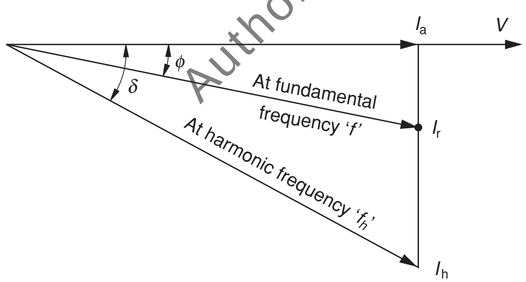


Figure 23.13 Rise in apparent current due to harmonic quantities

linear loads will respond to such voltage harmonics and draw harmonic currents against each harmonic present in the system, and generate the same order of current harmonics.

3 When the system voltage and the load are both non-linear: a condition which is common. The voltage harmonics will magnify and additional harmonics will generate, corresponding to the non-linearity of the load, and hence further distort an already distorted voltage waveform.
Harmonics will mean
– Higher voltage and current than apparent
– Adding to line loading and losses, and
– Reducing the actual load p.f.
Harmonic effects are reduced by the use of shunt capacitors installed to improve the p.f. of the system or an individual load, as they provide a very low impedance path to harmonic quantities and absorb them. But using shunt capacitors alone is not sufficient as at certain harmonic frequencies, the capacitive reactance of these capacitors, along with leakage capacitance C_o of the line, if it is an HV or EHV line (Table 24.1(b)) may tune up with the line inductive reactance L and cause a series or parallel resonance and develop high voltages. This phenomenon will be more apparent on an HV and EHV system than in LV system. On LV systems, the line resistance itself is enough to provide an in-built damping effect to a possible resonance ($Z = R_o$ at least). To avoid resonance, filter-circuits are used. Filter-circuits may be tuned for the lowest harmonic content which may be more prominent or for each harmonic separately as discussed later, when the system is required to be as near to sinusoidal waveform as possible. The system may contain second, third and fifth and higher harmonics, but it may be sufficient to tune it to just below the fifth harmonic which are more prominent and will be able to suppress most of the other harmonics also to a great extent, as it will make the circuit inductive for all harmonics.

In an HV system, either the star is not grounded or it is a delta-connected system and hence the third harmonic is mostly absent, while the content of the second harmonic may be too small to be of any significance. For this purpose, where harmonic analysis is not possible, or for a new installation where the content of harmonics is not known, it is common practice to use a series reactor of 6% of the reactive value of the capacitors installed. This will suppress most of the harmonics by making the circuit inductive, up to almost the fourth harmonic, as derived subsequently. Where, however, second harmonics are significant, the circuit may be tuned for just below the second harmonic. To arrive at a more accurate choice of filters, it is better to conduct a harmonic analysis of the system through a harmonic analyser and ascertain the actual harmonic quantities and their magnitudes present in the system, and provide a correct series or parallel filter-circuits for each harmonic.

As noted from general experience, except for specific large inductive loads such as of furnace or rectifiers, the fundamental content of the load current is high compared to the individual harmonic contents. In all such cases, it is not necessary to provide a filter-circuit for each harmonic unless the current is required to be as close to a sinusoidal waveform as possible, to cater to certain critical loads or instruments and devices or protective schemes operating in the system, where a small amount of harmonics may lead to malfunctioning of such loads and devices. Otherwise only the p.f. needs be improved to the desired level. Also to eliminate a parallel resonance with the source reactance, an inductor equivalent to 6% value of the capacitive reactance can be provided in series with the shunt capacitors.

Note
Where, however, individual harmonics may exceed the prescribed levels than shown in Tables 23.2 and 23.3 it shall be a good practice by the consumer to suppress them within prescribed limits at the source itself to abide by the EMC/EMI norms.

Preferable locations where the series inductor or the filter-circuits can be installed are:

1 At the supply end and/or
2 At the receiving end of the consumer, using power at HV and generating high harmonics (e.g. rolling mills, induction and arc furnaces, electrolysis plants, chemicals and paper mills).

Electricity companies will always want the consumers to suppress the harmonics at their end. Even if this practice is adopted by some, small harmonics generated by many small and large consumers, who may not take adequate preventive steps to contain the harmonics generated by their plants, at their end may still exist in the system. As a result, the distribution network may contain some harmonics and affect the performance of other loads on the system. If the level of harmonics is unacceptably high (Tables 23.2 and 23.3) they must be suppressed at the supply end by the power supply companies.

23.9 Filter circuits: suppressing harmonics in a power network

The use of a reactor in series with the capacitors will reduce the harmonic effects in a power network, as well as their effect on other circuits in the vicinity, such as a telecommunication network (see also Section 23.11 and Example 23.4). The choice of reactance should be such that it will provide the required detuning by resonating below the required harmonic, to provide a least impedance path for that harmonic and filter it out from the circuit. The basic idea of a filter circuit is to make it respond to the current of one frequency and reject all other frequency components. At power frequency, the circuit should act as a capacitive load and improve the p.f. of the system. For the fifth harmonic, for instance, it should resonate below 5×50 Hz for a 50 Hz system, say at around 200–220 Hz, to avoid excessive charging voltages which may lead to

- Over-voltage during light loads
- Over-voltage may saturate transformer cores and generate harmonics
- Failure of capacitor units and inductive loads connected in the system.

It should be ensured that under no condition of system disturbance would the filter circuit become capacitive when it approaches near resonance. To achieve this, the filter circuits may be tuned to a little less than the defined harmonic frequency. Doing so will make the L and hence X_L always higher than X_C, since

$$L = \frac{1}{(2\pi f)^2 \cdot C} \text{ [for } X_L = X_C \text{]}, \qquad \therefore L \propto \frac{1}{f^2}$$

This provision will also account for any diminishing variation in C, as may be caused by ambient temperature, production tolerances or failure of a few capacitor elements or even of a few units during operation.

The p.f. correction system would thus become inductive for most of the current harmonics produced by power electronic circuits and would not magnify the harmonic effects or cause disturbance to a communication system if existing in the vicinity (see Figure 23.14). A filter circuit can be tuned to the lowest (say the fifth) harmonic produced by an electronic circuit. This is because LV capacitors are normally connected in delta and hence do not allow the third harmonic to enter the circuit while the HV capacitors are connected in star, but their neutral is left floating and hence it does not allow the third harmonic to enter the circuit. In non-linear or unbalanced loads, however, the third harmonic may still exist though its quantity will be low as noted in Section 23.8. For a closer compensation, uni-frequency filters can be used to compensate individual harmonic contents by tuning the circuit to different harmonics, as illustrated in Figures 23.15(a) and (b). For more exact compensation, the contents and amplitudes of the harmonic quantities present in the system can be measured with the help of an oscilloscope or a harmonic analyser before deciding on the most appropriae filter circuit/circuits. Theoretically, a filter is required for each harmonic, but in practice, filters adjusted for one or two lower frequencies are adequate to suppress all higher harmonics also to a large extent and save on cost.

Refer to Table 23.1, which shows the average cumulative effect of all the harmonics that may be present in a power system. If we can provide a series reactor of 6% of the total kVAr of the capacitor banks connected on the system, most of the harmonics present in the system can be suppressed. With this reactance, the system would be tuned to below the fifth harmonic (at 204 Hz) for a 50 Hz system as derived below.

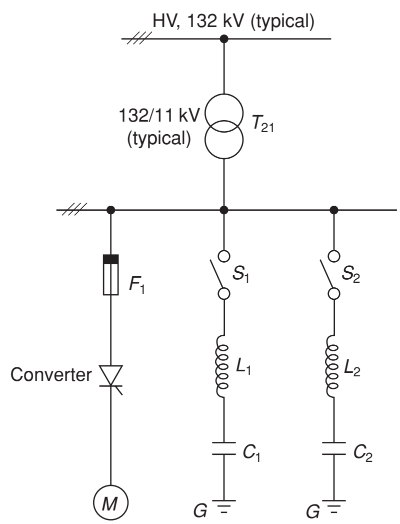
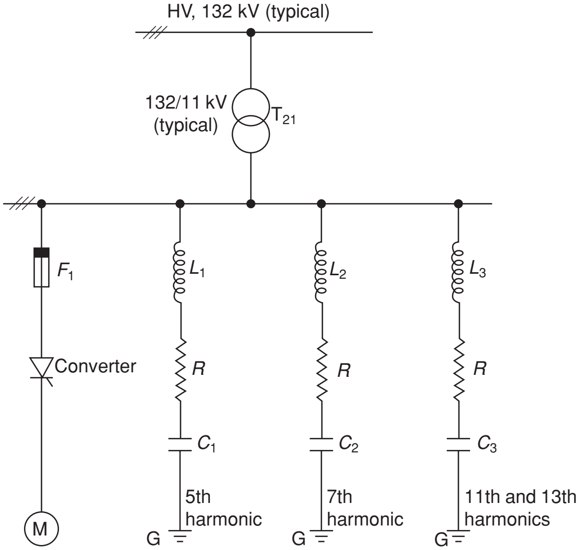


Figure 23.14 Compensation of harmonic currents by the use of reactors in the capacitor circuits



Filter circuits to compensate the harmonics

R = Resistance to limit the fault level and also resonance situation

Figure 23.15(a) Compensation of harmonics by tuning each capacitor circuit at different harmonics

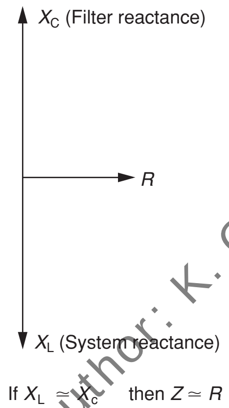


Figure 23.15(b)

If X_L is the 6% series reactance of the value of the shunt capacitors installed, then

$$X_L = 0.06\, X_C$$

or $$2\pi f L = \frac{0.06}{2\pi f C}$$

where

L = inductance of the series reactor in henry and
C = capacitance of the shunt capacitors in farad

or $$LC = \frac{0.06}{(2\pi f)^2}$$

When such a reactance is used to suppress the system harmonics it will resonate at a frequency f_h such that

$$2\pi f_h \cdot L = \frac{1}{2\pi \times f_h C}$$

or $$f_h = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{2\pi f}{2\pi\sqrt{0.06}}$$

$$= \frac{50}{\sqrt{0.06}} \text{ for a 50 Hz system}$$

$$\simeq 204 \text{ Hz, i.e. at the fourth harmonic.}$$

But when the third and/or second harmonics are also present in the system, at a certain fault level it is possible that there may occur a parallel resonance between the capacitor circuit and the inductance of the system (source), resulting in very heavy third or second harmonic resonant currents, which may cause failure of the series reactor as well as the capacitors. In such cases, a 6% reactor will not be relevant and a harmonic analysis will be mandatory to provide more exacting filter circuits.

It is pertinent to note that since a filter circuit will provide a low impedance path to a few harmonic currents in the circuit (in the vicinity of the harmonic, to which it has been tuned) it may also attract harmonic currents from neighbouring circuits which would otherwise circulate in those circuits (see Figure 23.12 (b)). This may necessitate a slightly oversized filter circuit. This aspect must be borne in mind when designing a filter circuit for a larger distribution network having more than one load centre.

It is, however, advisable to conduct a harmonic study of the system to select a more appropriate size of reactor, particularly where the installation is expected to experience high harmonic disorders.

Case Study

The following harmonic study was conducted at a steel melting plant using a 33 kV, 6 pulse induction furnace,

Harmonic order	*Harmonic contents %*
2	–
4	–
5	18.0
7	12.5
11	16.6
13	4.5
17	2.5
19	2.0
23	0.9
25	0.9

Courtesy: Energe Capacitors

Harmonics 5th, 7th and 11th are quite severe. Providing a 6% reactor tuning just up to 4th harmonic will not be adequate in this case if a reasonably sinusoidal voltage system is desired. It is advisable that filter circuits be tuned separately for prominent 5th, 7th and 11th harmonics to ensure a near sinusoidal supply system. Otherwise harmonics shall prevail and render the system non-sinusoidal and unstable, shoot-up maximum demand (MD) and cause excessive heating to inductive loads (like motors and transformers), besides voltage fluctuations and frequent failures of capacitors. It may also lead to further erosion of MD, even a shutdown of the plant and downtime to replace the failed capacitors. It may also distort the power distribution network beyond desirable limits (Section 23.7.1)

Designing capacitors alone for higher voltages to sustain harmonics is not a good practice because it shall not improve the quality of power which shall remain a source of perennial disturbances even if the capacitors do not fail so frequently.

Use of a reactor will enhance the voltage across the capacitor banks and must be considered in the design of the capacitor units. Refer to Figures 23.16(a) and (b) illustrating this. If

V_{ph} = system voltage
V_C = voltage across the capacitor banks = $I_C \cdot X_C$
V_L = voltage across the series reactor = $I_C \cdot X_L$

where

X_C = capacitive reactance
X_L = inductive reactance, and
I_C = current through the capacitor circuit

then

$V_{ph} = V_C - V_L$ (phasor diagram, Figure 23.16(b))
$= I_C X_C - I_C X_L$

and the rise in voltage across the capacitor banks, as a ratio of the system voltage

$$\frac{V_C}{V_{ph}} = \frac{I_C X_C}{I_C X_C - I_C X_L} = \frac{X_C}{X_C - X_L} \qquad (23.8)$$

For a series reactor of 6%, for instance,

$$\frac{V_C}{V_{ph}} = \frac{X_C}{X_C - .06X_c} = 1.0638$$

That means, the voltage across the capacitor banks will increase by 6.38%. This voltage must be considered in the design of capacitor units.

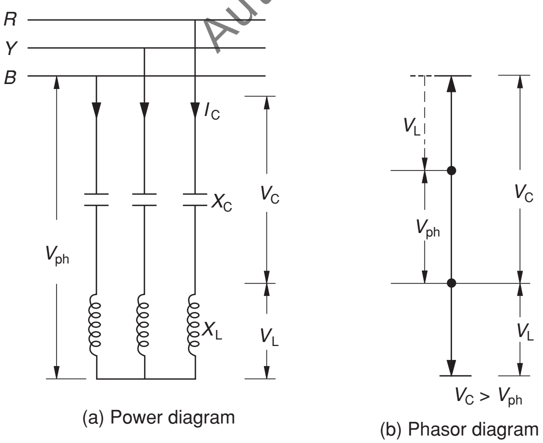


Figure 23.16 Voltage across the capacitor units rises with the use of series reactors

Similarly, the third harmonic may also be suppressed by grounding the generator or the transformer neutral through a suitable impedance (LC circuit), as discussed in Section 23.5.2(D).

23.9.1 Compensating for the series reactor

When a capacitor circuit is compensated through a series reactor, either to suppress the system harmonics or to limit the switching inrush currents (Section 23.11) or both, it will require suitable adjustment in its voltage and capacitive ratings. The series reactor will damp the switching currents but consume an inductively reactive power and offset an equivalent amount of capacitive kVAr, and require compensation. The following example will elucidate this.

Example 23.1
To determine the basic parameters of a 6% series reactor and its capacitive compensation, consider Example 23.6 with 3000 kVAr banks (1000 kVAr per phase) rated for 33.4 kV:

- Then the voltage rating of the capacitor units should be chosen for

$= 1.0638 \times \frac{33.4}{\sqrt{3}}$ (from Equation (23.8))

say, $= \frac{35.5}{\sqrt{3}}$ kV instead of

$\frac{33}{\sqrt{3}}$ or $\frac{34}{\sqrt{3}}$ kV (see Figure 23.17)

- Since the rating of the series reactor is = 0.06 × 3000 = 180 kVAr. The capacitors' rating must be enhanced by the rating of the reactor to obtain the same level of effective kVAr.

$\therefore$ The rating of the capacitor banks should be chosen for

= 3000 + 180

= 3180 kVAr.

- For the basic parameters of the reactor on a per phase basis

$I_C = \frac{1000}{35.5/\sqrt{3}}$

= 48.8 A

and rating of reactor, $V_L \cdot I_C$ = 60 kVAr

$\therefore \quad V_L = \frac{60 \times 1000}{48.8}$ V

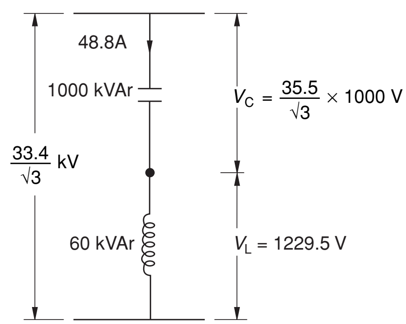


Figure 23.17 Phasor diagram for Example 23.1

= 1229.5 V

and $X_L = \dfrac{1229.5}{48.8}$

= 25.2 Ω

If this is designed for, say, 200 Hz, then its inductance

$$L = \frac{25.2}{2 \times \pi \times 200}\ \text{H}$$

= 20 mH

23.9.2 Studying and nullifying the effects of harmonics

The following example shall elucidate the practical approach to tackle harmonics in a power system.

Example 23.2
A distribution network 33 kV, three-phase 50 Hz feeding an industrial belt with a number of medium-sized factories some with non-linear loads and some with static drives and some with both. It was observed that while the lines were apparently running reasonably loaded, the active power supplied was much below the capacity of the network. Accordingly, a harmonic study of the network was conducted and it was revealed that despite localized p.f. control by most factories, the p.f. of the network itself was well below the optimum level and the voltage was also distorted by more than it was permissible. To improve this network to an acceptable level, we have considered the following load conditions, as were revealed through the analysis.

Rating of primary distribution transformer = 30 MVA, 132/33 kV

z_p = 10% (after applying the negative tolerance)

I_r = 525 A (Figure 23.18(a))

Let us assume the following line parameters:
Phase displacement at fundamental frequency, i.e. apparent p.f. as measured by a normal p.f. meter,

$\cos \phi_1$ = 0.88 lagging (Figure 23.18(a))

$\therefore \quad \phi_1 = 28.36°$.

Rating of the secondary distribution transformer = 30 MVA, 33/0.4 kV,

z_p = 10% (after applying the negative tolerance)

Load currents at different harmonics are recorded as follows:

Harmonic order	*Load current (A)*
1 (fundamental)	400
3	[a]
5	50
7	27.5
9	[a]
11	10
13	5

[a] The third harmonic was almost absent, hence it was not considered. The second and other even harmonics were also insignificant. Similarly, higher harmonics (above the thirteenth) were also insignificant, hence were not considered for ease of illustration.

∴ Actual loading of the system.

$$I_h = [400^2 + 25 \times 50^2 + 49 \times 27.5^2 + 121 \times 10^2 + 169 \times 5^2]^{1/2} \quad (23.2)$$

= 525.2, say, 525 A.

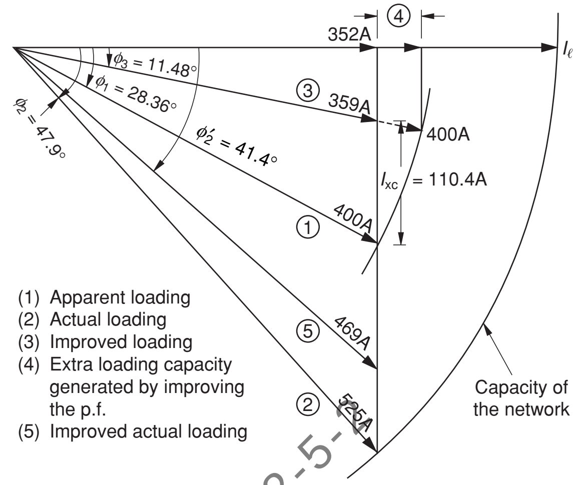


Figure 23.18(a) Enhanced capacity utilization of the network with the improved p.f.

The ampere meters, however, indicated only 400 A. While it appeared that the line was not fully loaded, in fact, it was loaded to its rated capacity of 525 A and was utilized by only 400 × 0.88, i.e. 352 A or by 67%, considering the system p.f. at 0.88.

Actual, p.f., $\cos \phi_2 = \dfrac{352}{525}$

= 0.67

$\therefore \quad \phi_2 = 47.9°$

Let us improve the apparent load p.f. to 0.98

i.e. $\cos \phi_3 = 0.98$

and $\phi_3 = 11.48°$

From Example 24.3 and Figure 24.25(b) inductive reactance of line = 6 Ω per phase.

Reactance of each transformer = 3.63 Ω.

∴ Total inductive reactance of the network

= 3.63 + 6 + 3.63

= 13.26 Ω per phase, and

line inductance $L = \dfrac{13.26}{2\pi f}$

= 42.23 mH/phase

Since the p.f. is to be improved from 0.88 to 0.98

∴ Shunt reactive compensation required

$I_{XC} = 400\,[\sin \phi_1 - \sin \phi_3]$

= 400 [sin 28.36 – sin 11.48]

= 400 [0.475–0.199]

= 110.4 A

and kVAr required $= \sqrt{3} \times 33 \times 110.4$

= 6310 kVAr

Say, 6300 kVAr

The shunt capacitors can be provided on the LV or the HV side, whichever is more convenient. In the above case, since it is large, the HV side of the load-end transformer will be more convenient. The receiving-end transformer, however, will now be operating under more stringent conditions as there is no compensation on its secondary side and that must be taken in account. Or the capacitors may be provided on the LV side of the receiving-end transformer to relieve this transformer also from excessive currents. In Figure 23.18(b) we have considered them on the HV side of the load-end transformer.

Improved actual p.f., $\cos\ \phi_2' = \frac{0.98}{0.88} \times 0.67 \simeq 0.75$

$\therefore \qquad \phi_2' = 41.4°$

and improved actual current

$= \frac{0.67}{0.75} \times 525$

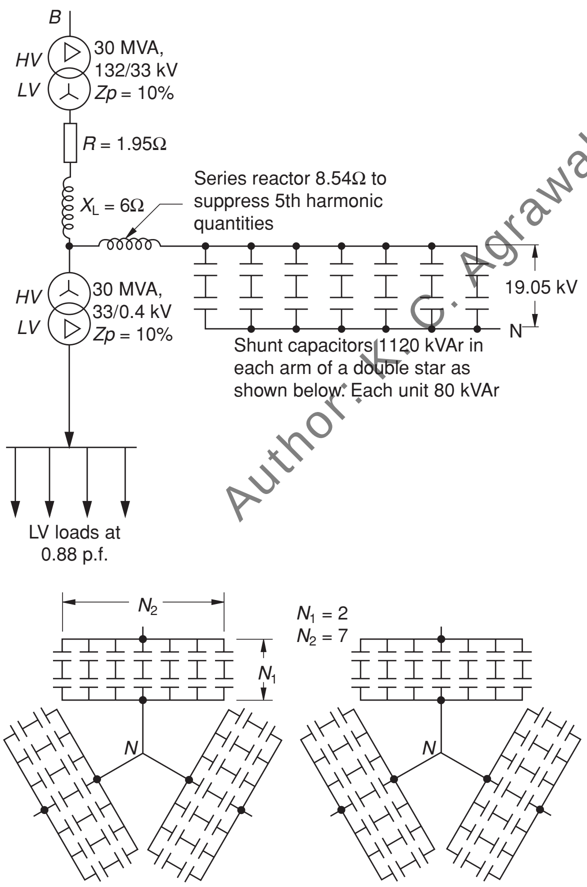
$= 469$ A (Figure 23.18(a))

and improved apparent line current $= 400 \times \frac{0.88}{0.98} = 359$ A

and $X_C = \frac{\text{kV}^2 \times 1000}{\text{kVAr}}$

$= \frac{33^2 \times 1000}{6300}$

$= 172.86\ \Omega$



Arrangement of capacitors in double star, 1120 kVAr in each arm.

Figure 23.18(b) Network of Figure 24.25 shown with shunt compensation

$$\therefore \qquad C = \frac{10^6}{2\pi \times 50 \times 172.86}\ \mu\text{F}$$

$$= 18.42\ \mu\text{F}$$

We have ignored any leakage capacitance between line to line or line to ground at 33 kV.

Tackling the harmonics

To eliminate all the harmonic contents from the supply it is essential to provide shunt-filter circuits separately for each harmonic disorder. As this is a costly arrangement it is not followed in practice. It is enough to drain the highest (in magnitude) harmonic disorder. This will substantially improve the current and voltage waveforms and make the circuit inductive for all higher harmonics, preventing a condition of resonance at any harmonic disorder during a line disturbance. The line reactance and capacitance of the capacitors may resonate at a frequency

$$f_h = \frac{1}{2\pi\sqrt{LC}} \qquad (23.6)$$

$$= \frac{1}{2\pi} \times \frac{1}{\sqrt{42.23 \times 10^{-3} \times 18.42 \times 10^{-6}}}$$

$$= 180.5 \text{ Hz}$$

say, at about the third or fourth harmonics. But both these harmonics are considered negligible in the system hence, the filter circuit will be essential for the fifth harmonic. The series reactor required in the capacitor circuit is tuned, say, at about 225 Hz to resonate below the 5th harmonic to be on the safe side and to also account for variation in the line parameters and the inductor itself to keep the circuit inductive under all conditions of line disturbances:

$$\therefore \quad 2\pi \times 225 \times L' = \frac{1}{2\pi \times 225 \times C}$$

$$\text{or} \qquad L' = \frac{1}{(2\pi)^2 \times (225)^2 \times 18.42 \times 10^{-6}}$$

$$= 27.2 \text{ mH}$$

$$\text{or} \qquad X_L' = 2\pi \times f \times 27.2 \times 10^{-3}$$

$$= 8.54\ \Omega \text{ at fundamental frequency.}$$

This is about 4.94% of X_C, and must be compensated by providing additional capacitor units to maintain the required level of p.f. as discussed in Section 23.9.1.

$\therefore$ Modified size of capacitor banks = 6300 × 1.0494

= 6611.2 kVAr

Let us choose a bank size of 6720 kVAr for easy selection of each unit. To adopt a better protective scheme, let us select the configuration of a double star (Figure 25.5(b)).

$\therefore$ Each bank for each arm of a double star

$= \frac{6720}{6}$

$= 1120$ kVAr

Let us arrange them two in series and seven in parallel, based on recommendations made in Section 25.5.1 (iii) and as shown in Figure 23.18(b).

$\therefore$ Size of each unit $= \frac{1120}{2 \times 7} = 80$ kVAr and voltage rating $= \dfrac{36^{a}}{\sqrt{3} \times 2}$

$= 10.39$ kV

[a] *Note*

The capacitor units are generally designed for the highest system voltage, as shown in Tables 26.4 or 13.1 unless specified for still higher voltages by some users. Accordingly Equation (23.8) does not apply in this case. Some local electricity distribution authorities, depending upon the likely maximum voltage variation on their systems, may sometimes ask for still higher voltages. But such distribution networks may not remain stable in the long run and must be improved as far as possible with the use of reactive controls, as discussed later.

The above configuration or size of each unit is not mandatory and can be altered, depending upon the economics of capacitor voltage and size of units available. Protection for all types of configurations is easily available through various schemes discussed in Section 26.1.

From the above it can be inferred that for an accurate analysis of a system, particularly where the loads are of varying nature or have non-linear characteristics it is necessary to conduct a harmonic analysis. The above corrective measures will provide a reasonably stable network, operating at high p.f. with the harmonics greatly suppressed.

The improved actual line loading, eliminating the fifth harmonic component, which is compensated,

$$I'_{\mathrm{h}} = [400^2 + 49 \times 27.5^2 + 121 \times 10^2 + 169 \times 5^2]^{\frac{1}{2}}$$

$$= 461.9\text{A as against } 525 \text{ A}$$

and improved actual p.f. $= \dfrac{352}{461.9}$

$= 0.76$

and $\phi_4 = 40.5°$

A phasor diagram (Figure 23.18(c)) illustrates the reduction in the actual loading and enhanced load transfer capacity of the network which can be achieved with the help of harmonic suppressions. For even better utilization, the system may be tuned for higher harmonic disorders also.

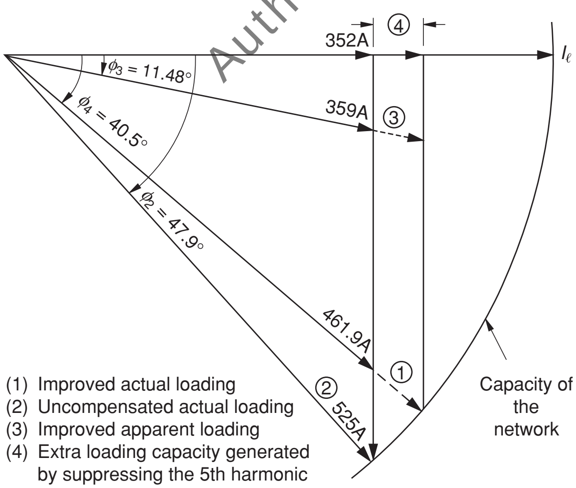


Figure 23.18(c) Reducing the actual loading of line by tuning for the fifth harmonic

23.10 Excessive charging currents (switching inrush or making currents)

The circuit of an uncharged capacitor unit, when switched, acts like a short-circuit due to the very high natural (transient) frequency, f_s, of the switching circuit, causing the capacitor reactance X_c, to approach zero. The value of the making current will depend upon the magnitude of the applied voltage and the impedance of the circuit (motor and cables) or of the system that will form the switching circuit. In other words, it will depend upon the fault level of the circuit and the rating of the capacitor units connected in that circuit. This switching transient current, as illustrated in Figure 23.19, as such being high, will be even higher if the circuit already has some switched capacitor units due to partial discharge of the already charged units into the uncharged units, as discussed in Section 23.10.2. The behaviour of the capacitor switching circuit under various switching conditions is described below.

23.10.1 Single-capacitor switching

Inrush current

The capacitor inrush current is a function of steady state and the transient components of the current, i.e.

$I_m = I_s + I_{st}$

where

I_m = maximum inrush or making current when switching an uncharged capacitor unit

I_s = maximum steady-state current (capacitor peak full-load current $(\sqrt{2}I_C)$)

I_{st} = transient component of the current, which is

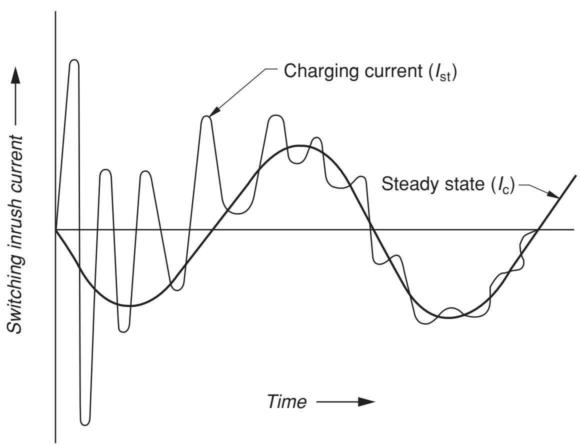


Figure 23.19 Current waveform on switching of a capacitor

a function of the short-circuit power of the switching circuit, i.e. the kVA of the transformer, if a transformer is feeding the circuit, and the kVAr of the capacitor being switched.

i.e. $$I_{st} = I_s \sqrt{\frac{\text{Short-circuit kVA}}{\text{Capacitor kVAr}}}$$

$$= I_s \sqrt{\frac{I_{sc}}{I_s}}$$

$$\therefore \quad I_m = I_s \left(1 + \sqrt{\frac{I_{sc}}{I_s}}\right) \tag{23.9}$$

When a single uncharged capacitor unit is switched on a power circuit, as illustrated in Figure 23.20, then

$$I_{sc} = \frac{V_p}{Z_{sc}}$$

and $$I_s = \frac{V_p}{Z}$$

where

V_p = line to neutral peak voltage

$$= \frac{\sqrt{2}}{\sqrt{3}} \cdot V_1 = 1 \text{ p.u. (Section 17.6.7)}$$

and Z_{sc} = short-circuit impedance of the switching circuit

Z = steady-state impedance of the switching circuit.

If R, L_1 (of cable, transformer and load inductances) and C_1 are the switching circuit parameters then

$$Z = \bar{R} + \bar{X}_{L1} - \bar{X}_{C1}$$

During a steady-state condition, i.e. at power frequency f, $X_{C1} >> X_{L1}$ and during a transient condition, i.e. during a switching operation when

$$f << f_s = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{17.1}$$

$X_{L1} >> X_{C1}$ (at surge frequency f_s)

For simplicity and to obtain a close approximation, the value of R may be considered to be negligible and therefore ignored. It may give a higher value of inrush current, which is on the safe side to select the switching device.

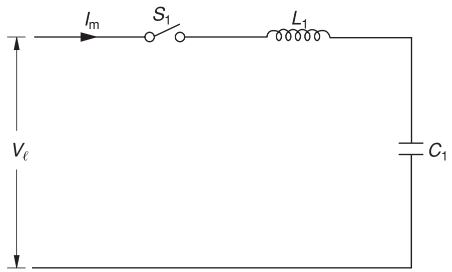


Figure 23.20 A single capacitor switching

$$\therefore \quad Z \simeq X_{C1} = \frac{1}{2\pi \times f \times C_1} \text{ and } I_S = \frac{V_p}{X_{C1}}$$

$$\text{and } Z_{sc} \simeq X_{L1} = 2\pi \times f_s \times L_1 \text{ and } I_{sc} = \frac{V_p}{X_{L1}}$$

$$\therefore \quad I_m = I_s \left(1 + \sqrt{\frac{X_{C1}}{X_{L1}}}\right) \tag{23.10}$$

Notes

1 If the capacitor was already charged, the switching would mean an additional impressed voltage, V_p of the trapped charge of the capacitor, i.e. up to $2V_p$, and the maximum inrush current may rise up to $2 \cdot I_m$.
2 The I_m can rise up to 5 to 25 times the normal capacitor current, I_c, as illustrated in Example 23.3.
3 The normal switching devices (switch, contactor or breaker) are normally suitable to meet such a switching requirement.

Switching frequency

This can also be expressed as

$$f_s = f \sqrt{\frac{(\text{Short-circuit kVA})}{(\text{Capacitor kVAr})}} = f \cdot \sqrt{\frac{X_C}{X_L}} \tag{23.11}$$

where

f_s = switching or transient frequency
f = power frequency
X_C = power frequency capacitive reactance of the circuit and
X_L = power frequency inductive reactance of the circuit.

Switching over-voltage

This is seen to rise up to 1.8–2 p.u. of the peak applied voltage, V_p, when switching an uncharged capacitor and around 2.6–3 p.u. when switching an already charged capacitor (Section 23.5.1).

Rating of the switching device

This is as recommended in Section 25.6 and is equally applicable to LV and HV capacitor units.

Example 23.3

Consider the same LV system of 415 V, as of Example 23.8, three-phase 50 Hz, and having a fault level of 36 MVA and employing capacitor banks of 360 kVAr.

Inrush current

Capacitor full-load current

$$I_c = \frac{360}{\sqrt{3} \times 0.415}$$

$$\simeq 500 \text{ A}$$

and static current $I_s = \sqrt{2} \times 500 = 707$ A

and $$I_m = 707\left(1 + \sqrt{\frac{36 \times 1000}{360}}\right)$$

$$= 707\ (1 + 10)$$

$$= 7777 \text{ A}$$

or eleven times the capacitor peak rated current. This is when totally uncharged capacitors are switched. If the capacitors are already charged when they are switched, the inrush current may rise up to twice this, i.e. almost twenty-two times the rated peak current (but not exceeding the fault level of the system).

Note
Here we have considered the fault level of the switching circuit to be same as that of the entire system, as they are the total capacitor banks connected in the system and switched together as a single unit.

Switching frequency

$$f_s = 50\sqrt{\frac{36 \times 1000}{360}}$$

$$= 500 \text{ Hz}$$

23.10.2 Parallel switching of capacitor units

This shows yet more complex circuit behaviour and requires more detailed analysis as discussed below.

We have considered the switching of capacitor banks that are installed on one power circuit and mounted in close proximity with another set of banks of almost similar capacity such as a capacitor control panel, having a set of capacitor banks arranged to switch ON and OFF, depending upon load variations of that circuit. Capacitor units installed on the same system but not in close proximity may not influence the switching behaviour of these capacitor units as severely as when they are installed in close proximity due to the extra line impedance thus introduced.

Inrush current

In this switching, the cumulative effect of the applied voltage and the trapped charge of the already charged capacitors is of little relevance but the resultant current is extremely high as derived below.

Consider a typical circuit as shown in Figure 23.21:

$$I_m \simeq \frac{V_p}{Z_s}$$ (when the applied voltage was at its peak and the switching capacitor had no trapped charge)

where

I_m = peak inrush current in parallel switching
Z_s = surge impedance

$$= \sqrt{\frac{L_2}{C_{eq}}} \qquad (17.2)$$

where

L_2 = circuit inductance between the banks in henry (ignoring the negligible self-inductance of the capacitor banks)
C_{eq} = equivalent series capacitance of the two capacitors C_1 and C_2 in farad

i.e. $$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}$$

or $$C_{eq} = \frac{C_1 \cdot C_2}{C_1 + C_2}$$

$$\therefore \quad Z_s = \sqrt{\frac{L_2(C_1 + C_2)}{C_1 \cdot C_2}} \qquad (23.12)$$

and $$I_m = V_p\sqrt{\frac{C_1 \cdot C_2}{L_2(C_1 + C_2)}} \qquad (23.13)$$

This is a generalized formula to simplify the equation. In fact, the actual switching current will be much less than this, due to circuit impedance. For more accurate results, the inductance of the capacitor banks may be introduced into the total inductance, L_2, i.e., it should be the summation of all the reactances of the capacitors already switched, plus the series reactance of the capacitor being switched. See Figure 23.22.

∴ Equivalent reactance of the capacitors already switched

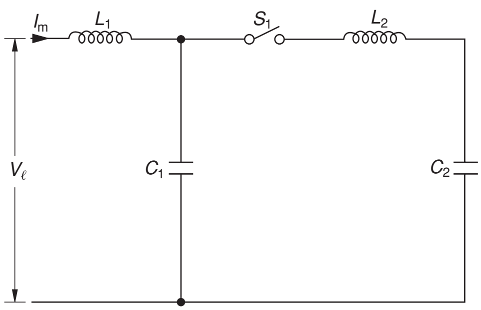
$$L_{1eq} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \dots \frac{1}{L_n}}$$

and $$L_{2eq} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \dots \frac{1}{L_n}} + L_x$$

L_x = series inductance of the capacitor being switched (this is L_2 of Equation (23.13))

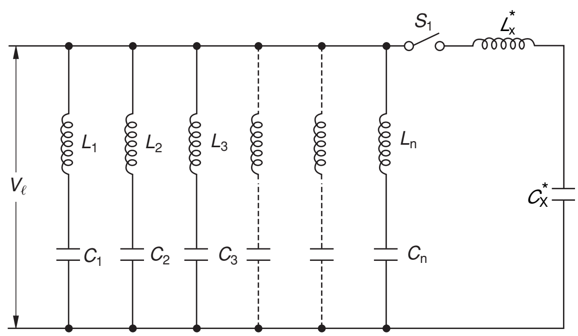
and $C_{1eq} = C_1 + C_2 + C_3 + \dots C_n$

(this is C_1 of Equation (23.13))



Parallel operation of capacitor bank C_2 with an already switched capacitor C_1

Figure 23.21 A simplified capacitor switching circuit



*L_x being L_2 and C_x (now being switched) is C_2 of Figure 23.21

Figure 23.22 Equivalent circuit for *n* number of capacitor banks already switched on the circuit and another (C_x) being switched

The figures of L_{2eq} and C_{1eq} may be substituted in Equation (23.13) for L_2 and C_1 respectively to derive a more accurate switching inrush current.

Notes

1 In the above discussions it is assumed that the capacitor C_2 has no trapped charge when it is switched ON. If this is not so, the current may rise up to $2 \cdot I_{m,}$ as discussed in Section 23.10.1.

2 Field experiments have revealed that such currents may be as high as up to 15–250 times the steady state current I_s (not exceeding the fault level of the system), but will last only up to the first current zero.

Switching frequency

As discussed above, a capacitor circuit is an L-C circuit, and the switching frequency f_s can be expressed as

$$f_s = \frac{1}{2\pi\sqrt{L_{2eq} \cdot C_{eq}}} \qquad (17.1)$$

where

$$C_{eq} = \frac{1}{\dfrac{1}{C_{1eq}} + \dfrac{1}{C_x}} \qquad \text{(as in Figure 23.22)}$$

C_x = capacitance of the capacitor being switched

$$\text{or} \quad C_{eq} = \frac{C_{1eq} \cdot C_x}{(C_{1eq} + C_x)}$$

$$\therefore \quad f_s = \frac{1}{2\pi}\sqrt{\frac{(C_{1eq} + C_x)}{L_{2eq} \cdot C_{1eq} \cdot C_x}} \qquad (23.14)$$

The parameters C_{1eq} and L_{2eq} are the same as those derived above.

The switching frequency in capacitor switching is very high. We have already witnessed this in a single capacitor unit. The situation becomes highly complicated when switching is effected in a circuit that already has a few switched capacitor units. In Example 23.4 we will see that a circuit with only 6 nos. of 60 kVAr capacitor units can have a switching frequency as large as over 13 kHz (in operation, it may not exceed 5–7 kHz because of the circuit's actual impedance), when five of these capacitors are already switched and the sixth is switched. This high to extremely high switching transient frequency is detrimental in giving rise to the switching inrush currents, of the order of 15 to 250 times and more, of the steady-state current I_s. Since the switching capacitive reactance is inversely proportional to the switching frequency, it offers an almost short-circuit condition during a switching operation.

Summary

1 At the instant of switching the surge impedance, Z_s (Equation (23.12)), and the natural frequency of the switched circuit, i.e. the transient frequency, f_s (Equation (23.14)), determine the amount of inrush current.

2 The natural (surge) frequency, f_s, of parallel capacitor switching is extremely high, of the order of 5–7 kHz or more. It may not exceed this because of the circuit's own parameters *R* and *L* that have been ignored in our analysis for easy illustration. The actual frequency, f_s, will depend upon the size of capacitors being switched compared to the capacitors that were already switched, and their corresponding inductance in the switching circuit. A high f_s will diminish the capacitive reactance of the capacitor to an almost negligible value. This leads to a near-short-circuit condition during the switching operation, causing extremely high transient inrush currents of the order of 15–250 times and even more of the capacitor's steady-state current I_s (but not exceeding the fault level of the system).

3 This extremely high inrush current at a frequency of almost 5–7 kHz will release an enormous amount of let-through energy during contact making,

i.e. $\propto I_m^2 \cdot t$

say $(250 \cdot I_s)^2 \cdot \dfrac{I}{2 \times 50}$

(for an I_m of $250 \cdot I_s$ occurring at a transient frequency of 6 kHz and existing up to the first current zero in a 50 Hz system).

The interrupting device, which may be a breaker or a contactor, must be suitable to sustain this energy without deterioration of or damage to its contacts, while the fuses must stay intact when provided for backup protection.

Notes

1 For air-break LV switches and contactors IEC 60947-3 and IEC 60947-4-1 have specified the making capacities for heavy-duty AC-3 components as follows (also refer to Section 12.10):

(i) For rated current up to 100 A – 10 times the r.m.s. value.
(ii) For rated currents beyond 100 A – 8 times the r.m.s value. The manufacturers of such devices, however, may declare the making capacity of such devices to be even higher than this when the higher value may be considered to design the inductance, to limit the inrush current (Section 23.11).
(iii) Light-duty switches and contactors up to AC-2 duty are not suitable for such applications.

2 NEMA publication ICS.2-210 for general-purpose contactors provides data for ratings prevalent in the USA. These data are summarized as follows:

(i) Table 23.4 gives continuous current ratings and maximum making currents, I_m, for various sizes of contactors.
(ii) Choice of contactors for different values of capacitor switching currents is provided in Table 23.5.

Table 23.4 General-purpose contactor rating

Size of contactor	*Continuous current rating Amps (r.m.s.)*		*Maximum making current, I_m Amps (peaks)*
	Enclosed	*Open*	
00	9	10	87
0	18	20	140
1	27	30	288
2	45	50	483
3	90	100	947
4	135	150	1581
5	270	300	3163
6	540	600	6326
7	810	900	9470
8	1215	1350	14,205
9	2250	2500	25,380

4 The transient condition is of extremely short duration and ceases to exist after the first current zero.
5 Such heavy currents are more prevalent in an HV rather than in an LV system. An HV system will have a much smaller impedance, Z, compared to the applied voltage, V_p, than an LV system, which will have a much higher value of Z compared to the applied voltage $V_{p.}$

Thus, the analysis conducted above to derive I_m on a parallel switching is more pertinent for an HV system, and offers only a theoretical analysis for LV systems. Nevertheless, for large LV installations such as, 2000–2500 kVA for a single circuit, as discussed in Section 13.4.1(5), employing large capacitor banks close to the feeding transformer, it may be desirable to limit the inrush current to a desirable level on the LV side also. In all probability, switching devices selected at 150% of the capacitors' normal current as in Section 25.6 will be sufficient to meet any switching contingency even a parallel switching.

23.11 Limiting the inrush currents

Let us refer to Equation (23.13) for the inrush current, I_m, on parallel switching. If we can increase the impedance of the switching circuit by introducing a resistance R or inductance L, or both, we can easily control this current to a desired level.

Note
If we add L or R in the circuit it will increase the surge impedance, reduce the surge frequency of the switching circuit, and damp the 90° lead surge current to a moderately leading surge current, small in magnitude and steepness. At every current zero when the contacts of the switching device tend to separate, the recovery voltage will be much less than its peak value due to smaller phase displacement between the current I_m and the TRV, and thus help to interrupt the switching device with a lesser severity.

For more details see Section 17.7.2(ii). The principle of restrike in capacitive switching is almost the same as in the case of inductive switching. Consider Figure 23.23, where for ease of analysis, an additional inductance, L, is introduced to increase the circuit impedance, which

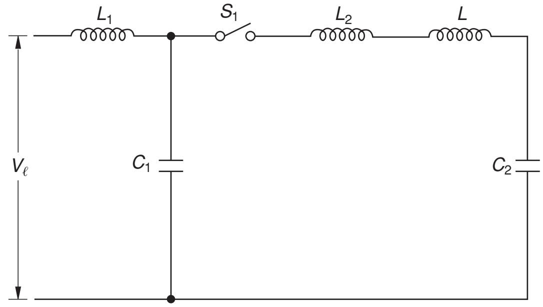


Figure 23.23 Inductance L introduced into the switching circuit

will also damp the resonant frequency of the switching circuit. The improved I'_m of Equation (23.13) can now be expressed as:

$$I'_m = V_p \sqrt{\frac{C_1 \cdot C_2}{(L_2 + L)(C_1 + C_2)}} \qquad (23.15)$$

where L_2 and C_1 can further be substituted by L_{2eq} and C_{1eq} respectively.

Example 23.4
Consider the LV system of Example 23.8, where we have considered six banks of 60 kVAr each.
Assume that three units of 20 kVAr each are used to make each bank of 60 kVAr, and let there be six such banks.

Data available:

System – 415 V, 3-ϕ, 50 Hz

Each unit of 20 kVAr has

$\left.\begin{array}{l} C = 120\ \mu f \\ L = 1.2\ \mu H \end{array}\right\}$ Typical, may be obtained from the capacitor manufacturer

Consider each capacitor unit of 20 kVAr to be connected in delta, as shown in Figure 23.24(a).

Step 1
There will be three such parallel circuits to make it 60 kVAr. To calculate equivalent capacitance and reactance in delta, we may convert it into an equivalent star as shown in Figure

Table 23.5 Contactor rating for capacitor switching at different transient (switching) currents I_m

Size of contactor	*Continuous rating of contactors Amps (r.m.s.)*	*Maximum size of three-phase capacitors in kVAr at different switching currents I_m*					
		Capacitor switching current I_m					
		3000 A	*5000 A*	*10 000 A*	*14 000 A*	*18 000 A*	*22 000 A*
2	45	25	16	8	6	4	4
3	90	53	53	31	23	18	15
4	135	80	80	80	61	49	41
5	270	160	160	160	160	160	149
6	540	320	320	320	320	320	320
7	810	480	480	480	480	480	480
8	1215	720	720	720	720	720	720
9	2250	1325	1325	1325	1325	1325	1325

23.24(b) by maintaining the same line parameters as in Figure 23.24(a). If the impedance of each phase in delta is Z, then to maintain the same steady-state line current, 'I_S', in star also let the equivalent impedance of each phase in star be Z'. Then,

$$I_s \text{ (delta)} = \frac{415}{Z}\sqrt{3}$$

and $$I_s(\text{star}) = \frac{415}{\sqrt{3}\cdot Z'}$$

or $$\frac{415\sqrt{3}}{Z} = \frac{415}{\sqrt{3}\cdot Z'}$$

or $$Z' = \frac{1}{3}\cdot Z$$

Since $$X_L = 2\pi\cdot f\cdot L \quad \therefore\; X'_L = \frac{1}{3}\times 2\pi\cdot f\cdot L$$

$\therefore$ equivalent L' will be $= \frac{1}{3}L$

and $$X_C = \frac{1}{2\pi\cdot f\cdot C}$$

$$\therefore \quad X'_C = \frac{1}{3}\times\frac{1}{2\pi\cdot f\cdot C} = \frac{1}{2\pi\cdot F\cdot C'}$$

$\therefore$ equivalent $C' = 3\,C$

i.e. inductance of each phase in star $L' = \frac{1.2}{3}\,\mu\text{H}$

$$= 0.4\ \mu\text{H}$$

and capacitance of each phase in star $C' = 3\times 120\ \mu\text{F}$.

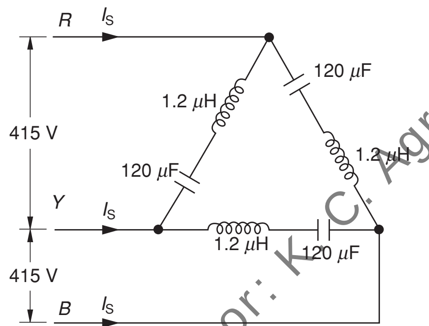


Figure 23.24(a) Equivalent Δ circuit for a 20 kVAr capacitor unit

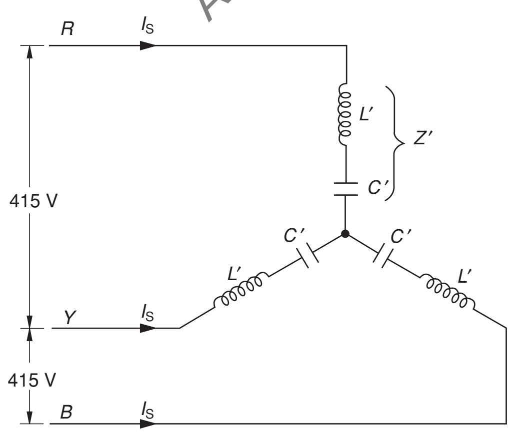


Figure 23.24(b) ⅄ circuit, equivalent to Δ circuit of Figure 23.24(a)

For 60 kVAr bank, the equivalent circuit can be drawn as shown in Figure 23.25.

$$\therefore \quad L' = \frac{1}{\frac{1}{0.4}+\frac{1}{0.4}+\frac{1}{0.4}} = \frac{0.4}{3}\ \mu\text{H}$$

and $$C' = 3\times 120 + 3\times 120 + 3\times 120$$
$$= 3\times 3\times 120\ \mu\text{F}$$

Capacitor normal current for each 60 kVAr bank

$$I_c = \frac{60\times 1000}{\sqrt{3}\times 415} \simeq 83.5\ \text{A}$$

Switch and HRC fuses and contactor rating, as in Section 25.6

$= 1.5\times 83.5$

or 125.25 A

Thus, for a single capacitor switching of a 60 kVAr bank, a rating of 125 A will be required for the switch, fuses and the contactor etc.

Step 2: Effect of parallel switching

Consider the case when all five units are already energized and the sixth is switched. The equivalent circuit can now be represented as shown in Figure 23.26.

$\therefore$ L_{eq} for five switched capacitor banks

$$= \frac{1}{\frac{1}{0.4/3}+\frac{1}{0.4/3}+\frac{1}{0.4/3}+\frac{1}{0.4/3}+\frac{1}{0.4/3}}$$

$$= \frac{0.4}{3\times 5}\ \mu\text{H}$$

and L_{2eq} for the total circuit

$$= \frac{0.4}{3\times 5}+\frac{0.4}{3}\ \mu\text{H}$$

$$= \frac{0.4+5\times 0.4}{3\times 5}\ \mu\text{H}$$

or $$\frac{0.4\times 6}{3\times 5}\times 10^{-6}\ \text{H}$$

and $$C_{1eq} = 9\times 120 + 9\times 120 + 9\times 120 + 9\times 120 + 9\times 120$$
$$= 5\times 9\times 120\ \mu\text{F}$$

or $$5\times 9\times 120\times 10^{-6}\ \text{F}$$

$$\therefore \quad I_m = \sqrt{2}\times\frac{415}{\sqrt{3}}\sqrt{\frac{C_{1eq}\times C_2}{L_{2eq}(C_{1eq}+C_2)}}$$

[as per Equation (23.13)]

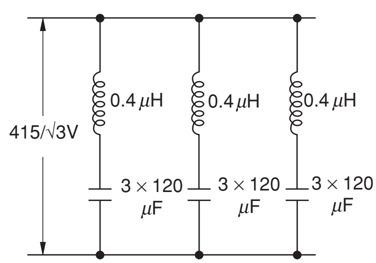


Figure 23.25 Equivalent circuit for a 60 kVAr bank in star made of 3 × 20 kVAr units

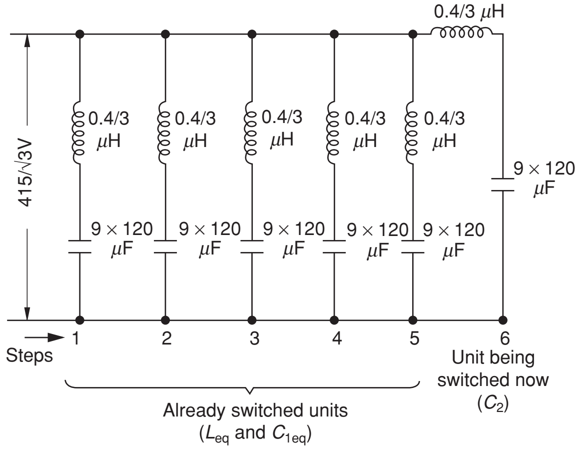


Figure 23.26 Equivalent switching circuit for six capacitor units of 60 kVAr each

$$= \frac{\sqrt{2}}{\sqrt{3}} \times 415 \sqrt{\frac{5 \times 9 \times 120 \times 10^{-6} \times 9 \times 120 \times 10^{-6}}{\frac{0.4 \times 6}{3 \times 5} \times 10^{-6} (5 \times 9 \times 120 \times 10^{-6} + 9 \times 120 \times 10^{-6})}}$$

$$= 415 \sqrt{\frac{2}{3} \times \frac{5 \times 9 \times 120 \times 9 \times 120}{\frac{0.4 \times 6}{3 \times 5} \times 6 \times 9 \times 120}}$$

$$= 415 \times \sqrt{3750}$$

or 25 414.6 Amps

if switching is effected when the incoming capacitor is already charged, then the inrush current I_m, will be nearly twice this, i.e.

= 25 414.6 × 2

= 50.80 kA

However, in no case will the switching current exceed the short-circuit kA of the switching circuit.

Inference

This current is excessive for a normal switching device to make frequently, even for one half of a cycle each time. However, on an LV circuit, it would be much below this due to the circuit's own resistance and inductance, which have been ignored in the above analysis. Nevertheless, it would be advisable to limit such a switching surge to a reasonable value to protect the system from damage during repeated switchings as well as the switching devices (selected at 150% of the capacitor's normal current).

Step 3: Limiting the inrush current

Consider an inductance L μH introduced into each capacitor circuit as shown in Figure 23.27(a) or (b) to limit the switching current within the making capacity of the switching device. Then

$$L'_{eq} = \frac{\left(\frac{0.4}{3} + L\right)}{5} \times 10^{-6}\,\text{H}$$

$$L'_{2eq} = \frac{\left(\frac{0.4}{3} + L\right) \times 6}{5} \times 10^{-6}\,\text{H}$$

and $\quad C'_{1eq} = 5 \times 9 \times 120 \times 10^{-6}\,\text{F}$

The equivalent switching circuit is shown in Figure 23.27(c):

∴ Improved

$$I'_m = \frac{\sqrt{2}}{\sqrt{3}} \times 415 \sqrt{\frac{5 \times 9 \times 120 \times 10^{-6} \times 9 \times 120 \times 10^{-6}}{\frac{\left(\frac{0.4}{3} + L\right) \times 6}{5} \times 10^{-6} \times 6 \times 9 \times 120 \times 10^{-6}}}$$

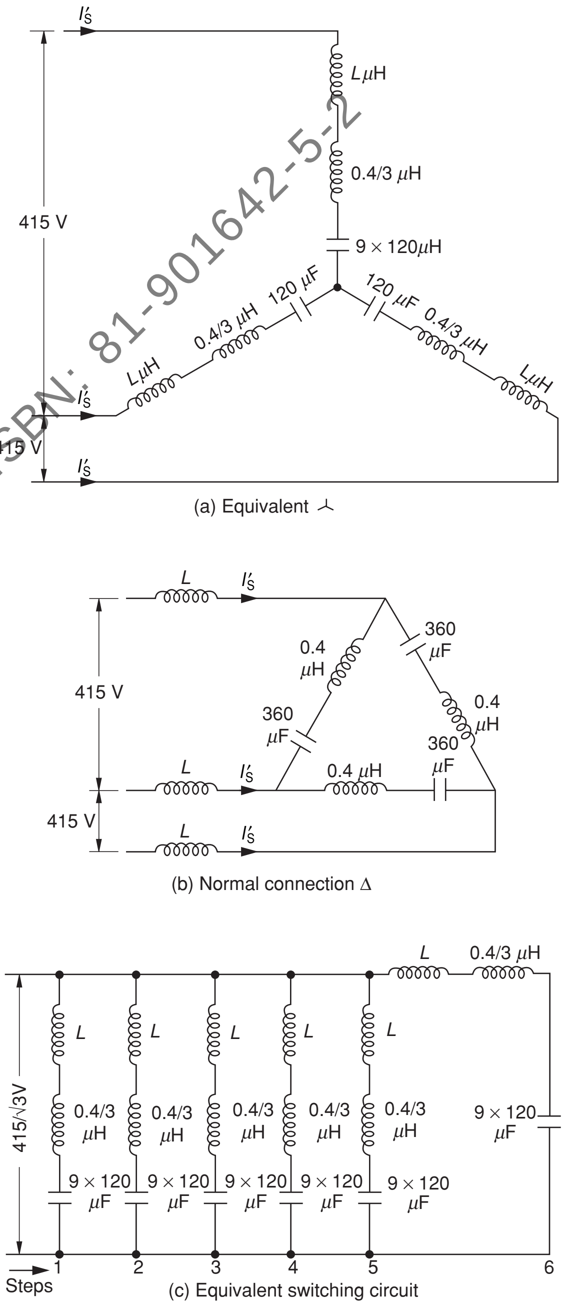


Figure 23.27 Equivalent switching circuits

$$\text{or}\quad \left(\frac{0.4}{3} + L\right) = 415^2 \times \frac{2 \times 5 \times 9 \times 120 \times 5}{3 \times 6 \times 6 \times I_m'^2}$$

$$\text{or}\quad L = \frac{415^2 \times 2 \times 5 \times 9 \times 120 \times 5}{3 \times 6 \times 6 \times I_m'^2} - \frac{0.4}{3}\ \mu\text{H}$$

In this case we have considered the switching device to be rated for 125 A for each bank. In an LV system the switching devices such as the switch or the contactor will generally have a making capacity of nearly eight times (peak value $\sqrt{2} \times 8$) its normal rating. These data are provided by the component manufacturers. Let us therefore assume that I_m' is to be restricted up to $\sqrt{2} \times 125 \times 8$, i.e. $\sqrt{2} \times 1000$ A (the actual value may be more than this, which may be obtained from the manufacturers' catalogues). Therefore, in the above case,

$$L = \frac{415^2 \times 2 \times 5 \times 9 \times 120 \times 5}{3 \times 6 \times 6 \times 2 \times 1000^2} - \frac{0.4}{3}\ \mu\text{H}$$

$$= 43.06 - \frac{0.4}{3}\ \mu\text{H}$$

$$\text{or}\quad 42.93\ \mu\text{H}$$

If we are able to provide an inductance of this value with each capacitor bank of 60 kVAr the problem of excessive inrush transient current can be overcome and the component ratings as chosen above will be sufficient to switch a parallel circuit.

Step 4: Reactive power of the series inductance

However small, the reactive kVAr of series inductance, it would offset as much of the capacitive kVAr. It would be worthwhile therefore to keep this aspect in mind to ensure that the capacitive kVAr chosen to improve the p.f. of the system to a certain level is not over-adjusted. Otherwise a higher capacitive kVAr would become necessary to achieve the same level of p.f. as was envisaged initially. In the above case,

$$\text{Inductive kVAr} = 3 \times \frac{I_L^2 \cdot X_L}{1000}\ [X_L \text{ reactance in } \Omega/\text{phase}]$$

where

$$I_L = \text{the capacitive current } I_c$$

$$= 83.5\text{A}$$

and

$$X_L = 2\pi \times 50 \times 42.93 \times 10^{-6}\ \Omega/\text{phase}$$

$$= 0.0135\ \Omega$$

$$\therefore\ \text{Inductive kVAr} = 3 \times \frac{(83.5)^2 \times 0.0135}{1000}$$

$$\simeq 0.28$$

Which is even less than 0.5% of the capacitor kVAr per bank and may be ignored.

Note

1 For large LV or HV banks compensating large installations, transmission or distribution networks, the value of series reactance may become large. In which case, the significance of the above phenomenon will appear to be more meaningful. It is, however, seen that in view of the line impedances (which have been ignored in the above estimate) the actual reactance may not normally be required by more than 0.5% to 1% of the total installed kVAr. Using a series reactance equal to 0.2% of the kVAr rating to control the inrush currents is quite prevalent.
2 In HV systems, where a series reactor is already being used, to suppress the system harmonics the same would also serve to limit the switching inrush currents and no separate reactor would be necessary.
3 Since a series reactor is of a relatively small value, it may not be able to withstand the system fault conditions. In that case, it is advisable to connect it on the neutral side of the star-connected bank rather than on the line side.

Conversion from delta to star

Whenever an electrical network has different configurations, such as star and delta, it must first be converted to an equivalent star or delta before conducting any analysis. As derived above, the following rules of thumb may be applied:

$$\text{Reactances in star} = \frac{1}{3} \times \text{reactances in delta}$$

i.e. $L' = \frac{1}{3} L$

and capacitance is star = 3 × capacitance in delta,

i.e. $C' = 3C$

where

L = inductance in Δ per phase
L' = inductance in Y per phase
C = capacitance in Δ per phase
C' = capacitance in Y per phase

23.11.1 Transient-free switching

With the use of static switchings through IGBTs or thyristors (SCRs), as discussed in Sections 6.13 and 24.10 both switching over-voltages and inrush currents can be completely eliminated. Switchings are now possible at the instant the applied voltage wave passes through its natural zero. Since such a switching scheme is free from any over-voltage or inrush currents, the number of switching operations is no problem. Also refer to Section 6.16.1 on soft switchings.

Although costlier, when a smoother and faster p.f. correction is desirable, without causing an over-voltage or inrush current, static switchings should be chosen. They have extensive application in large automatic reactive power controls, as discussed in Section 24.10.

23.11.2 Designing an inductor coil to limit the inrush currents

For this we can employ a current limiting reactor (Section 27.4.2) that can be an air core inductor coil discussed in Section 27.3. A simple coil (even a straight length of cable will serve the same purpose, unless it is too long) as shown in Figure 23.28, will provide a self-inductance when a sinusoidal current is passed through it. We will make use of such a coil to control the excessive currents. The induced inductance in such a coil can be expressed by

$$L = \frac{4 \cdot N^2}{10^9} \cdot r \left(\log_e \frac{8 \cdot r}{0.7788 \cdot r_1} - 2\right) \text{henry} \qquad (23.16)$$

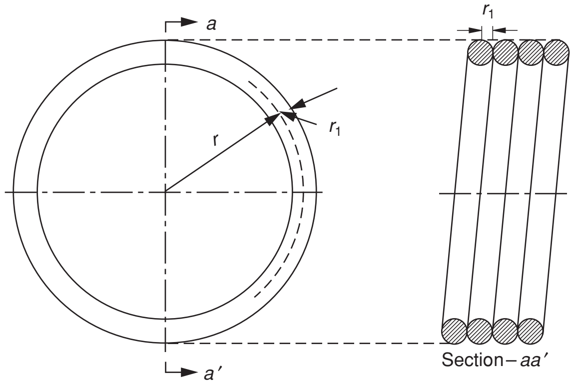


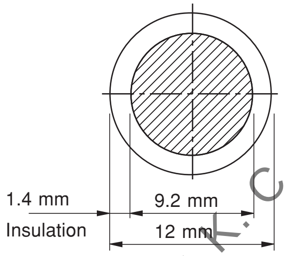
Figure 23.28 A circular coiled coil

where

L = self-induced inductance of the coil in henry
N = number of turns of the coil
r = mean radius of the conductor in cm
r_1 = radius of the cross-section of the cable in cm.

Example 23.5 (see Example 23.4)

For obtaining a self-inductance of 42.93 μH consider a coil of 15 cm mean diameter (r = 7.5 cm) made of the same cable that is connecting each capacitor bank through the switching device.



(a) For a feeder rating of 125 A (peak current $\sqrt{2} \times 8 \times 125$ A) select a cable of 50 mm² of copper, rated for 172 A at 30°C ambient (Table 13.15). This cable can withstand a short-time current of $\sqrt{2} \times 8 \times 125$ A for about 18 seconds. See also Section 28.4.1 and the graph of Figure 28.5, where

$$\frac{\sqrt{2} \times 8 \times 125}{50 \times 1000} \cdot \sqrt{t} = 0.12$$

or t = 18 seconds

Using a PVC insulated flexible copper cable, having a nominal outer diameter of 12 mm and an insulation thickness of 1.4 mm (typical).

Diameter of conductor = 12 – 2 × 1.4

= 9.2 mm

and $r_1 = \frac{9.2}{2} = 4.6$ mm = 0.46 cm

Therefore,

$$42.93 \times 10^{-6} = \frac{4\pi}{10^9} \times N^2 \times 7.5 \left(\log_e \frac{8 \times 7.5}{0.7788 \times 0.46} - 2 \right)$$

$$= \frac{4\pi}{10^9} \times N^2 \times 7.5\ (\log_e 167.48 - 2)$$

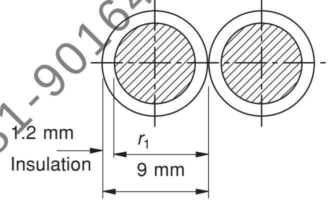
$$= \frac{4\pi}{10^9} \times N^2 \times 7.5 \quad (5.12 - 2)$$

$$= \frac{4\pi}{10^9} \times N^2 \times 7.5 \times 3.12$$

or $$N = \sqrt{\frac{42.93 \times 10^{-6} \times 10^9}{4\pi \times 7.5 \times 3.12}}$$

= 12.08 say, 12 turns

By providing 12 turns of 150 mm mean diameter of the 50 mm² flexible copper cable connecting each 60 kVAr capacitor bank a self-inductance of roughly 42.93 × 10^{-6} H can be introduced into each switching circuit, which will limit the switching inrush current to almost the permissible value of the making current (I_m) of the switching device.



(b) If we use two of 25 mm² cables as shown, then

r_1 = 7.8 mm or 0.78 cm

and the number of turns that will be necessary:

$$42.93 \times 10^{-6} = \frac{4\pi}{10^9} \times N^2 \times 7.5 \left(\log_e \frac{8 \times 7.5}{0.7788 \times 0.78} - 2 \right)$$

$$= \frac{4\pi}{10^9} \times N^2 \times 7.5\ (\log_e 98.77 - 2)$$

$$= \frac{4\pi}{10^9} \times N^2 \times 7.5 \times 2.593$$

or N = 13.26

Say, 13 turns

Note

Technical data of the cables considered above are of a different manufacturer and differs slightly from that of Table 13.15.

Switching frequency

As calculated above:

$$L_{2\,eq} = \frac{0.4 \times 6}{3 \times 5} \times 10^{-6}\ \text{H}$$

$$C_{1\,eq} = 5 \times 9 \times 120 \times 10^{-6}\ \text{F}$$

and $C_X = C_2 = 9 \times 120 \times 10^{-6}$ F

$$\therefore \quad f_s = \frac{1}{2\pi} \sqrt{\frac{(C_{1eq} + C_X)}{(L_{2eq} \cdot C_{1eq} \cdot C_X)}} \tag{23.14}$$

$$= \frac{1}{2\pi} \sqrt{\frac{(5 \times 9 \times 120 \times 10^{-6}) + (9 \times 120 \times 10^{-6})}{\left(\frac{0.4 \times 6}{3 \times 5} \times 10^{-6}\right)(5 \times 9 \times 120 \times 10^{-6})(9 \times 120 \times 10^{-6})}}$$

$$= \frac{10^3}{2\pi}\sqrt{\frac{6 \times 3 \times 5 \times 10^6}{0.4 \times 6 \times 5 \times 9 \times 120}}$$

= 13.26 kHz

This will be the surge frequency of the switching circuit when the sixth capacitor is switched on a circuit that has five capacitor units already switched. The improved value of this switching frequency, f_s', after the introduction of inductance 42.93 μH in each capacitor circuit will become

$$L_{2eq'} \simeq \frac{\left(\frac{0.4}{3} + L\right) \times 6}{5} \times 10^{-6}\,\text{H}$$

$$= \left(\frac{(0.4 + 3L) \times 6}{3 \times 5}\right) \times 10^{-6}\,\text{H}$$

$$C_{1eq'} = C_{1\,eq} = 5 \times 9 \times 120 \times 10^{-6}\,\text{F}$$

$$C_x = C_2 = 9 \times 120 \times 10^{-6}\,\text{F}$$

Therefore the only change in the previous calculation is for L_{2eq} which is now substituted by (0.4 + 3L), i.e. (0.4 + 3 × 42.93) or 129.19 for 0.4 in the numerator,

$$\therefore\ f_s' = 13.26\sqrt{\frac{0.4}{129.19}}\ \text{kHz}$$

$$= 13.26 \times 0.0556 \times 10^3\ \text{Hz}$$

$$= 738\ \text{Hz}$$

which is substantially damped with the use of additional inductance, and is only slightly more than the switching frequency on single capacitor switching as worked out in Example 23.3.

23.12 Capacitor panel design parameters

Since this device is also associated with the same power system as a switchgear assembly, it should generally meet the same specifications (Section 13.4) except for small variations in operating conditions and test requirements. Capacitors generate excessive heat when in service. Installations employing large capacitor banks must therefore have a capacitor mounting structure suitable to dissipate heat freely and permit circulation of fresh air during normal operation. To achieve this, open-type enclosures are usually preferred when it is possible to house the panel in a separate room or mount the units on a structure in an open switchyard. It may also be provided with an expanded metal enclosure. Forced cooling within the enclosure or the room where such banks are installed is common practice to dissipate the excessive heat. For more details refer to the following publications:

IEC 60831-1 and 60931-1 for LV, and IEC 60871-1 and IEC 60143-1 for HV systems

23.12.1 Selecting the voltage rating of the capacitor units

When selecting the voltage of the capacitor units care must be taken that during operation the voltage across the capacitor units does not fluctuate beyond ±10%. If this happens the voltage rating of the capacitor units must be chosen so that the variation across the units under unfavourable operating conditions does not exceed ±10%.

Example 23.6

If 3000 kVAr capacitor banks are required for a system of 33 kV + 7.5%, –5% and the capacitors are rated for $34/\sqrt{3}$ kV then the output of the capacitors at nominal voltage will reduce to

$$\left(\frac{33}{34}\right)^2 \times 3000 = 2826\ \text{kVAr}$$

which will result in an under-compensation by 174 kVAr or 5.8%. If the system voltage falls to, say, 31.5 kV during peak load periods the rating of the capacitor banks will fall further and may render the system unstable,

Effective kVAr at 31.5 kV

$$= \left(\frac{31.5}{34}\right)^2 \times 3000$$

= 2575 kVAr

which will result in an under-compensation by 425 kVAr, or 14.2%. It is therefore advisable to select the voltage rating of the capacitor units at almost the average voltage of the system, which in the above case, will be

$$= \frac{33 \times 1.075 + 33 \times 0.95}{2} = 33.4\ \text{kV}$$

The capacitor banks may be designed for $33.4/\sqrt{3}$ kV. See also Example 23.1 to account for the voltage rise due to series reactor in case series reactors are used.

Note

All voltages referred to above are nominal system voltages. The manufacturer will design the capacitor units for the maximum system voltage corresponding to the nominal voltage.

23.12.2 Determining the kVAr rating of a power circuit

Consider Figure 23.29(a), where, the p.f. of a power circuit is to be improved from cos ϕ_1, to cos ϕ_2. If kVAr_1 is the reactive component of power at p.f. cos ϕ_1 which is to be improved to kVAr_2, at p.f. cos ϕ_2, through the reactive power compensation, then the reactive component of power compensated or kVAr rating of the required capacitor banks

$$\text{kVAr} = \text{kVAr}_1 - \text{kVAr}_2$$

From Figure 23.29(a)

$$\frac{\text{kVAr}_1}{\text{kW}} = \tan\phi_1$$

and $$\frac{\text{kVAr}_2}{\text{kW}} = \tan\phi_2$$

$$\therefore\ \text{kVAr}_1 - \text{kVAr}_2 = \text{kW}(\tan\phi_1 - \tan\phi_2) = \text{kW} \cdot \text{K} \qquad (23.17)$$

where K is a multiplying factor. For quick application of this equation and to simplify calculations, the factor K has been worked out for different values of cos ϕ_1 and cos ϕ_2 and reproduced in the form of Table 23.6.

Example 23.7

For a load of 75 kW, having a p.f. of 0.75, the capacitor rating to improve it to 0.95 can be calculated as follows:

$\cos \phi_1 = 0.75$

$\therefore \quad \phi_1 = 41.41°$

and $\quad \tan \phi_1 = 0.882$

$\cos \phi_2 = 0.95$

$\therefore \quad \phi_2 = 18.19°$

and $\quad \tan \phi_2 = 0.329$

$\therefore \quad \tan \phi_1 - \tan \phi_2 = 0.882 - 0.329$

or $\quad K = 0.553$

(the same value can easily be determined from Table 23.6) and the required rating of capacitors,

$\text{kVAr} = 75 \times 0.553$

$= 41.5 \text{ kVAr}$

Say, 40 kVAr

See also Figure 23.29(b).

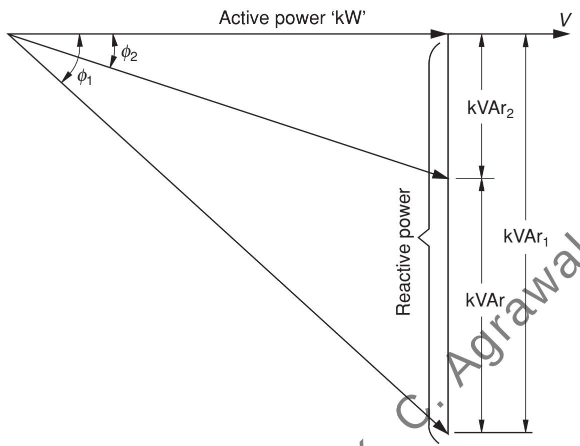


Figure 23.29(a) Determining the kVAr rating of a shunt capacitor

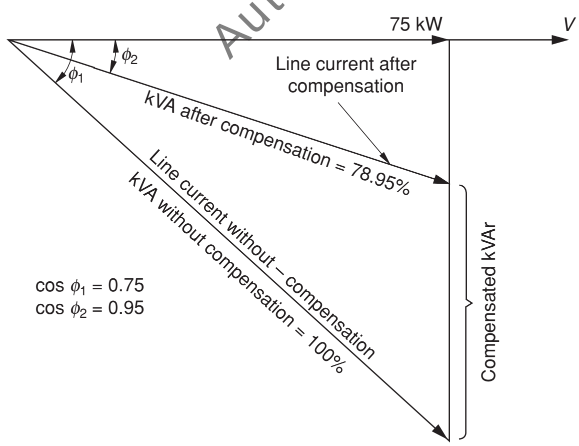


Figure 23.29(b) Reduction in line current after power factor compensation

23.13 Capacitor rating for an induction motor

The selection of capacitor rating, for an induction motor, running at different loads at different times, due either to change in load or fluctuation in supply voltage, is difficult and should be done with care because the reactive loading of the motor also fluctuates accordingly. A capacitor with a higher value of kVAr than the motor kVAr, under certain load conditions, may develop dangerous voltages due to self-excitation. At unity power factor, the residual voltage of a capacitor is equal to the system voltage. It rises at leading power factors (Figure 23.30). These voltages will appear across the capacitor banks when they are switched off and become a potential source of danger to the motor and the operator. Such a situation may arise when the capacitor unit is connected across the motor terminals and is switched with it. This may happen during an open transient condition while changing over from star to delta, or from one step to another, as in an A/T switching, or during a tripping of the motor or even while switching off a running motor. In all such cases the capacitor will be fully charged and its excitation voltage, the magnitude of which depends upon the p.f. of the system, will appear across the motor terminals or any other appliances connected on the same circuit. The motor, after disconnection from supply, will receive the self-excitation voltage from the capacitor and while running may act as a generator, giving rise to voltages at the motor terminals considerably higher than the system voltage itself. The solution to this problem is to select a capacitor with its capacitive current slightly less than the magnetizing current, I_m, of the motor, say, 90% of it. See also Figure 1.15.

At voltages lower than rated, the no-load current, $I_{n\ell}$, and the magnetizing current, I_m, of the motor is low and rises with the voltage. At loads lower than rated, although the p.f. will diminish sharply as discussed in Section 1.8, the reactive component I_m and the no-load current $I_{n\ell}$, i.e. component OA of Figure 1.16, will remain the same.

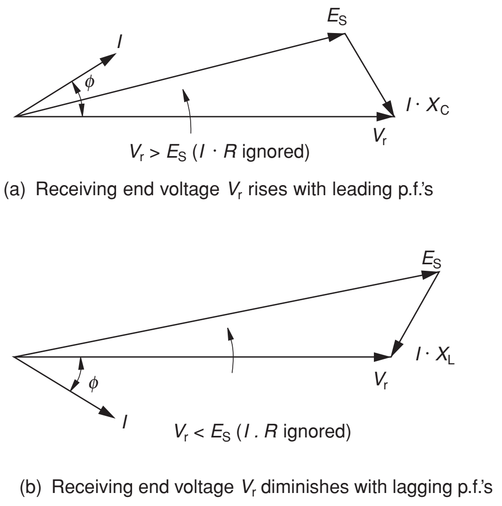
If these facts are not borne in mind when selecting the capacitor rating, particularly when the p.f. of the motor is assumed to be lower than the rated p.f. at full load, then at certain loads and voltages it is possible that the capacitor kVAr may exceed the motor reactive component, and cause a leading power factor. A leading p.f. can produce dangerous over-voltages. This phenomenon is also true in an alternator.

If such a situation arises with a motor or an alternator, it is possible that it may cause excessive torques. Keeping these parameters in mind, motor manufacturers have recommended compensation of only 90% of the no-load kVAr of the motor, irrespective of the motor loading. This, for all practical purposes and at all loads, will improve the p.f. of the motor to around 0.9–0.95, which is satisfactory.

Table 23.7, based on the recommendations of motor manufacturers, suggests the likely capacitor ratings for different motor ratings and speeds. For higher ratings, interpolate or calculate the rating as illustrated in Section 23.12.2.

Table 23.6 Chart for selection of shunt capacitor rating, to improve the existing p.f. to a higher level

Present power factor	*Factor K for required power factor*												
	0.80	*0.85*	*0.90*	*0.91*	*0.92*	*0.93*	*0.94*	*0.95*	*0.96*	*0.97*	*0.98*	*0.99*	*Unity*
0.40	1.537	1.668	1.805	1.832	1.861	1.895	1.924	1.959	1.998	2.037	2.085	2.146	2.288
0.41	1.474	1.605	1.742	1.769	1.798	1.831	1.860	1.896	1.935	1.973	2.021	2.082	2.225
0.42	1.413	1.544	1.681	1.709	1.738	1.771	1.800	1.836	1.874	1.913	1.961	2.022	2.164
0.43	1.356	1.487	1.624	1.651	1.680	1.713	1.742	1.778	1.816	1.855	1.903	1.964	2.107
0.44	1.290	1.421	1.558	1.585	1.614	1.647	1.677	1.712	1.751	1.790	1.837	1.899	2.041
0.45	1.230	1.360	1.501	1.532	1.561	1.592	1.626	1.659	1.695	1.737	1.784	1.846	1.988
0.46	1.179	1.309	1.446	1.473	1.502	1.533	1.567	1.600	1.636	1.677	1.725	1.786	1.929
0.47	1.130	1.260	1.397	1.425	1.454	1.485	1.519	1.552	1.588	1.629	1.677	1.758	1.881
0.48	1.076	1.206	1.343	1.370	1.400	1.430	1.464	1.497	1.534	1.575	1.623	1.684	1.826
0.49	1.030	1.160	1.297	1.326	1.355	1.386	1.420	1.453	1.489	1.530	1.578	1.639	1.782
0.50	0.982	1.112	1.248	1.276	1.303	1.337	1.369	1.403	1.441	1.481	1.529	1.590	1.732
0.51	0.936	1.066	1.202	1.230	1.257	1.291	1.323	1.357	1.395	1.435	1.483	1.544	1.686
0.52	0.894	1.024	1.160	1.188	1.215	1.249	1.281	1.315	1.353	1.393	1.441	1.502	1.644
0.53	0.850	0.980	1.116	1.144	1.171	1.205	1.237	1.271	1.309	1.349	1.397	1.458	1.600
0.54	0.809	0.939	1.075	1.103	1.130	1.164	1.196	1.230	1.268	1.308	1.356	1.417	1.559
0.55	0.769	0.899	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316	1.377	1.519
0.56	0.730	0.860	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1.338	1.480
0.57	0.692	0.822	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1.300	1.442
0.58	0.655	0.785	0.921	0.949	0.976	1.010	1.042	1.076	1.114	1.154	1.202	1.263	1.405
0.59	0.618	0.748	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165	1.226	1.368
0.60	0.584	0.714	0.849	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131	1.192	1.334
0.61	0.549	0.679	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.048	1.096	1.157	1.299
0.62	0.515	0.645	0.781	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062	1.123	1.265
0.63	0.483	0.613	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.030	1.091	1.233
0.64	0.450	0.580	0.716	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997	1.058	1.200
0.65	0.419	0.549	0.685	0.713	0.740	0.774	0.806	**0.840**	0.878	0.918	0.966	1.027	1.169
0.66	0.388	0.518	0.654	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935	0.996	1.138
0.67	0.358	0.488	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905	0.966	1.108
0.68	0.329	0.459	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876	0.937	1.079
0.69	0.299	0.429	0.565	0.593	0.620	0.654	0.686	0.720	0.758	0.798	0.840	0.907	1.049
0.70	0.270	0.400	0.536	0.564	0.591	0.625	0.657	0.691	0.729	0.769	0.811	0.878	1.020
0.71	0.242	0.372	0.508	0.536	0.563	0.597	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.72	0.213	0.343	0.479	0.507	0.534	0.568	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.73	0.186	0.316	0.452	0.480	0.507	0.541	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.74	0.159	0.289	0.425	0.453	0.480	0.514	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.75	0.132	0.262	0.398	0.426	0.453	0.487	0.519	**0.553**	0.591	0.631	0.673	0.740	0.882
0.76	0.105	0.235	0.371	0.399	0.426	0.460	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.77	0.079	0.209	0.345	0.373	0.400	0.434	0.466	0.500	0.538	0.578	0.620	0.687	0.829
0.78	0.053	0.183	0.319	0.347	0.374	0.408	0.440	0.474	0.512	0.552	0.594	0.661	0.803
0.79	0.026	0.156	0.292	0.320	0.347	0.381	0.413	0.447	0.485	0.525	0.567	0.634	0.776
0.80	–	0.130	0.266	0.294	0.321	0.355	0.387	0.421	0.459	0.499	0.541	0.608	0.750
0.81	–	0.104	0.240	0.268	0.295	0.329	0.361	0.395	0.433	0.473	0.515	0.582	0.724
0.82	–	0.078	0.214	0.242	0.269	0.303	0.355	0.369	0.407	0.447	0.489	0.556	0.698
0.83	–	0.052	0.188	0.216	0.243	0.277	0.309	0.343	0.381	0.421	0.463	0.530	0.672
0.84	–	0.026	0.162	0.190	0.217	0.251	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.85	–	–	0.136	0.164	0.191	0.225	0.257	0.291	0.329	0.369	0.417	0.478	0.620
0.86	–	–	0.109	0.140	0.167	0.198	0.230	0.264	0.301	0.343	0.390	0.450	0.593
0.87	–	–	0.083	0.114	0.141	0.172	0.204	0.238	0.275	0.317	0.364	0.424	0.567
0.88	–	–	0.054	0.085	0.112	0.143	0.175	0.209	0.246	0.288	0.335	0.395	0.538
0.89	–	–	0.028	0.059	0.086	0.117	0.149	0.183	0.230	0.262	0.309	0.369	0.512
0.90	–	–	–	0.031	0.058	0.089	0.121	0.155	0.192	0.234	0.281	0.341	0.484
0.91	–	–	–	–	0.027	0.058	0.090	0.124	0.161	0.203	0.250	0.310	0.453
0.92	–	–	–	–	–	0.031	0.063	0.097	0.134	0.176	0.223	0.283	0.426
0.93	–	–	–	–	–	–	0.032	0.066	0.103	0.145	0.192	0.252	0.395
0.94	–	–	–	–	–	–	–	0.034	0.071	0.113	0.160	0.220	0.363
0.95	–	–	–	–	–	–	–	–	0.037	0.079	0.126	0.186	0.329
0.96	–	–	–	–	–	–	–	–	–	0.042	0.089	0.149	0.292
0.97	–	–	–	–	–	–	–	–	–	–	0.047	0.107	0.250
0.98	–	–	–	–	–	–	–	–	–	–	–	0.060	0.203
0.99	–	–	–	–	–	–	–	–	–	–	–	–	0.143



(a) Receiving end voltage V_r rises with leading p.f.'s

(b) Receiving end voltage V_r diminishes with lagging p.f.'s

Figure 23.30

23.14 Location of capacitors

Refer to a typical distribution network shown in Figure 23.31. The capacitor is of maximum use when located as near to the load-point as possible, especially in induction motors, because:

1 The reactive load is confined to the smallest part of the system.
2 The motor starter can be used to switch the capacitor as well as the motor, eliminating the cost of an extra switch and fuse for the capacitor.
3 By employing the same switch for motor and capacitor, the capacitor is automatically controlled. The capacitor is required to be in the circuit only when the motor is in operation.
The capacitor panel can be a part of the main power control centre (PCC) or the motor control centre (MCC) or it can also be a separate panel, as shown in Figure 23.32. In group loads such as an industrial or a power-house application, it may be more economical and practical to instal capacitors in groups, whose kVAr

Table 23.7 Recommended capacitor ratings for direct switching with induction motors, to improve power factor to 0.95 or better at all loads

Motor H.P.	*Capacitor rating in kVAr at a motor r.p.m.*						*Motor H.P.*	*Capacitor rating in KVAr at a motor r.p.m.*					
	3000 r.p.m.	*1500 r.p.m.*	*1000 r.p.m.*	*750 r.p.m.*	*600 r.p.m.*	*500 r.p.m.*		*3000 r.p.m.*	*1500 r.p.m.*	*1000 r.p.m.*	*750 r.p.m.*	*600 r.p.m.*	*500 r.p.m.*
2.5	1	1	1.5	2	2.5	2.5	105	22	24	27	29	36	41
5	2	2	2.5	3.5	4	4	110	23	25	28	30	38	43
7.5	2.5	3	3.5	4.5	5	5.5	115	24	26	29	31	39	44
10	3	4	4.5	5.5	6	6.5	120	25	27	30	32	40	46
12.5	3.5	4.5	5	6.5	7.5	8	125	26	28	31	33	41	47
15	4	5	6	7.5	8.5	9	130	27	29	32	34	43	49
17.5	4.5	5.5	6.5	8	10	10.5	135	28	30	33	35	44	50
20	5	6	7	9	11	12	140	29	31	34	36	46	52
22.5	5.5	6.5	8	10	12	13	145	30	32	35	37	47	54
25	6	7	9	10.5	13	14.5	150	31	33	36	38	48	55
27.5	6.5	7.5	9.5	11.5	14	16	155	32	34	37	39	49	56
30	7	8	10	12	15	17	160	33	35	38	40	50	57
32.5	7.5	8.5	11	13	16	18	165	34	36	39	41	51	59
35	8	9	11.5	13.5	17	19	170	35	37	40	42	53	60
37.5	8.5	9.5	12	14	18	20	175	36	38	41	43	54	61
40	9	10	13	15	19	21	180	37	39	42	44	55	62
42.5	9.5	11	14	16	20	22	185	38	40	43	45	56	63
45	10	11.5	14.5	16.5	21	23	190	38	40	43	45	58	65
47.5	10.5	12	15	17	22	24	195	39	41	44	46	59	66
50	11	12.5	16	18	23	25	200	40	42	45	47	60	67
55	12	13.5	17	19	24	26	205	41	43	46	48	61	68
60	13	14.5	18	20	26	28	210	42	44	47	49	61	69
65	14	15.5	19	21	27	29	215	42	44	47	49	62	70
70	15	16.5	20	22	28	31	220	43	45	48	50	63	71
75	16	17	21	23	29	32	225	44	46	49	51	64	72
80	17	19	22	24	30	34	230	45	47	50	52	65	73
85	18	20	23	25	31	35	235	46	48	51	53	65	74
90	19	21	24	26	33	37	240	46	48	51	53	66	75
95	20	22	25	27	34	38	245	47	49	52	54	67	75
100	21	23	26	28	35	40	250	48	50	53	55	68	76

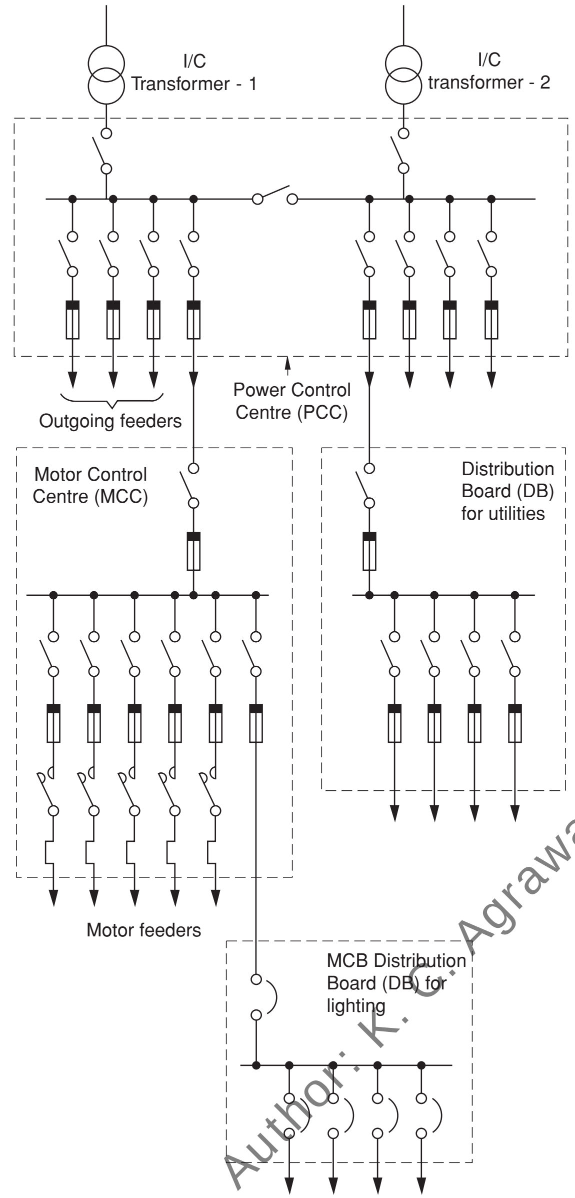


Figure 23.31 Receiving and distribution of power in an industrial unit

value can be varied as desired, depending upon the system loading at a time. This can also be done automatically through a preset power factor correction relay (Figure 23.38). The advantages of a group installation can be:

- Diversity: When a number of motor loads are connected on a common bus, normally not all the motors will be operating at a time. A capacitor bank near the MCC would permit the use of lesser total kVAr than if the capacitors were located separately at each individual load.
- When many small motors are operating simultaneously it is economical to instal larger capacitors in several sections than to have many small capacitors installed at each motor.

Figures 23.33 and 23.34 illustrate the locations discussed so far. Figure 23.33 suggests the locations of the capacitor in respect of the motor whose p.f. is to be improved, e.g. at position 1* the capacitor is connected on the motor side after the starter. The same starter will switch both the motor and the capacitor. Since the capacitor will reduce the kVAr demand, the current through the starter relay will be low and it should be set at a lower value accordingly.

At position 2 the capacitor is connected on the line side, although switched by the same switching device. The relay setting is not affected since only the full motor current will flow through the starter. In position 3 the capacitor is connected to the circuit, through an additional switch fuse unit.

Figure 23.34 suggests possible locations where the capacitor banks can be installed for individual or group controls, depending upon cost and simplicity. Location 1 will be suited for individual loads and is effective when there are not many load points. For group controls, location 3 is ideal and most economical. Compared to location 3, location 2 is not appropriate unless there are feeders on the main bus that would require a power factor improvement in addition to capacitors at location 3. In this case the capacitors at location 2 will be for the feeders on the main bus and not for the downstream distribution feeders. Location 4 controls the power factor from one point. This location is suitable for improving the system power factor, reducing the kVA demand and the strains on the main supply and distribution network. Technically speaking, it has no advantages for in-plant power distribution, nor does it help to reduce the kVA strain on the feeding cables or the loading on the power distribution feeders. But for simplicity and ease of control for the entire plant it is used most often.

23.15 Automatic PF correction of a system

As discussed above, for an industrial or power plant application or an installation with a number of inductive load points a group capacitor control is always more effective, simple and economical. Such an installation generally has a frequent variation in its load demand due to some feeders coming on the bus and some falling out at different times. There may be variation in the individual feeder's load demand, such as a tool room, where not all the machines will be working at a time, or a pulp and paper mill, where the paper mill is a continuous load, the pulp mill is an intermittent one. A water treatment plant

* When adopting this location, care must be taken that the capacitors are not subjected to a quick reclosing (Section 25.6.2(4)). In a Y/Δ or A/T switching the capacitors would be subjected to a quick reclosing and may endanger the motor insulation as well as its own. In this case it would be essential to make a suitable modification in its switching circuit to keep the capacitor out of the circuit during the changeover, as suggested in Figure 25.7.

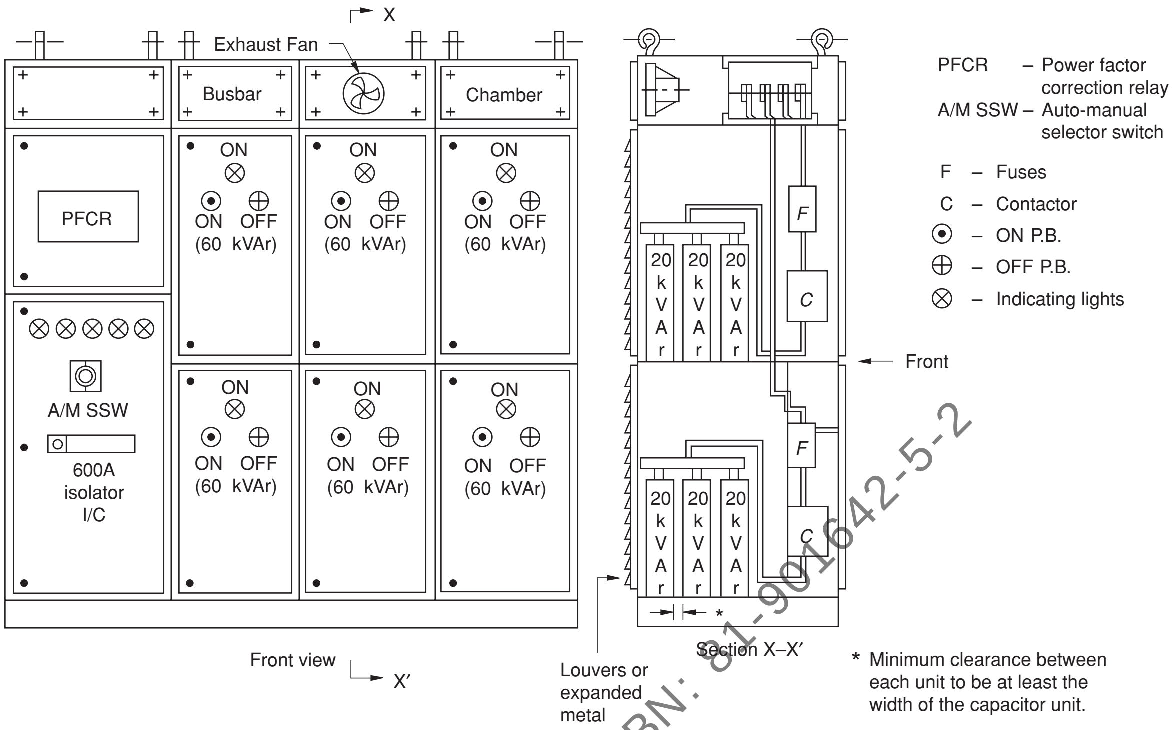


Figure 23.32 General arrangement of capacitor panel

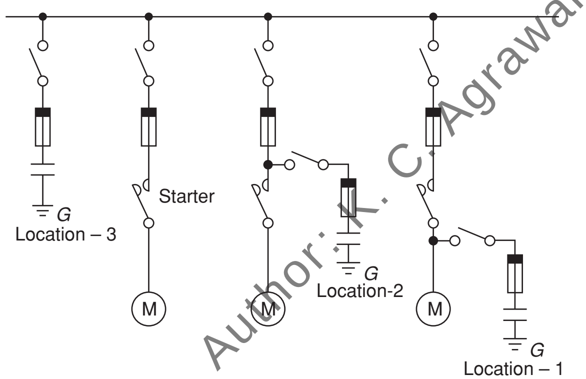


Figure 23.33 Capacitor locations for individual compensation

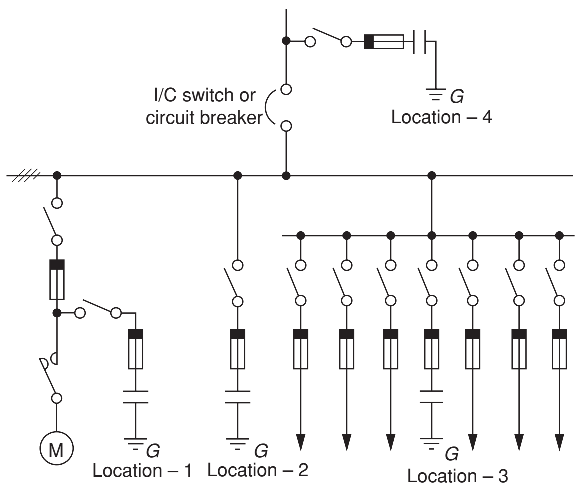


Figure 23.34 Capacitor locations for individual or group loads

or a pump house are similar installations where all or some of the loads would be in operation at a time. For such installations, the total capacitive load demand at a required power factor level is worked out and the total capacitor banks are installed at a convenient point and suitably grouped (banked) for the type of loading and system demand. Each bank is controlled through a power contactor and a common power factor correction relay to automatically monitor and control the power factor of the system to a predetermined level, preset in the relay, by switching a few capacitor banks ON or OFF, depending upon the load demand and the power factor measured by the relay. The relay actuates the required number of capacitor feeders through their contactors.

Automatic correction is always recommended to eliminate manual dependence and to achieve better accuracy. It also eliminates the risk of a leading power factor by a human error that may cause an excessive charging voltage at the motor and the control gear terminals.

The following example illustrates the method of selecting the capacitors' value, their grouping and their control for a system having a number of load points.

Example 23.8
Consider a system shown in the single-line diagram of Figure 23.35, where total load on MCC-1 as in the single-line diagram of Figure 23.36 is

3 × 10 h.p	=	30 h.p.
4 × 5 h.p.	=	20 h.p.
2 × 20 h.p.	=	40 h.p.
2 × 40 h.p.	=	80 h.p.
2 × 30 h.p.	=	60 h.p.
1 × 100 h.p.	=	100 h.p.
1 × 50 h.p.	=	50 h.p.
Total		380 h.p. + spares and lighting load

Notes

1 Lighting loads are not considered for the following reasons:
   (i) All incandescent lamps are resistive and do not influence the power factor of the system,
   (ii) Mercury vapour lamps and sodium vapour lamps are invariably provided with built-in p.f. improvement capacitors by their manufacturers,
   (iii) Fluorescent tubes used for industrial installations and domestic use are also provided with p.f. improvement capacitors.
2 Similarly, 100 A and 25 A spares are also not considered, assuming that the utility of such feeders would be rare and for short durations (such as for maintenance).
3 Spare motor feeders are also not considered for similar reasons.

Total loads for other MCCs, as in the single-line diagram of Figure 23.35:

MCC-2	–	75 h.p.	+	Spare and lighting load
MCC-3	–	150 h.p.	+	Spare and lighting load
MCC-4	–	200 h.p.	+	Spare and lighting load

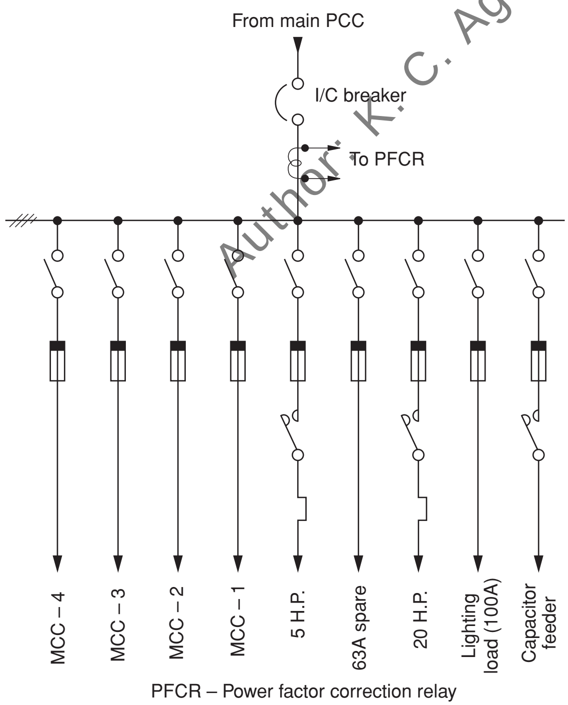


Figure 23.35 Single-line diagram for an industrial load

Then the total inductive load connected on the main PCC-cum-MCC:

MCC-1	–	380 h.p.
MCC-2	–	75 h.p.
MCC-3	–	150 h.p.
MCC-4	–	200 h.p.
5 h.p. × 1	–	5 h.p.
20 h.p. × 1	–	20 h.p.
Total	–	830 h.p.

Considering the diversity factor (Table 13.4) for such a plant to be 70%, or as the system may require, which can be determined by the type of industry and the process demand:

∴ Total inductive load on the system at any time

$= 830 \times 0.7$

$= 581$ h.p.

or 581×0.746, i.e. 433.43 kW

Assume the plant p.f. before the power factor correction to be 0.65. (We have provided in Table 23.8 the likely operating power factors for different types of industries, as a rough guide.) If this p.f. is to be improved to say, 0.95, then from Table 23.6,

Factor $K = 0.84$

and total capacitor banks required $= 433.43 \times 0.84 = 364$ kVAr

Thus capacitor banks of 360 kVAr should be adequate for this system and can be arranged in six steps of 60 kVAr each.

For the rating of the incoming feeder (also see Section 25.6),

$$I_C = \frac{360}{\sqrt{3} \times 0.415} \simeq 500 \text{ A}$$

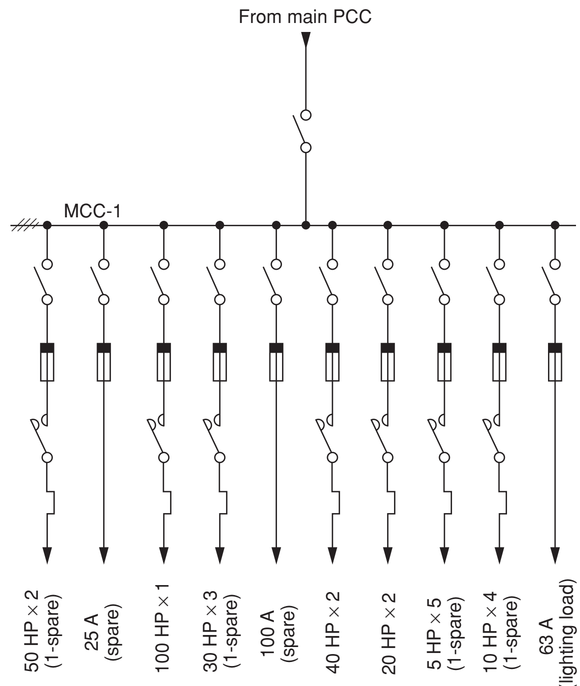


Figure 23.36 Single-line diagram for MCC-1

Table 23.8 Likely operating power factors for different types of industries

Type of industry	*Likely power factor*	*Type of industry*	*Likely power factor*
Cold storage and fisheries	0.76 to 0.80	Flour mills	0.61
Cinemas	0.78 to 0.80	Gas works	0.87
Metal pressing	0.57 to 0.72	Textile mills	0.86
Confectionery	0.77	Oil mills	0.51 to 0.59
Dyeing and printing (textile)	0.60 to 0.87	Woollen mills	0.70
Plastic moulding	0.57 to 0.73	Potteries	0.61
Film studios	0.65 to 0.74	Cigarette manufacturing	0.80
Newspaper printing	0.58	Cotton press	0.63 to 0.68
Heavy engineering works	0.48 to 0.75	Foundries	0.59
Rubber extrusion and moulding	0.48	Tiles and mosaic	0.61
Pharmaceuticals	0.75 to 0.86	Structural engineering	0.53 to 0.68
Oil and paint manufacturing	0.51 to 0.69	Chemicals	0.72 to 0.87
Silk mills	0.58 to 0.68	Municipal pumping stations	0.65 to 0.75
Biscuit factory	0.60	Refineries and petrochemicals	0.64 to 0.83
Printing press	0.65 to 0.75	Telephone exchange	0.66 to 0.80
Food products	0.63	Rolling mills	0.72 to 0.80
Laundries	0.92	Irrigation pumps	0.50 to 0.70

Note:
These figures are only indicative.

$\therefore$ Rating of the incoming switch = 1.5 × 500 = 750 A

The nearest standard rating available = 800 A
For the rating of outgoing fuses and contactors

$$I_C = \frac{60}{\sqrt{3} \times 0.415} \simeq 83.5 \text{ A}$$

$\therefore$ Rating of the outgoing feeders = 1.5 × 83.5 = 125 A

Automatic control
Select a six- or eight-step power factor correction relay. In the case of an eight-step relay, the seventh and eighth steps can be left as spares, which may be used later when more capacitor banks are considered necessary. A typical control scheme and the power circuit for such a system is shown in Figure 23.37. A general arrangement for such a capacitor control panel is shown in Figure 23.32.

23.15.1 Other methods for PF correction

LV installations may be subject to frequent load variations and inductive switchings. It will be more desirable in such cases to provide them with an automatic p.f. correction scheme than manual correction. It may be impracticable to keep a close monitoring of such system variations and alter the capacitive reactance manually to maintain the desired p.f. level.

The situation in an HV installation will, however, be different. An HV system is mostly a fixed-load one, where a variation in the load may be only occasional and at certain periodic intervals. To provide an automatic switching in such cases will be a costly arrangement due to expensive switchgear equipment. In addition, it will also cause cumulative switching surges as a result of rapid reclosing and interrupting sequences unless a static switching control is adopted as discussed in Section 24.10, which will further add to the cost. To mitigate such constraints, the following may be considered as the more recommended methods for p.f. control of such installations:

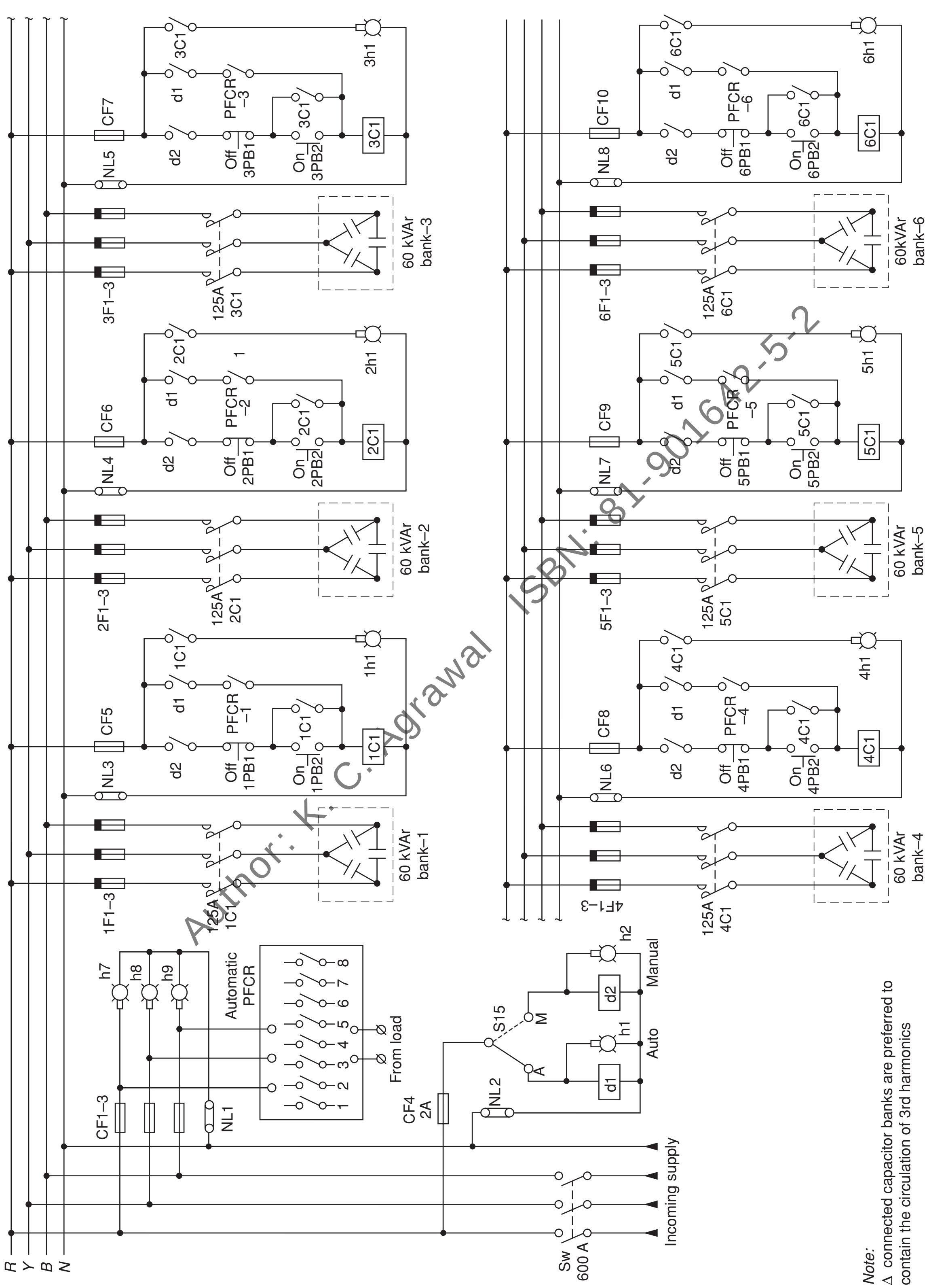
1 Identify the likely variations in load and p.f. during a 24-hour period. Maintain a minimum fixed kVAr permanently connected in the system, at the distribution point for the likely constant loads. For the rest, the banks may be selected so that only one or two are sufficient to control the whole system for the desired p.f. level or system regulation. This will also limit operations of the banks to only three or four a day and less than a thousand during a year, as recommended in Section 26.1.1(2). Control may now be carried out:
   - Manually, as variations in load would almost be specific and periodic and easy to monitor or
   - By making it automatic, which would now be economical with one or two variable banks.

2 In a secondary transmission or a primary distribution network it is common practice to provide the maximum possible size of fixed capacitor banks at the transmission point or on the pole at the distribution point with the feeder transformer. This is done to maintain the p.f. and the regulation of the system up to a certain minimum level.

   Capacitors mounted out of sight or away from easy reach may sometimes be ignored for maintenance or periodic checks. This must be taken into account while installing the capacitor units. To monitor the health of capacitor units one may instal an ammeter or a kVAr meter in each phase and maintain a logbook. The health of capacitor units/ banks can then be ascertained through the unbalance in the three phases of the capacitor circuit. When warranted, preventive measures such as cleaning the insulators, tightening the terminals, and replacing or adding of a few capacitor units to make up for the lost capacitances and to balance the system can be undertaken.

23.16 Switching sequences

A switching sequence that can be employed for a particular load cycle may be one of the following:



Note:
Δ connected capacitor banks are preferred to contain the circulation of 3rd harmonics

Figure 23.37 A power schematic drawing for an automatic capacitor control panel

23.16.1 First in last out

This is the simplest type of switching. Capacitors are switched ON in the sequence of 1-2-3 . . . *n* and switched OFF in the reverse sequence, i.e. *n* . . . 3-2-1. In this switching the last switched capacitor is made to switch again. This switching is therefore more stressful for the capacitor as well as for the system, due to surge voltages. During a switch ON therefore some time delay must be introduced into the switching circuit for the capacitor charge to decay to a safe level. In this sequence, the capacitors of each step are normally the same. It is a primitive and unscientific switching sequence and therefore not in much use.

23.16.2 True 'first in first out' (FIFO)

Capacitors are switched ON in the sequence of 1-2-3 . . . *n* but an additional logic is used to switch OFF in the same sequence 1-2-3 . . . *n,* i.e. the oldest OFF capacitor is switched ON first and the oldest ON capacitor is switched OFF first. This apparently is the best switching sequence, giving enough time to an OFF capacitor to discharge before it is switched again. Each stage capacitor rating must be equal to avoid a wide fluctuation in the p.f. correction and hence undesirable subsequent switchings, which may be necessitated when the capacitors are not of equal ratings.

23.16.3 Pseudo (false) 'first in first out'

In a way this is more appropriate than the FIFO, for it can have unequal stage capacitors. Capacitors, however, are arranged in ascending order such as 10, 20, 50 . . . kVAr etc., or large or small capacitors. But, as mentioned above, this may not provide accurate correction in the first instance. Now the relay may have to operate on the theory of probability and resort to a lot of sequencing to arrive at the right correction. Such a sequencing may also lead to hunting and cause voltage fluctuations, because of varying p.fs. and also cause switching currents and voltage surges.

23.16.4 1+2+2 . . .

The first capacitor is half the rating of the remaining ones, which are all equal. The p.f. correction is delayed, due to allowing discharge time. The smallest unit is more stressed.

23.16.5 Direct combinatorial or auctioneering switching

Here the relay assesses the kVAr requirement of the system and switches ON all the required capacitors simultaneously. Theoretically any size of capacitor units can be used. But when a capacitor is taken out for maintenance, this can create confusion in the p.f. correction. The relay will not be aware of this and act accordingly. The bank size may also be large and cause switching surges.

23.16.6 Special sequencing

These are sequencers and can sequence the switching of capacitors in any fixed pattern. Capacitors can be automatically taken out of the circuit and others introduced in their place by a device known as 'the load rotator'.

A good relay can be modified to perform a particular switching sequence during ON and OFF and both sequences need not be same. A binary switching relay discussed below is a type of relay that can be modified to perform any desired switching pattern.

23.16.7 Binary switching

This is a highly recommended method of capacitor switching for installations that are large and require very fine monitoring and corrections of p.f. with the smallest number of banks. The entire reactive requirement is arranged in only a few steps yet a small correction up to the smallest capacitor unit is possible. The relay is sequenced so that through its binary counter the required switching is achieved in small steps, with just four or six sets of capacitor units or banks. The operation of the entire sequence can be illustrated as follows:

1 **A four-stage binary** The capacitor units or banks are arranged in the ratio 1 : 2 : 4 : 8. The four-stage capacitor bank is switched in one to fifteen steps (summation of 1 + 2 + 4 + 8), giving fifteen different values of reactive power control in small steps of one unit each. To achieve this, the relay goes up and down only one step at a time. For example, if we have to switch 75 kVAr in small steps, this can be arranged in the ratio of 5 : 10 : 20 : 40 kVAr units. These capacitors can be switched in steps of 5 kVAr each (total 15 steps). Table 23.9 illustrates the switching sequence for switching ON or OFF all the capacitor units through

Table 23.9 A four-stage binary scheme

Switching steps	*Capacitor units*				*Total switched kVAr in steps of 5 kVAr each*
	1st 5 kVAr	*2nd 10 kVAr*	*3rd 20 kVAr*	*4th 40kVAr*	
1	×	–	–	–	5
2	–	×	–	–	10
3	×	×	–	–	15
4	–	–	×	–	20
5	×	–	×	–	25
6	–	×	×	–	30
7	×	×	×	–	35
8	–	–	–	×	40
9	×	–	–	×	45
10	–	×	–	×	50
11	×	×	–	×	55
12	–	–	×	×	60
13	×	–	×	×	65
14	–	×	×	×	70
15	×	×	×	×	75

× indicates the units that are ON.

a four-stage relay. Since the relay will switch ON in steps of 5 kVAr only, fast switching may be constrained, particularly when a charged unit, which had been recently out and may be fully charged, is required to be switched again. The problem of holding the charge can be eliminated with the use of special discharge devices, which would make it possible to achieve fast switching. Timers may be introduced into the switching circuit to allow for the thus reduced discharge time between two consecutive switchings.

2 **A six-stage binary** Now the capacitors are arranged in the ratio of 1 : 2 : 4 : 8 : 16 : 32 units, i.e. a six-stage capacitor bank can be switched in 63 steps, with different switching combinations, at a difference of just one unit. If the smallest unit is of 5 kVAr, a total correction of 315 kVAr is possible in steps of 5 kVAr each with just six sets of capacitor units and banks in the ratio of 5 : 10 : 20 :40 : 80 :160 kVAr. The rest of the sequencing is the same, as illustrated for four-stage binary. The six-stage sequencing scheme can also be developed along similar lines to those in Table 23.9.

A six-stage binary scheme should normally be adequate to switch even very large banks. Yet this sequencing can be further modified to achieve a more particular sequencing pattern when required, as noted below.

23.16.8 Modified binary switching

A fifteen- or sixty-three-step switching, as noted above, may be cumbersome and require too large a time gap to switch. Switchings in such small steps may indeed not be necessary when the correction is large. It is possible to modify the sequencing of the relay to switch all the units in just a few steps by accepting a few specific jumps, skipping a few steps in between still retaining the feature of small corrections. A typical modified six-stage binary scheme requiring 15 steps is shown in Table 23.10, achieving full switching in just 18 steps and yet maintaining quite small steps, in this case 20 kVAr and corrections, still in steps of 5 kVAr each. A four-stage binary scheme requiring 15 steps can be modified to only six steps, as indicated in the first six steps of this table.

The binary scheme can be modified to suit any other requirement also. For example, for an induction furnace, requiring very fast correction, the scheme may be modified, to have six stages in the ratio of 10 : 20 : 40 : 80 : 160 : 160 kVAr to make a total of 470 kVAr and corrections in steps of 10 kVAr each.

For loads with fast variations, this type of a modified version too may be sluggish, due to step-by-step tuning. In such cases it is possible to employ two relays, one for coarse correction, such as through a serial relay (FIFO) which can quickly switch the large banks, and the other for fine-tuning, which may be a binary relay. These two relays may be combined into one hybrid unit. The binary scheme can thus be modified to suit any required duty with prompt and finer corrections and least strain on a particular unit or on the system.

23.17 PF correction relays

The basic principle of this relay is the sensing of the phase displacement between the fundamental waveforms of the voltage and current waves of a power circuit. Harmonic quantities are filtered out when present in the system. This is a universal practice to measure the p.f. of a system to economize on the cost of relay. The actual

Table 23.10 A six-stage modified binary scheme

Switching steps	*Capacitor bank*						*Total switched kVAr*
	1st 5 kVAr	*2nd 10 kVAr*	*3rd 20kVAr*	*4th 40kVAr*	*5th 80 kVAr*	*6th 160 kVAr*	
1 *	×	–	–	–	–	–	5
2 *	–	×	–	–	–	–	10
3 *	×	×	–	–	–	–	15
7 *	×	×	×	–	–	–	35
11 *	×	×	–	×	–	–	55
15 *	×	×	×	×	–	–	75
19	×	×	–	–	×	–	95
23	×	×	×	–	×	–	115
27	×	×	–	×	×	–	135
31	×	×	×	×	×	–	155
35	×	×	–	–	–	×	175
39	×	×	×	–	–	×	195
43	×	×	–	×	–	×	215
47	×	×	×	×	–	×	235
51	×	×	–	–	×	×	255
55	×	×	×	–	×	×	275
59	×	×	–	×	×	×	295
63	×	×	×	×	×	×	315

*A four-stage binary scheme is modified to six steps

Note:
It is possible to achieve any correction within a step of one unit only (5 kVAr in the above case).

p.f. of the circuit may therefore be less than measured by the relay. But one can set the relay slightly higher (less than unity), to account for the harmonics, when harmonics are present in the system.

From this phase displacement, a d.c. voltage output is produced by a transducer circuit. The value of the d.c. voltage depends upon the phase displacement, i.e. the p.f. of the circuit. This d.c. voltage is compared with a built-in reference d.c. voltage, adjustable by the p.f. setting knob or by selecting the operating band provided on the front panel of the relay, as shown in Figure 23.38. Corrective signals are produced by the relay to switch ON or OFF the stage capacitors through a built-in sequencing circuit to reach the desired level of p.f.

A little lower p.f. than set would attempt to switch another unit or bank of capacitors, which may overcorrect the set p.f. Now the relay would switch off a few capacitor units or banks to readjust the p.f. and so will commence a process of hunting, which is undesirable. To avoid such a situation the sensitivity of the comparator is made adjustable through the knob on the front panel of the relay. The sensitivity control can be built in terms of phase angle (normally adjustable from 4 to 14 degrees electrical) or percentage kVAr. The sensitivity, in terms of an operating band, helps the relay to avoid a marginal over-correction or under-correction and hence the hunting.

As soon as the system's actual p.f. deviates from the pre-set limits, the relay becomes activated and switches in or switches out capacitor units one by one, until the corrected p.f. falls within the sensitivity limit of the relay.

The p.f. correction relays are normally available in three versions, i.e.

- Electromagnetic (being quickly outdated). They are very slow, and may take up to 2 minutes or more to initiate a correction.
- Solid state-based on discrete ICs.
- Microcontroller and microprocessor based relays.

A delayed correction may not be desirable in applications that have a fast variation of loads such as rolling mills, induction furnaces, arc furnaces, all types of welding loads, power presses, hammers and elevators etc. Such type of loads draw reactive power from the supply source. Since the loads change rapidly, unless they are compensated promptly they may cause voltage fluctuations, low p.f. and high harmonics. A rapid voltage drop may even trip the load, which may cause serious damage to machines in operation. For instance, in a rolling mill, the mill may be damaged as the process ingots may be half-way through between the rolls when the mill stops.

With application of solid-state technology, this shortcoming of an electromagnetic relay is automatically overcome. The solid-state relays are available with switching stages as many as from 2 to 16. For special applications, they can be designed for even higher numbers of steps.

A time delay is built in to allow discharge of a charged capacitor up to 90% before it is reswitched. This is achieved by introducing a timer into the relay's switching circuit. The timer comes on whenever an OFF signal occurs, and blocks the next operation of a charged capacitor, even on an ON command, until it is discharged

(a) Electromagnetic relay (Courtesy: Syntron)

(b1) Microcontroller based relay (Courtesy: Syntron)

(b2) Microprocessor based relay (Courtesy: Syntron)

Figure 23.38 Typical front views of automatic power factor correction relays to at least 90% of the applied voltage. This feature ensures safety against an over-voltage. Normally this time is 1–3 minutes for LV and 5–10 minutes for HV shunt capacitors (Section 26.3.1(5)) unless fast-discharge devices are provided across the capacitor terminals to reduce this time. Fast-discharge devices are sometimes introduced to discharge the capacitors faster than these stipulations to match with quickly varying loads. The ON action begins only when the timer is released.

The time of switching between each relay step is, however, quite short, of the order of 3–5 seconds. It includes the timings of the control circuit auxiliary relays (contactors). It may be noted that of this, the operating time of the static relay is scarcely of the order of three to five cycles.

In rapidly changing loads it must be ensured that enough discharged capacitors are available in the circuit on every close command. To achieve this, sometimes it may be necessary to provide special discharge devices (Section 25.7) across the capacitor terminals or a few extra capacitor units to keep them ready for the next switching. It may require a system study on the pattern of load variations and the corresponding p.fs. Fast switching, however, is found more often in LV systems than in HV. HV systems are more stable, as the variable loads are mostly LV.

The above discussion is generally related to IC-based solid-state relays and in most parts to microcontroller based relays of the more rudimentary types.

Note

1. To ensure proper sensing of the incoming current and its phase displacement by the relay it is essential that the CTs ratio and their VA burden chosen for the required duty are close to the actual requirement as noted in Table 15.8. Sometimes this fact is over-looked and CTs with a much higher VA burden or ratio or both are chosen while the secondary circuit may not be adequately loaded. In this case the CTs may not accurately transform the primary parameters to the secondary and, in turn, the relay may not send accurate signals. Moreover, the relay itself may operate only at minimum 1% or more of its rated current (1 or 5 A), depending upon its design and type (IEC 60051-1).
2. Electromagnetic and solid state relays that measure fundamental quantities may act erratic in presence of harmonics in the system. Harmonics is a usual feature in a capacitor compensated network and may not influence a microprocessor based relay which measures r.m.s. quantities (see also Table 13.17).

23.17.1 Microcontroller and microprocessor based relays

Microcontrollers are the latest technology in the field of p.f. correction. They are intelligent electronic devices (IEDs) and can be used for remote supervision and control (see Section 13.8). Switching can be programmed through any of the switching sequences described above. Correction now is much faster, as noted already.

The relay can also be programmed to identify a discharged capacitor of the required capacity for the next switching, in which case it would require no sequential operation. By calculating the p.f. level of the system the relay can switch ON/OFF the necessary capacitor units from among the eligible units available for the next switching. The switching is so programmed that all the

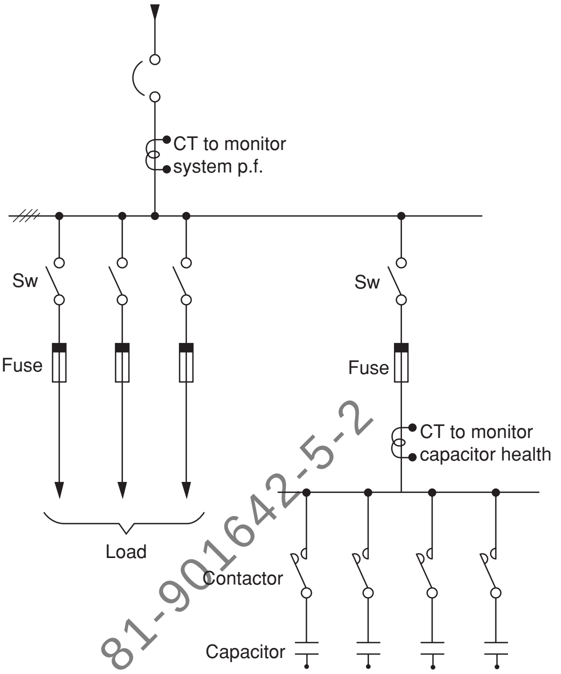


Figure 23.39 Location of monitoring CTs for p.f. correction relays

units of the same rating have almost the same operating hours. The normal operation of a microcontroller-based relay can be programmed along the following lines:

- As soon as it is switched on, it shifts to a 'learn mode'.
- In 'learn mode', it measures the kVAr value of each capacitor unit in terms of C in μF by switching them one by one through the CTs provided in the incoming of the capacitor circuit. The CTs are provided so as to measure the current of the capacitor circuit alone and not of other loads (Figure 23.39).

Note

To avoid erratic functioning of the relay ensure that the CT is connected in the phase that is not connected to the voltage terminal of the relay.

- It stores all these data in its memory.
- After every correction the relay again carries out the measurements on the capacitor units (periodically, say, in 24 hours in supervisory mode), to monitor their health and to detect for any deterioration. When the capacitance of a unit falls below the acceptable level it can emit an alarm or a blinker.
- Similarly it can be programmed to measure the load unbalance if any, by measuring the kVAr in each phase and provide an appropriate signal.*
- At the start of the correction cycle the relay calculates the required kVAr, examines the available capacitor values stored in its memory, takes a decision to switch

* These are special features that can be built into the relay. But each may involve an element of cost and the relay manufacturers may therefore provide only the essential features as standard and the remaining ones on request.

ON or OFF the appropriate capacitors and switches them in rapid succession to reach the target p.f. in the least possible time. Now it uses the CTs provided in the main incoming circuit (Figure 23.39).

- It can identify the next ideal unit for switching.
- To achieve the desired level of p.f. it switches on the capacitor unit which is nearest to the required rating and available for the next switching or switches off a few units in a similar way.
- Each capacitor circuit has a software timer which reswitches the unit only when it has timed out.
- It is not necessary to arrange capacitors in any particular order, nor of particular ratings for the different stages. But, as mentioned earlier, when desired it can also be programmed for any switching scheme noted above.
- The units need not be very small or very large.
- The relay can be programmed to store the operating history of the cumulative service hours for each unit to obtain uniformity in ageing of each unit.
- The relay can also be programmed to provide a counter for the number of switching operations each capacitor has already performed on daily, monthly or yearly basis.*
- Since the relay is connected in the same way as a meter is, it can read, calculate, and display all the desired operating parameters such as, *V, I, f,* p.f., kVAr, kW, and kVA as well as kWh, kVArh and maximum demand.*
- The relay can be connected to a computer and transmit all such data to a remote station for further monitoring and control.

SECTION II

23.18 Electromagnetic compatibility (EMC) and electromagnetic interferences (EMI)

EMC/EMI is a vast subject. We have attempted to provide a brief reference of it so as to enable a reader, user or a manufacturer of electrical and electronic equipment and devices to comprehend the implications of EM interferences, their adverse influence on the performance of sensitive electrical and electronic equipment and devices operating in such environments and tackling the same at source as far as possible. We have suggested possible safeguards and certain disciplines for the user and the manufacturer to follow, to save the environment from EMI and protect the sensitive equipment and devices from the influence of the same. Since electronic circuits are affected the most, our present thrust is on electronic equipment and devices.

One may recall that until around 1970 electronics was still in its infancy and was rapidly picking up in power system applications such as static controls and drives. The power networks also were not so large and complex in those days. Consequently, the EM interferences too were not severe and the electronic equipment and devices were not much influenced by EM interferences, electrostatic discharges (ESDs), or radio frequencies present in the environment. (For ease of reference all these disturbances are usually referred to as EM interferences). With the large and ever rising power generation and distribution networks and adaptation of electronics in all walks of life, communication, computation, automation and miniaturization, industries and large to very large power systems, the EM interferences and their adverse influences on electronic equipment and devices and communication networks have magnified to an intolerable level. EMI therefore is the frequency spectrum pollution that impairs the performance of electrical and electronic equipment and devices by not allowing them perform their intended functions.

There are several directives from the governments of various countries for the general awareness to the manufacturers and the users of the implications of EM interferences generated by electrical and electronic equipment and devices and also those equipment and devices that are susceptible to such interferences and to practise means to mitigate these effects.

Some of these devices may be for medical health care and prove fatal if their function is corrupted or behaviour is erratic during course of their operation under such an environment. There are cautions stated by the manufacturers of such equipment and devices to the users to protect these equipment and devices from EM interferences. Some such equipment and devices can be for diagnostic and monitoring of body functions. Similarly, distortion of voice or vital data meant for monitoring, control and protection of a power network may also throw the whole network into a disarray or out of synchronism if the crucial meters and relays or other IEDs (intelligent electronic devices) operating on the system function erratically and relay out erroneous signals. The directives however, also suggest the means to mitigate these interferences,

EMC

It is a term used to describe the interaction of electrical equipment and devices through their EM environment with the electronic equipment and devices susceptible to such environments and are supposed to operate under the influence of the same. It deals with the severity of emission and immunity of electronic equipment and devices from the influence of the same. A good EMC design will minimize, both generation of EM disturbances and susceptibility of electronic equipment and devices from the influence of the same, to perform their intended functions without distortions. It basically aims at improving the performance of electronic circuits by their lesser noise nuisance and other disturbances in turn to improving the power system and also the quality of life. The aim of EM compatibility is therefore to ensure the safety and integrity of all electronic equipment and devices operating in presence

* These are special features that can be built into the relay. But each may involve an element of cost and the relay manufacturers may therefore provide only the essential features as standard and the remaining ones on request.

of EM interferences. EMC now forms a fundamental requirement to be complied with at the design stage itself for all electrical and electronic equipment and devices.

There are three essential elements of EMC,

– **Sources of EMI** – equipment and devices that emit EMI: All electrical and electronic equipment and devices generate emissions and are also susceptible to some extent to EM phenomena. Electronic equipment and devices being the most susceptible of them all.
– **Receptor (victim)** – equipment and devices that may be influenced by such interferences and not function reliably.
– **Path** – between the above two, through which the source interferes with the receptor. There may be multiple coupling paths due to radio waves, EM fields and electrostatic discharges (ESDs). And then there may be more than one source in the vicinity generating such interferences. Such that sometimes, controlling of one may even enhance the other. The path can be through,
  - Conduction – through the current flowing in the power lines. Harmonics and surges travel through power lines only
  - Induction – through inductive coupling (magnetic field) (Section 23.5.2(F))
  - Capacitive coupling – through electrostatic discharges (ESDs) because of high frequencies and voltages (Section 23.5.2(F))
  - Electrostatic discharges (ESDs) of charged air
  - Radiated (radio frequency (RF) fields) – These fields sometimes are very strong and transmit interferences like an antenna.

An environment may be polluted with the following types of electrical, electronic and electromagnetic (EM) interferences.

Causes

1. Sources causing EM interferences through conduction, induction and radiation

- Motors and generators
- Transformers
- Inductive reactors
- Transmission and HV distribution lines (Section 23.5.2)
- High current systems – PCCs, MCCs and Bus systems

The above-mentioned electromagnetic equipment and high powered power systems induce their own inductive fields. Under normal operating conditions they may not be potential EMI sources to generate RF fields. But susceptible electronic circuits may be influenced by EM interferences through conduction and induction if they are connected on the same power system or fall within their inductive interference environment (Section 23.5.2F). There is no significant radiation, electrostatic discharges (ESDs) or surges except system harmonics. They however, become potentially rather worst sources of EM disturbances during a line disturbance, such as during a switching sequence or a ground fault. In both cases they can generate severe surges at high frequencies resulting in arcing grounds at the line insulators or at the grounded phase conductor and cause RF interferences (Section 20.2). These surges themselves travel in the system through conduction and cause transference of surges through inductive and capacitive couplings (Section 18.5.2). Capacitive coupling causing electrostatic discharges (ESDs), while high switching or fault currents inducing high electromagnetic space fields. All these are severe EM inductive and conductive interferences.

2. Electrostatic discharges (ESDs)

It is usually a high frequency or high voltage fast transient phenomenon (responsible for conductive burst immunity test (Table 14.6a)) and can be through

(i) System disturbances such as,
  - Lightning strokes (Section 17.5)
  - Indirect lightning surges – lightning on nearby objects causing EM fields may induce high voltages on equipment and devices installed in close vicinity and cause ESDs through them also
  - Switching surges as noted above
  - Transference of surges as noted above
  - Corona discharges (for brief reference see Section 23.5.2F), flash-overs and fault conditions

(ii) ESD can also occur due to discharge of charged air through contact or separation of two non-conducting bodies. When a charged body is brought in proximity with another body of lower potential, energy is released in the form of electrostatic discharges. Generation of electrostatic charge is especially favoured by the combination of synthetic fabrics and dry atmosphere. These discharges too can be quite severe and seriously impair or damage the sensitive electronic circuits. Adequate protection is therefore essential in all sensitive electronic circuits to withstand such discharges also. ESD immunity test is conducted on sensitive electronic circuits to check their compatibility in such environments (Table 14.6a). Below we discuss the causes of such discharges.

ESD is the abrupt release of static charge accumulated by a body or an object. The body or object can accumulate static charge as a result of various phenomena. ESD coupling with the equipment can happen directly or indirectly through radiation. Direct coupling will include any user accessible entry points such as input/output ports, switches, knobs and equipment housings, while the radiated coupling will result from a discharge between two bodies that are external to the system. A common situation can be that a person walking over a carpet and with each step losing electrons from his body to the fabric. Friction between the person's clothing and the chair can also produce an exchange of charge. The person's body may be charged either directly or by electrostatic induction. In the latter case a conducting carpet will not give protection unless the person is adequately grounded to it. Depending on circumstances the discharge voltage can reach up to 15 kV. Such discharges can permanently damage or impair the functions of sensitive electronic circuits.

3. Harmonics

They are generated by non-linear loads as discussed in Section 23.5.2. Power electronic circuits such as thyristor operated converters, PWM based inverters and other electronic switching circuits generating the most.

Effects

- Communication networks – the EM waves superpose on the radio (RF) waves and distort their quality of speech (non-clarity of voice) and transfer of vital data and documents even failure of the network. Superposition of various interferences magnifies the noise level which makes EMC all the more meaningful and imperative for all electronic equipment and devices that are influenced by such interferences to comply with EMC/EMI norms.
- In an aircraft for instance, it may distort its communication and navigation system. A reason why the use of mobile phone is presently prohibited in a flying aircraft. After strict compliance with EMC/EMI norms it is possible that such restrictions are lifted in course of time.
- Similarly, they influence TV video signals.
- Metering instruments – Induction disc type instruments measure only fundamental quantities and function erratically under the influence of such interferences.
- Relays – The new generation numerical relays (since about 1978) measure r.m.s. values and are not influenced by such pollutants except at very high harmonic interferences (Table 13.17). While the static relays and so also the electromagnetic relays would behave erratic under the influence of harmonic distortions.
- Ballasts of fluorescent or mercury lights usually employ in-built capacitors that can cause resonance with any of the harmonic frequencies and magnify the harmonics.

4. Radiated radio frequency (RF) fields

They may be generated by

(a) Electronic equipment and devices: They are the main sources of radio frequency (RF) interferences like,

- Radio and TV transmitters, receivers and radars
- Hand-held communication devices like walkie-talkies used by maintenance and security personnel
- Mobile phones, pagers
- PCs
- Tape recorders
- Household appliances
- All kinds of power electronic circuits such as converter and inverter circuits (Section 23.6b) having frequent switching operations, causing switching surges, harmonics and radio frequency emissions. Circuit inductances and capacitances magnifying the same.

(b) Electrical equipment

- Slip-ring, synchronous and d.c. motors and rotating armature generators have continuous arcing due to brushes and so also
- Arc furnaces due to movement of electrodes

All these equipment generate radio frequencies. These radiations are classified in two groups,

- Conducted RFI – They are noticed in the low frequency range say 15 kHz–30 MHz. They propagate through conduction over signal and power cables.
- Radiated RFI – 30 MHz–10 GHz. They propagate through free space.

5. **Microprocessors and computing devices**

They cause conductive interferences.

Note

One may notice that each electrical and electronic equipment and device has the potential to generate conductive, inductive and radiated interferences in different proportions under different operating conditions. The most common source being the electrical power conductor of the electronic device itself that may act as an antenna. Similarly, conducted EM interferences can also become radiated interferences during a line to ground disturbance as noted for sources in item 1.

Requirements of EMC/EMI

The purpose of EMC/EMI exercise is to limit the interferences at source only as far as possible to improve the quality of power and EMIs adverse effects on all susceptible equipment and devices operating under the influence of such environments. Accordingly all electrical and electronic equipment and devices must ensure.

Limited Emission: That the EM disturbances generated by the electrical or electronic equipment and devices do not exceed a level that may adversely affect the susceptible equipment and devices (mostly electronic) and radio and telecommunication systems operating in the vicinity. Such as by providing them with L-C filter circuits (Figure 17.25).

Immunity: That the susceptible equipment and devices possess adequate level of intrinsic immunity from EM disturbances and harmonic effects to enable them operate as intended under such environments. Such as by providing them with adequate screening and noise immunity (Section 13.3.6) and isolated ground system (Section 6.13.3).

EMI

Electromagnetic interferences are classified according to the kind of emissions. EM induced fields interfere with the operation of another device, equipment or system falling under its interference environment, while the radio frequency emissions travel in free space at the speed of light and interfere with other RF waves.

Remedy

According to EMC requirements all EM emissions must necessarily be suppressed at the source itself, similar to p.f. control by the individual consumer. This can be achieved,

- By controlling the emissions (EMI) to the desired level from all equipment and devices that emit them, such as by using shunt filters-L-C circuits (Section 23.5.2)
- By phase multiplication in case of converter units –

by using 12 pulse, 18 pulse or higher converter circuits using dedicated transformers with two or three secondaries (Section 6.13.1)

- Similarly by minimizing the effects of interferences on equipment and devices susceptible to such interferences by making them EM compatible to the desired level (Section 6.13). In case of electronic circuits it can be achieved by using Faraday Cages and adapting to isolated grounding system as discussed in Section 6.13.3.
- Harmonics are suppressed to their permissible levels by the manufacturers of electronic equipment and devices, as discussed in Section 6.13.

Faraday Cage

Faraday Cage or electrostatic shield named after its inventor Michael Faraday (1791–1867) provides an electrical shielding to the electronic equipment and devices operating inside the enclosure from the EM interferences existing in the vicinity. Similarly, it also helps provide electrical shielding to the outside environment from the EM interferences generated inside. The cage is provided a grounded shield to have all parts of the cage at ground potential (Section 6.13.3). It is a highly specialized subject and needs careful consideration of the kind of interference, its intensity and equipment or device to be shielded. Consideration is also necessary for future magnification of these interferences as a consequence of more equipment and devices generating such interferences getting added in the vicinity with passage of time and magnifying the interferences.

Faraday Cage is a well grounded metal enclosure and depending upon application can be of aluminium or copper to keep losses and consequent heat generated low or of galvanized steel. Steel enclosure is particularly used for RF communication signals. The cage can be perforated or solid depending upon severity of EM interferences and equipment or device to be shielded. The enclosure, perforated or solid acts like a shield to the enclosed devices/apparatus from low energy, high frequency EM disturbances in the vicinity. A carefully designed and meticulously manufactured enclosure (cage) can effectively separate electronic data and signals from power system and minimize EM distortions. Cooling provision may be necessary to dissipate inside heat, such as for an inverter unit generating large heat. Perforations are made small to prevent the escape of EM radiations. The cage is isolated from the inverter unit. The theory is similar to isolated phase bus enclosure (Section 31.1) to absorb the induced field and the proximity effect. An ideal cage is a completely sealed enclosure without openings. But it is a costly affair as for perfect sealing it may call for a welded enclosure. Moreover, openings are necessary for cables and too much welding may be cumbersome. These openings are however, kept small and to the bare minimum. To contain the noise at source the EM and RF emitting devices like CPUs, RTUs or microprocessors can be placed inside a Faraday Cage.

Typical application of Faraday Cage is in RF communications to cage and shield transmitters, receivers and radars. For these applications they are used extensively. The radio frequency (RF) can be of the order of a few MHz in case of transmitters and receivers and in GHz in case of radars. To shield such high frequency signals only magnetic material such as galvanized steel is recommended that can arrest most of EM interferences. Non-magnetic cages will provide only partial shielding and may not be very effective. In case of radars' very high RF waves they may not be effective at all.

Test facilities

Special test facilities are created by the manufacturers, even independent labs are established and test methods created by a country to address these requirements to ensure compliance of electronic equipment and devices with EMC/EMI requirements. Different test methods and procedures to conduct the tests are mentioned in various EMC Standards established for such purposes. Most national and international Standards cover for EMC/EMI requirements and prescribe test methods with permissible test results in terms of induced e.m.fs. (dB(μV/m)) as caused by EMI. For brief test description for switchgear and controlgear assemblies see Section 14.3.13.

Similar EM environmental conditions are simulated in a test laboratory and those EMC tests are performed on an equipment or device that it would usually be subject to in actual operation. There is no need to conduct other tests that the device may not be subject to in normal course, as a logical approach to economize on such tests without sacrificing the compatibility of the equipment or device from the EM pollutants. Immunity tests from radio frequency interferences (RFIs) and EM fields would however, usually be essential on all electronic equipment and devices.

EMC/EMI Standards

A few EMC/EMI Standards are mentioned under Relevant Standards. It is noticed that more stringent the local (national) rules are, more meticulous and religious approach of a manufacturer and user is to comply with the same. For example European Standards are regarded to be more stringent (Table 23.2). Their EMC regulations (SI-1992/2372) and directives 89/336/EEC (for all European economic community countries) stipulate that electrical and electronic products manufactured and sold should not cause excessive EMI nor be unduly affected by EMI. Usually, a country would specify permissible emission Standards relating to different applications such as for defence, communications, railways, civil aviation and medical health services etc. Like US has an EMC Standard MIL-STD-461 for its military services. Similarly, Standards exist for personal gadgets like computer and computer driven devices, static and numerical relays, electronic controls and static drives.

Since harmonic voltage V_h ($I_h \cdot Z$) is a consequence of harmonic current I_h and circuit impedance Z, therefore the emphasis of these Standards is on limiting I_h rather than voltage. All these Standards and a few mentioned at the end of the chapter specify harmonic limits in terms of current for each harmonic disorder and the manufacturer is required to suppress individual harmonic current as well as total harmonic distortions (THD) of the electronic circuit to their permissible levels within the equipment itself. The objective is to ensure that the susceptible equipment and devices operating in the vicinity of such harmonics, function as intended, without getting corrupted by equipment and devices emitting EMI. Nor they emit unwarranted interferences by themselves that affect performance of other equipment and devices operating in the vicinity.

Relevant Standards

IEC	*Title*	*IS*	*BS*	
60051-1 to 9	Direct acting indicating analogue electrical measuring instruments and their accessories. Definitions and general requirements.	1248-1 to 9	BS 89-1 to 9	–
60143-1/2004	Series capacitors for power systems. General performance, testing and rating. Safety requirements. Guide for installation.	9835-1/2001	BS EN 60143-1/1993	–
60831-1/2002	Shunt power capacitors of the self healing type for a.c. systems having rated voltage up to and including 1000 V.	13340/1998	BS EN 60831-1/1998	–
60871-1/1998	Shunt capacitors for a.c. power system having rated voltages above 1000 V.	13925-1/1998	BS EN 60871-1/1998	–
60931-1/2002	Shunt power capacitors of non self-healing types up to and including 1000 V. General performance, testing and rating. Safety requirements. Guide for installation and operation.	13585-1/1999	BS EN 60931-1/1998	–
60947-3/2001	Specification for LV switchgear and controlgear. Switches, disconnectors, switch-disconnectors and fuse-combination units.	13947-3/1998	BS EN 60947-3/2003	–
60947-4-1/2001	Low voltage switchgear and controlgear. Electromechanical contactors and motor starters including rheostatic rotor starters.	13947-4-1/1998	BS EN 60947-4-1/2001	–
61000-4-1/2000	Electromagnetic compatibility (EMC). Testing and measurement techniques – overview of IEC 61000-4 series.	–	–	–
61000-4-2	Electrostatic discharge immunity test.	–	–	–
61850 (1 to 10)	Communication networks and systems in substations.	–	–	–
–	Methods of measurement of electromagnetic interference from high voltage transmission systems.	6873-6/1983	–	–
–	Radio interference characteristics of overhead power lines and HV equipment. Methods of measurement and procedure for determining limits.	–	BS 5049-2/1994	–

Relevant US Standards ANSI/NEMA and IEEE

ANSI/IEEE-519/1993	Guide for harmonic control and reactive compensation of static power converters.
ANSI/IEEE-643/1992	Guide for power line carrier application.
ANSI/IEEE-776/1998	Recommended practice for inductive coordination of electrical supply and communication lines.
ANSI/IEEE-1036/1993	Guide for application of shunt power capacitors.
ANSI/IEEE-1137/1998	Guide for the implementation of inductive coordination mitigation techniques and application.
ANSI/IEEE-C37.012/1989	Application guide for capacitive current switching of a.c. HV circuit breakers rated on a symmetrical current basis.
ANSI/IEEE-C37.26/2004	Guide for methods of power factor measurement for LV inductive test circuits.
ANSI-C63.4/2003	Method of measurement of radio and electronic noise emissions for LV electrical equipment.
ANSI-C93.1/1990	Power line carrier coupling capacitors.
NEMA*-107/1998	Method of measurement of Radio Influence Voltage (RIV) of HV apparatus.
NEMA/ICS-2/2000	Industrial control and systems, controllers, contactors and overload relays, rated not more than 2000 V a.c. or 750 V d.c.
DIN 6 1800-3/2002	Cage Induction motors when fed from converters. Application guide.
G 5/4-2001	Managing harmonics – A guide to E A Engineering recommendation.

* NEMA – National Environmental Management Act (South Africa)

Notes

1 In the table of relevant Standards while the latest editions of the Standards are provided, it is possible that revised editions have become available or some of them are even withdrawn. With the advances in technology and/or its application, the upgrading of Standards is a continuous process by different Standards organizations. It is therefore advisable that for more authentic references, one may consult the relevant organizations for the latest version of a Standard.
2 Some of the BS or IS Standards mentioned against IEC may not be identical.
3 The year noted against each Standard may also refer to the year it was last reaffirmed and not necessarily the year of publication.

List of formulae used

Influence of harmonics on the performance of a capacitor unit

(i) By the harmonics voltage

$$V_h = \sqrt{(V_1^2 + V_{h3}^2 + V_{h5}^2 + V_{h7}^2 + \ldots V_{hn}^2)} \tag{23.1}$$

V_h = effective harmonic voltage
V_1 = system voltage
V_{h3}, V_{h5}, V_{h7} and $V_{hn\ etc.}$ = magnitudes of the harmonic voltage components in terms of fundamental voltage, at different harmonic orders

(ii) By the harmonic currents

$$I_{ch} = \sqrt{(I_c^2 + 9I_{ch3}^2 + 25I_{ch5}^2 + 49I_{ch7}^2 + \ldots n^2\ I_{chn}^2)} \tag{23.2}$$

I_{ch} = effective harmonic current
I_c = rated current of the capacitor
I_{ch3}, I_{ch5}, I_{ch7} and I_{chn} etc. = magnitude of the harmonic current components at different harmonic orders

(iii) Harmonic output of a capacitor unit

Rating of a shunt capacitor

$$\text{kVAr} = \frac{\sqrt{3} \cdot V^2}{1000 \cdot X_c} \tag{23.3}$$

$$\text{or kVAr} = \frac{\sqrt{3} \cdot V^2 \cdot 2\pi f \cdot c}{1000} \tag{23.4}$$

Effective harmonic output

$$\text{kVAr}_h \propto \sqrt{V_1^2 + 3 \cdot V_{h3}^2 + 5 \cdot V_{h5}^2 + 7 \cdot V_{h7}^2 + \ldots n \cdot V_{hn}^2)} \tag{23.5}$$

Influence of harmonics on telephone lines

(1) Electrostatic induction

Blocking circuit

$$f_h = \frac{1}{2\pi \cdot \sqrt{LC}} \tag{23.6}$$

f_h = notch frequency

$$V_c = \frac{C_c}{C_c + C_g} \cdot \frac{V_r}{\sqrt{3}} \tag{23.7}$$

V_c = induced electrostatic voltage in the communication lines
C_c = coupling capacitance between the power and the communication lines
C_g = ground circuit capacitance of the communication lines

Filter circuits: use of reactor enhances voltage across the capacitor banks

Rise in voltage,

$$\frac{V_C}{V_{ph}} = \frac{X_C}{X_C - X_L} \tag{23.8}$$

V_{ph} = system voltage
V_C = voltage across the capacitor banks
X_C = capacitive reactance
X_L = inductive reactance

Single-capacitor switching

(i) Inrush current

$$I_m = I_s\left(1 + \sqrt{\frac{I_{sc}}{I_s}}\right) \tag{23.9}$$

I_m = maximum inrush or making current, while switching an uncharged capacitor unit.
I_s = maximum steady-state current (capacitor peak full load current $(\sqrt{2}I_c)$)
I_{sc} = fault level of the system

$$I_m = I_s\left(1 + \sqrt{\frac{X_{C1}}{X_{L1}}}\right) \tag{23.10}$$

L_1 and C_1 are the switching circuit parameters

(ii) Switching frequency

$$f_s = f\sqrt{\frac{\text{(Short circuit kVA)}}{\text{(Capacitor kVAr)}}} = f \cdot \sqrt{\frac{X_C}{X_L}} \tag{23.11}$$

f_s = switching or transient frequency
f = power frequency
X_C = power frequency capacitive reactance of the circuit
X_L = power frequency inductive reactance of the circuit

Parallel switching of capacitor banks

(i) Inrush current

$$Z_s = \sqrt{\frac{L_2(C_1 + C_2)}{C_1 \cdot C_2}} \tag{23.12}$$

Z_s = surge impedance
L_2 = circuit inductance between the capacitors in henry
C_1, C_2 = capacitances of two capacitors

$$I_m = V_p\sqrt{\frac{C_1 \cdot C_2}{L_2(C_1 + C_2)}} \tag{23.13}$$

I_m = peak inrush current in parallel switching
V_p = line to neutral peak voltage

(ii) Switching frequency

$$f_s = \frac{1}{2\pi}\sqrt{\frac{(C_{1eq.} + C_x)}{L_{2eq} \cdot C_{1eq} \cdot C_x}} \quad (23.14)$$

L_{eq} = equivalent inductance of the capacitors already switched
$L_{2eq} = L_{eq} + L_x$
C_{1eq} = equivalent capacitance of the capacitors already switched
C_x = capacitance of the capacitor being switched

Limiting inrush currents

$$I'_m = V_p \sqrt{\frac{C_1 \cdot C_2}{(L_2 + L)(C_1 + C_2)}} \quad (23.15)$$

I'_m = improved inrush current
L = series inductance being introduced
V_p = line to neutral peak voltage

Designing an inductor coil to limit the inrush currents

$$L = \frac{4 \cdot N^2}{10^9} \cdot r\left(\log_e \frac{8 \cdot r}{0.7788 \cdot r_1} - 2\right) \text{henry} \quad (23.16)$$

L = self-induced inductance of the coil in henry
N = number of turns of the coil
r = mean radius of the coil in cm
r_1 = radius of the cross-section of the coil in cm

Determining the kVAr rating for improving p.f. from cos ϕ_1 to cos ϕ_2

$$\text{kVAr}_1 - \text{kVAr}_2 = \text{kW}(\tan\phi_1 - \tan\phi_2) = \text{kW} \cdot \text{K} \quad (23.17)$$

Further Reading

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