Protection, maintenance and testing of capacitor units

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26.1 Protection and safety requirements

As discussed in the previous chapters, a capacitor may have to encounter many unfavourable service conditions when in operation. Most of them may lead to its direct over-loading. Summing up all such conditions, a capacitor would need protection against the following:

26.1.1 Protection of shunt capacitors

1 Over-voltage (Section 23.5.1)

Capacitors become over-loaded with over-voltages and long duration of over-voltages may reduce their life. The permissible over-voltages and their safe duration as in IEC 60831-1 for LV and IEC 60871-1 for HV capacitor units are indicated in Table 26.1. An over-voltage factor of up to 10% can be considered on account of this. In installations having wide voltage fluctuations and when series capacitors are used on such systems for improving their regulation, the capacitors must be protected against abnormal over-voltages. Over-voltage protection may be provided through an over-voltage relay with inverse time characteristics. For closer monitoring, it is better to have the relay in small steps of 1%.

2 Number of switching operations

In LV capacitors controlled through automatic p.f. correction relay it is recommended that the capacitors are not switched more than 1000 times during a year or, say, three or four switchings per day. More switchings will mean more frequent over-voltages and inrush currents which may reduce the life of a capacitor. In HV capacitor banks, however, such a situation may not be relevant as HV capacitors may be switched only once or twice a day.

3 Over-current

Due to harmonic effects the capacitors are designed for a continuous over-loading of up to 30% (Section 23.5.2(A)) and are accordingly rated for $1.3I_n$. Since the permissible capacitive tolerance may enhance the capacitance rating of a capacitor by 1.05–1.15* times its designed rating (Section 26.3.1(1)) the maximum permissible current may be considered up to $1.3 \times 1.15 = 1.5$ times its rated current. A capacitor generally is a fixed current device, its rating is greatly influenced by the circuit parameters, particularly the presence of harmonics and fluctuations in system voltage. Since a capacitor unit is designed for 150% of its nominal rating an over-load protection cannot be over-emphasized under normal operating conditions, particularly for an LV installation. For large HV installations, however, experiencing wide voltage fluctuations (which may be rare) and the presence of a large degree of harmonics, it may be mandatory to provide over-current protection, even if series reactors are used to suppress the harmonic currents. An IDMT (inverse definite minimum time) relay may be provided with over-load and short-circuit protections and a time delay to by-pass the momentary transient and switching inrush currents. Protection against a short-circuit is essential for both LV and HV capacitor units. On LV systems it may be provided through the HRC fuses or the in-built short-circuit releases of a circuit breaker when a circuit breaker is used to switch the capacitor banks. On HV systems also short-circuit protection is provided through HRC fuses or short-circuit releases of the breaker.

4 Switching currents

The switching currents must be limited to as low a value as possible. However, in general, capacitors are designed for switching currents up to $100I_n$ (r.m.s.) for milliseconds. If necessary, a series resistance or inductance can be introduced into the switching circuit to limit them to a desired level (Section 23.11).

5 Short-circuit and ground fault currents

These will depend upon the grounding system adopted. The level of fault current would generally be as follows:

- For grounded star capacitor units: In this case when a capacitor unit develops a short-circuit it will establish a line-to-ground fault with a high fault current. Use of current limiting HRC fuses will be easy because, for heavy fault currents, the fuses can be selected of a slightly higher rating to avoid an interruption due to switching surges and transient inrush currents without affecting operation of the fuses on an actual fault. However, a fuse free system (Section 12.11) is advisable by using an MCCB.

- For ungrounded star capacitor units: In this case when it causes a line to neutral fault the impedance of the other two phases will limit the fault current to almost three times the rated current. It is still easy to choose HRC fuses so that they would remain inoperative up to 150% of the rated current

Table 26.1 Likely over-voltages in service and their permissible durations

<table>
<thead>
<tr>
<th>Over-voltage factor</th>
<th>For capacitor units up to 1000 V</th>
<th>For capacitor units above 1000 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>1.10</td>
<td>8 h per 24 h</td>
<td>12 h per 24 h</td>
</tr>
<tr>
<td>1.15</td>
<td>30 min per 24 h</td>
<td></td>
</tr>
<tr>
<td>1.20a</td>
<td>5 min</td>
<td></td>
</tr>
<tr>
<td>1.30a</td>
<td>1 min</td>
<td></td>
</tr>
</tbody>
</table>

*a Not to occur more than 200 times during the total life span of the capacitor unit.*
For-delta connected capacitor units: In this case, it will establish a line-to-line fault with a heavy fault current. Protection by HRC fuses or an MCCB would be more appropriate than for a grounded star.

For series-parallel connected units: This is applicable in HV capacitor banks comprising a number of small units arranged in series and parallel combinations. The fault current in such cases for an isolated neutral can be expressed by

\[ I_t = \frac{3N_1 \cdot N_2}{3N_1 - 2} \cdot I_c \]  

(from Equation (25.3))

Now a breaker with an IDMT relay would provide the most appropriate protective scheme.

To summarize, HRC fuses or fuse-free MCCBs for LV and a breaker and IDMT relay arranged for 2 O/C and 1 G/F, with a short-circuit unit for HV capacitor banks, will provide a reliable protective scheme for short-circuit and ground fault protections.

6 Shell protection

This is applicable to both LV and HV capacitors. But it is more important in HV banks, which are relatively much larger and are built of a number of single units connected in series-parallel. These may encounter much higher fault currents in the event of a severe internal fault, even in one unit and are thus rendered more vulnerable to such ruptures. This phenomenon is more pertinent to units that are externally protected where the intensity of fault may be more severe, than internally protected units.

Protection with internal fuses is easier, as fuses are provided for each element which can contain the severity of the fault well within the safe zone in all probability. Some users even recommend capacitor units 250/300 kVAR and above with internal fuses only. Figure 26.1 shows a typical operating band of the internal fuses for an internally protected unit. It demonstrates a sufficient margin between the operation of the fuses and the shell’s safe zone. The fuse characteristics are almost the same for all manufacturers.

Since such explosions are dangerous and may cause a fire hazard through the dielectric liquid which may be inflammable, it is imperative that such faults are cleared before they may result in bursting of the shell. They will require short-circuit protection. Leading manufacturers producing units suitable for external protection provide a pressure-sensitive disconnector which operates and releases the pressure during a fault when the inside pressure builds up to a preset level. This may be in the form of expandable bellows, which expand on such excessive pressures inside and snap open the power connections. Safety through expansion bellows is usually a feature in LV, MPP capacitors. In HV, this technology is not used. NEMA has also provided probability curves for the case rupture in the form of \( I^2 \) versus \( t \). The curves are defined in Figure 26.1, which can be used to select the appropriate protection to isolate the unit on a fault before a possible rupture. The severity of fault is expressed in terms of the magnitude of explosion. The protection must be commensurate with the location and the criticality of the installation and is categorized in four zones, depending upon the severity of the fault:

1. Safe zone: There is only a slight swelling of the shell and no severe damage.
2. Zone I: There may be a slight rupture and fluid may leak. Safe for areas where the leakage will pose no hazard.
3. Zone II: There may be a violent rupture of the shell.
4. Hazardous zone: There may be a violent rupture with a blast, which may damage the adjacent units.

Note

The practice adopted by manufacturers, for all voltages and kVAR ratings in the making of the shell, particularly for its size, material and thickness, assume almost the same \( I^2 \) versus \( t \) characteristics, as provided by the NEMA curves (Figure 26.1).

For a more accurate selection of a protective scheme it is essential that the manufacturers provide the probability curves of their shell design for each voltage and rating.

Generally, the fault must be cleared well within Zone I and for which the protective scheme must be chosen. As discussed in Section 25.4.2, protection of capacitor units with external fuses is not easy. It is not practical to contain a mild internal fault as isolation of the units is not possible on mild internal faults until the fault current rises to the level of the fuse’s operating range (Figure 26.2 illustrates this). By then enough time will have elapsed to cause severe damage to the unit.

The only solution is to choose fuses of a lower rating as far as possible, with fast operating characteristics (low \( F_t \)) or provide IDMT protection. But the risk of a shell rupture is not eliminated. An unbalance protection is a
better choice in such cases, which may isolate the faulty unit much faster than the fuses. When it is so, the units remain intact. At this stage visual checks can be made to find all such units that may be excessively hot or have bulged out. The capacitance of the units can also be measured to identify the faulty unit(s) or the extent of damage to individual units and take corrective steps before reswitching the units. Example 26.1 illustrates a simple procedure to select external HRC fuses. The fuses are provided separately for each unit.

**Example 26.1**
Consider the same units as those in Example 25.2 where

\[ V_{ph} \text{ of each unit} = 11 \text{ kV} \]

- \[ kVAR = 75 \]
- \[ N_1 = 4 \]
- \[ N_2 = 8 \]
- \[ I_C = 6.82 \text{ A} \]
- \[ I_f = 65.47 \text{ A} \]

Minimum rating of fuses = 200% of \( I_C \)

Select from the manufacturer’s catalogue 16 A fuses for each unit, according to the characteristics in Figure 26.3 reproduced in Figure 26.2. The fuse characteristics fall well within the safe zone and provide adequate protection to the units. If series reactors are provided to control the inrush current, a fuse corresponding to 150% of \( I_C \), i.e. of 10 A, would be better to protect the unit more closely. We can see from Figure 26.2 that in an internally protected unit the characteristics of the internal fuses will fall well below that of an external fuse and provide a more exacting protection on a mild fault.

### 7 Voltage transients

These may be caused by internal switchings or external lightning strokes. HV capacitor units, particularly, may be protected through surge arresters against such voltage transients (Chapter 18). The voltage rating of the surge arrester may be chosen on the following basis:

- For ungrounded systems = \( V_r \)
- For grounded systems = 0.8 \( V_r \)

See also Table 18.2.

### 8 Voltage unbalance

An unbalance in the supply system causes an over-voltage across the capacitor units in phases that have a higher voltage. A partial or total failure of a capacitor unit in a
large capacitor bank will also cause an unbalance and an over-voltage across the healthy units connected in parallel. Such a situation is not desirable, and unless detected promptly, may result in a cascade failure of more units. It can be detected by the following methods for an alarm, indication or trip of the entire bank:

(i) Voltage unbalance method
This method is applicable to single-star or delta-connected capacitor banks. Unbalance can be detected through the use of an RVT (residual voltage transformer) (Section 15.4.3). See Figure 26.4. The theory of operation is that any unbalance, of the system or the capacitor bank, will shift the neutral and reflect as the residual voltage across the open delta and can be used for the protective scheme. The unbalance voltage across the open delta in the event of failure of a unit in any series group can be expressed by

\[ V_u = \frac{N \cdot V_{ph}}{3N_2 \cdot N_1 - 3N \cdot N_1 + 2N} \]  

(established by the capacitor manufacturers)

where

- \( V_u \) = unbalance voltage across the open delta. This is for grounded systems. For isolated systems it will be three times this (Section 15.4.3).
- \( V_{ph} = \frac{V_1}{\sqrt{3}} \)
- \( N \) = number of units failed
- \( N_1 \) = number of units in series per group per phase
- \( N_2 \) = number of units in parallel per group per phase.

A neutral displacement relay (NDR) with a suitable setting may be used across the open delta for unbalance protection.

Example 26.2
Referring to Example 25.2,

\[ V_{ph} = 44 \text{ kV} \]
\[ N_1 = 4 \]
\[ N_2 = 8 \]

Then the unbalance voltage for a grounded system, on a failure of any one unit (assuming the capacitor units to have external type fuses), according to Equation (26.1)

\[ V_u = \frac{1 \times 44 \times 1000}{3 \times 8 \times 4 - 3 \times 1 \times 4 + 2 \times 1} \]
\[ = \frac{44000}{86} \]
\[ = 511.6 \text{ V} \]

and for an ungrounded system

\[ V_u = 3 \times 511.6 = 1535 \text{ V} \]

If the ratio of VT is 44 kV/110 V, then the voltage across the open delta

\[ = \frac{1535 \times 110}{44000} \]
\[ = 3.84 \text{ V} \]

and suitable NDR may be selected for this voltage.

For more than one capacitor bank one RVT for each bank will be necessary for the correct discharge of each bank. (Figure 26.5). An RVT, if provided with an additional star-connected tertiary winding rated for 110 V line to line, can also check the discharge condition and its duration and if it meets the design requirements. This can even be monitored remotely through a relay and control panel.

Note
When an RVT is being used for the purpose of discharge also no protective fuses are recommended to ensure a positive discharge. On a trip, the RVT is programmed to be connected automatically to the capacitor units to discharge them.

(ii) Current unbalance method
This method is applicable to double-star-connected capacitor banks (Figure 26.6). In this method the neutrals of the two identical star-connected banks are interconnected and a protection Neutral CT (NCT) is inserted through it. In a balanced state, there will be no current through the neutral. On a partial or a total failure of a unit in either of the banks it will disturb the balance and cause a current through the inter-connected neutral. A ground fault relay will be most suitable for such a requirement. To avoid momentary transient tripings, a
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A time delay of a few seconds can be introduced into the trip circuit. Sensitivity and the setting of the relay will depend upon the size of the banks and the sensitivity of the system, i.e. whether an alarm or indicator will be sufficient initially while repairs are undertaken during off-peak periods, or whether a trip will be needed. The amount of unbalance current can be determined by the following formula:

\[
I_u = \frac{3N_2 \cdot N_1}{6N_2 \cdot N_1 - 6N_1 \cdot N_1 + 5N} \times I_c
\]

(26.2)

(established by the capacitor manufacturers)

where \( I_u \) = imbalance current through the inter-connected neutral, and

\( I_c \) = current per capacitor unit.

Note

Current-sensing protection is found to be more accurate than a voltage sensing. It is therefore recommended that the units are arranged in double star as far as possible.

(iii) Ampere meter method

To monitor the health of a capacitor unit it is advisable to provide an ammeter in each phase. When it is found, that there is an unbalance not caused by voltage unbalance then further investigations may be conducted to replace the defective unit(s) before a major fault occurs.

Example 26.3

Considering the earlier Example 25.2 with 14 400 kVAr banks, connected in double star where

\( N_1 = 4 \)

\( N_2 = 8 \)

Then the over-voltage developed in the event of a failure of

Figure 26.5 The use of RVTs with large capacitor banks

Figure 26.6 Detecting an unbalance in double-star identical capacitor banks through a current unbalance method
any one unit (assuming the capacitor units to have external type of fuses) as determined in the said example

\[ = 10.98\% \]

This over-voltage is higher than permissible. The fault condition must be removed before one full unit fails. Say, we permit only one half of a unit to fail for an alarm and maximum three quarters for a trip. Then over-voltage when one half of the unit has failed from Example 25.2

\[ = 5.2\% \]

and over-voltage when three quarters of the unit has failed

\[ \frac{6 \times \frac{1}{2} \times 4 - 5 \times \frac{1}{2}}{6 \times 8 \times 4 - 6 \times \frac{3}{4} \times 4 + 5 \times \frac{3}{4}} \times 100 = 8\% \]

which is well within the limits for a trip.

And \( I_a \) for an alarm from equation (26.2)

\[ = \frac{3 \times \frac{1}{2} \times 8}{6 \times 8 \times 4 - 6 \times \frac{1}{2} \times 4 + 5 \times \frac{1}{2}} \times 6.82 = 0.45 \text{ A} \]

and \( I_t \) for a trip

\[ = \frac{3 \times \frac{3}{2} \times 8}{6 \times 8 \times 4 - 6 \times \frac{3}{4} \times 4 + 5 \times \frac{3}{4}} \times 6.82 = 0.69 \text{ A} \]

One can use a 5/1 A CT and provide the desired setting in a 1A relay for alarm and trip.

9 Frequency variation and voltage variation

When capacitors are used to improve the p.f. of a varying frequency load, such as for an inductive heating or varying voltage loads for improving the regulation of a power system, they would be subjected to excessive over-loading due to frequency variation in the first case, since kVARr \( \propto f \) (Equation (23.4)), and voltage fluctuations in the latter. Capacitors performing such duties must therefore be protected, against over-loads by an IDMT over-load protection scheme.

10 No-volt protection

On supply failure capacitors must drop out and should not switch on automatically on resumption of the supply to avoid an over-voltage as a result of the trapped charge. Even sudden voltage dips may cause the charged capacitors discharge into the terminal equipment and damage them. On LV, to achieve the required protection, the capacitors may be switched through contactors which have a no-volt coil and drop out on failure of the supply. On HV an instantaneous under-voltage relay, with a low drop-off value (say, 30–60%) may be used with the interrupting device, which may be a breaker or a vacuum contactor. Reclosing may be through a lock-out relay with a time delay, for at least the safe discharge time or less, if the control is by a p.f. correction relay, whose time setting is low and the capacitors are provided with suitable discharge devices.

Figures 26.7 and 26.8 illustrate general layouts respectively for an 11 kV and 33 kV p.f. improvement system with switching and protective devices. Figure 26.9 illustrates a typical layout of a switching and protective scheme for an HV capacitor system, suggesting the recommended switching and protective devices. Based on this, an application engineer can plan a more prudent protective scheme for a particular system.

26.1.2 Protection of series capacitors

Series capacitors are subject to higher voltage variations as a result of generally fluctuating line current. During a fault in the line, such as a short-circuit, the voltage variation across the capacitors may be so high that it may cause an instantaneous failure of the capacitors unless the capacitors are selected for a higher insulation level. IEC 60143-1 for series capacitors suggests that the short-time maximum over-voltage across the capacitors should not exceed 2.15 times the capacitors’ voltage rating for 10 seconds. Since an over-loading results in an over-voltage, over-voltage protection becomes even more essential. IEC 60143-1 permits a temporary over-loading as in Table 26.2 based on which may be provided the over-voltage protection.

The following are a few common methods for the protection of series capacitors.

1 Protection against over-loads

For over-loading during normal operation, which may be due to load fluctuations or failure of a few capacitor elements, normal over-load protection will suffice, as discussed for shunt capacitors (Section 26.1.1(3)). This protection may be provided in conjunction with the line fault protection scheme, discussed below.

2 Protection against line faults

There may be a number of ways by which the series capacitors can be protected against line faults. Commonly used methods are briefly discussed below.

(i) Using a damping circuit

The theory of protection is based on a rapid voltage rise across the series capacitors during a line fault. This voltage rise is used to achieve the required high-impedance requirement of the system during a fault, i.e., restoring the near-natural impedance of the line as if it were without series capacitors. A simple R-L damping-cum-discharge circuit is illustrated in Figure 26.10. This consists of a resistor and reactor combination, which helps to limit the discharge current and hence the over-voltage across the series capacitors.

<table>
<thead>
<tr>
<th>Times the rated capacitor</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.10</td>
<td>For 8 h during a 12 h operation</td>
</tr>
<tr>
<td>1.35</td>
<td>For 30 min during a 6 h operation</td>
</tr>
<tr>
<td>1.50</td>
<td>For 10 min during a 2 h operation</td>
</tr>
</tbody>
</table>

Note:

1. Provided that the average output in a 24 h operation does not exceed the rated output.
2. See also the latest version of IEC-60143-1.
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Lightning arrester
Overhead bus bars
Cable box Supporting frame
Isolator Series reactor
Capacitor banks
Supporting frame
G.L
Residual voltage transformer (RVT)
Ground level
Figure 26.7 Installation of 11 kV capacitor banks and their protective equipment

* To limit the inrush and harmonic currents through the capacitor banks.
** For unbalance protection and also for capacitor discharge and measurement if required.

Gantry Isolator Current transformers Circuit interrupter Lightning arrester * Series reactor ** Residual voltage transformer (RVT) Capacitor bank

Figure 26.8 Typical layout of 33 kV power factor improvement system with switching and protective equipment
capacitors during a fault by almost offsetting the capacitor fault current, $I_C$ (fault), with the Inductive current, $I_L$, through the damping circuit, i.e. by achieving

$$I_L = I_C \text{ (fault)}$$

This realizes a near-zero or very small fault current through the capacitors and protects them besides restoring the fault level of the system to its original level.

(ii) Connecting a spark gap across the capacitor banks

If a breaker alone is used to bypass the capacitors during a line fault it may fail to discharge its required duty due to its definite minimum time of closing (Table 19.1).
This inherent time delay may be too long to protect the capacitors during a fault. To overcome this, a spark gap is additionally provided across the capacitors, which will spark-over instantaneously at the preset value and limit the fault current to the required level during a fault condition and bypass the capacitors as illustrated in Figure 26.11. Extinction of the arc is achieved by the bypass breaker, which closes soon after (3 to 5 cycles from initiation of the fault).

The excessive line current results in a high voltage drop across the capacitors \( (I_{SC} \cdot X_C) \), which sparks over the gap generally set at about 2.5 to 3 times the nominal voltage of the capacitors. This high voltage for an extremely short duration will economize on the cost of capacitors. The arc will be sustained only until the fault clears or the line de-energizes or the bypass breaker closes, whichever occurs first. The arc will extinguish at every current zero and attempt to insert the capacitors back into the line. The arc will reappear until the over-voltage attenuates to less than the spark-over-voltage, or the line de-energizes or the bypass breaker closes. The capacitors must therefore be suitable to withstand repeated transient voltages developed during each arcing.

A CT is provided in series with the spark gap to sense its operation during a line fault. As soon as there is arcing, it provides an instantaneous command to a short-circuit relay. The relay, in turn, closes the bypass breaker, within 3 to 5 cycles, leaving only the natural line impedance in the faulty circuit. Now \( X_C = 0 \), which limits the fault current to the natural level of the system, as if the capacitors were not connected. The shorting device is restored to its original status as soon as the fault condition is cleared. The device must be capable of interrupting the line fault current without a restrike. The scheme serves a dual purpose by providing necessary protection to the capacitors, on the one hand, and restoring the line natural impedance (i.e. the original fault level) by short-circuiting the capacitors, on the other.

Rapid reinsertion of the capacitors as soon as the fault conditions are removed is an important requirement to retain the stability of the system. This can be achieved with the use of an additional ZnO, non-linear resistance (ZnO being the latest in this field compared to SiC, which was being used earlier), across the capacitor banks (Figure 26.12). Generally, the ZnO resistor will be adequate to damp the fault current without initiating the spark gap, and will limit the over-voltage across the capacitors. It will also permit automatic reinsertion of the capacitors as soon as the fault conditions are removed without causing a delay. The spark gap will serve as a backup to the ZnO resistor in the event of very severe faults.

The above bypass facility can also be achieved with the use of a thyristor switch, which may be made current sensing or voltage sensing.

### 26.2 Installation and maintenance of capacitor units

The following are suggestions for the successful operation of the capacitor units installed on an LV or an HV system:

1. Over-heating shortens the life of a capacitor. Adequate ventilation and cooling facilities, through convection and radiation, must be made available at the place of installation. When housed inside a cubicle, as in a capacitor control panel and in a tier formation, sufficient space must be provided between each unit. Adequate

---

**Figure 26.11** Over-voltage protection with the help of a spark gap and a shorting switch

**Figure 26.12** Over-voltage protection with the help of a ZnO resistor, spark gap and a shorting switch
ventilation facilities should also be provided, either through louvres, exhaust fans or by providing an expanded metal enclosure, for the capacitors to ensure a free air circulation around each capacitor unit (Figure 23.32).

2 Concentration of capacitor banks at one point in a system may cause amplification of harmonics, self-excitation of machines, over-voltages due to switching and unsatisfactory working of audio frequency remote control apparatus. To overcome this, concentration of capacitor banks at one point must be avoided as far as possible. These may be installed at different locations in the system.

3 A loose contact within the circuit, producing sparks, will generate high-frequency oscillations (harmonics). However small these oscillations are, they may raise the system voltage and frequency. High-frequency oscillations will also reduce the impedance of the capacitors \( x_{ch} \alpha \frac{1}{f_h} \) and cause high currents, leading to premature failure of the capacitors. Loose contacts must therefore be thoroughly checked. It is recommended that a capacitor circuit particularly be checked periodically for loose connections or sparkings.

4 When the reactive control is not automatic, then during off-peak periods (such as during the night) it is important that some of the banks are dropped manually to avoid an over-compensation and a consequent over-voltage.

5 It is advisable to periodically check the condition (i.e. the capacitance value \( C \)) of each capacitor unit to detect failure of one or more of them and the consequent over-voltage across the healthy units. This can be measured by any of the methods discussed in Section 26.3.1(1). The capacitance value of each unit must fall within the permissible limits as indicated in that section. The failed units, if any, must be replaced promptly with units of the same rating and brand to avoid any performance variation. If this is not possible then the banks must be balanced by readjusting the units. When the banks are connected through a series reactor, the value of the reactor must also be readjusted to match changed parameters. Otherwise the reactor may resonate with the fifth or the seventh harmonic, for which it is designed, and cause an over-voltage.

### 26.2.1 Precautions in handling a capacitor unit with PCB

Although the manufacture of PCB-filled capacitor units has been discontinued, for older installations some may still be used. For the benefit of their users we give below the precautions that they must take when handling these units:

- Avoid any spillovers, leakage or vaporization of liquid or disposal of a waste unit. One can use Araldite, solder or any other means to stop a leakage. If this is not possible, collect carefully all the chemical PCB and carefully dispose it of.
- Soaked rags, cloth or papers, must be destroyed in an incineration plant at 1000°C. Disposal at a landfill area is not advisable for during rain they may be carried by storm drains into rivers, canals or ponds.
- Old units should not be sold to a scrap dealer for similar reasons.

### 26.3 Test requirements

Below we discuss briefly recommended tests on a finished capacitor unit based on various IEC recommendations. For Standards refer to the list provided at the end of the chapter.

#### 26.3.1 Routine tests

Routine tests are carried out on each capacitor unit.

(1) **Capacitance measurement**

This is to be determined at rated voltage and frequency and can be carried out between 0.9 to 1.1 times the rated voltage and 0.8 to 1.2 times the rated frequency. Permissible tolerances in capacitance from the declared values can be as follows:

- **For LV capacitor units up to 1000 V** For both self-healing and non-self-healing types:
  - –5% to +10% for units and banks up to 100 kVAr
  - –5% to +5% for units and banks above 100 kVAr.
- **For HV capacitors**
  - –5% to +15% for capacitor units or banks containing one unit per phase
  - –5% to +10% for capacitor banks less than 3 MVar
  - 0% to +10% for capacitor banks from 3 MVar to 30 MVar
  - 0% to +5% for capacitor banks above 30 MVar.
- **For series capacitors**
  - These are usually HV capacitor units/banks:
    - ±7.5% for capacitor units or banks containing one unit per phase
    - ±5% for capacitor banks less than 30 MVar
    - ±3% for capacitor banks 30 MVar and above.

#### Methods to determine the capacitance of a capacitor unit

Two common methods to determine this are:

- Voltage method and
- Bridge method.

In the voltage method the normal voltage is applied across the capacitor terminals and line current, \( I_c \), is measured. The value of capacitance, \( C \), can be determined from the equations provided in Section 23.5.2(A). In the bridge
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Method the capacitance is measured directly through a capacitance meter without disconnecting the unit from the circuit.

Note
The values thus obtained will be accurate when the system is free from harmonics. If harmonics are present in the system correction will be necessary for both $V$ and $f$, as in Equation (23.5).

(2) Measurement of capacitor loss in terms of $\tan \delta$

$\tan \delta$ is a measure of dielectric loss in a capacitor unit and is represented by the ratio of equivalent series resistance and capacitive reactance of a capacitor unit at the rated voltage and frequency (Figure 9.7), i.e.

$$\tan \delta = \frac{R}{X_c}$$

where equivalent series resistance, $R$, is the virtual resistance which, if connected in series with an ideal capacitor unit of capacitive value equal to that of the capacitor under reference, will have a power loss equal to the active power dissipated in that capacitor under specified operating conditions.

The test can be performed at voltages and frequencies, as noted in (1) above. The value of $\tan \delta$ should not exceed the declared value.

(3) Voltage test between terminals

Every capacitor unit will be subject to an a.c. test at a voltage specified in Table 26.3 at a frequency between 15 and 100 Hz, preferably as close to the rated as possible. During the test no permanent puncture or flashover should occur.

(4) Voltage test between terminals and container

The test procedure and test performance should be the same as noted in (3) above except the test voltages, which will be as specified in Table 26.3.

(5) *Test for the internal discharge device

This is required to determine the suitability of the resistance of the discharge device to ensure that it discharges a charged capacitor unit or bank at $\sqrt{2} V_t$ to 50 V or less in 1 minute in LV and in 10 minutes in HV shunt capacitor units or banks and in 5 minutes in series capacitors. The arrangements of discharge devices are illustrated in Figure 25.8.

(6) Scaling test

This is required to check the leakage of the capacitor dielectric during long operations. It is carried out by heating the unit uniformly on all sides, at least 20°C higher than the maximum ambient temperature of the capacitor unit, for at least 2 hours. There should be no leakage.

26.3.2 Type tests

(1) Thermal stability test

This is another name for a heat run test. A voltage sufficient to cause an output of the capacitor unit equal to 1.5 times the rated output is applied at the rated frequency and test conducted for at least 48 hours. During the last six hours of the test the temperature rise and $\tan \delta$ are measured at least four times. The temperature rise during the last six hours should not exceed 1°C, otherwise the test duration must be extended until the temperature stabilizes to a rise of only 1°C. The final test results

*These figures are only indicative, as different countries may specify different discharge voltages and discharge times. For instance, various IEC Standards mentioned at the end of the chapter specify the discharge voltage as 75 V, reached in 3 minutes in LV and 10 minutes in HV shunt as well as series capacitors. When required for fast switching operations, special discharge devices are sometimes employed to achieve a faster discharge, as discussed in Section 25.7.
compared to the measurement taken at the start of the test should not vary by more than the following:

• **For capacitance value**
  For LV units: 2% of its capacitance value
  For HV units: The two test values should be corrected to the same reference of dielectric temperature, say, 20°C or as agreed. The difference between the two test values should be less than an amount corresponding to either breakdown of an element or operation of an internal fuse.

• **For tan δ value**
  For LV units: \(2 \times 10^{-4}\)
  For HV units: \(1 \times 10^{-4}\) or as agreed between the manufacturer and the user.

(2) **Measurement of capacitor loss in terms of tan δ**

This is the same as for the routine test (2)

(3) **Voltage test between terminals**

This is similar to the routine test (3) except the duration of the test, which should be as specified in Table 26.4.

(4) **Voltage test between terminals and container**

This is similar to the routine test (4) except the duration of the test, which would be as specified in Table 26.4.

(5) **Lightning impulse voltage test between terminals and container**

The test should be conducted generally with a wave of 1.2 to 5/50 µs as illustrated below:

- **For LV units:** Three impulses should be applied of positive polarity followed by three of negative between the terminals joined together and the container.
- **For HV units:** Fifteen impulses should be applied of positive polarity followed by fifteen of negative between the bushings joined together and the container.

The value of the first peak of the test wave is specified in Table 26.4. During the test there should be no rupture or flashover at any part of the unit, which should be verified by a cathode ray oscillograph. An oscillograph should also be used to record the voltage and check the wave shape.

(6) **Short-circuit discharge test**

The unit should be first charged by d.c. and then discharged through a gap situated nearby. The test voltages should be as follows.

- **For LV units**
  - **Star-connected units** Test voltage \(4 V_r / \sqrt{3}\). The test should be carried out between any two terminals, leaving the third open.
  - **Delta-connected units** Test voltage \(2 V_r\). Any two terminals of the unit should be shorted and the test conducted between the third and the shorted terminal.

- **For HV units**
  The test voltage should be \(2.5 V_r\), irrespective of star- or delta-connected units. The capacitor unit should be charged with the test voltage and discharged five times within 10 minutes. Within 5 minutes after the test the unit may be subjected to voltage test (3) between the terminals. The capacitance of the test unit may be measured before the

| Table 26.4 Insulation levels for power capacitor units |
|---------------------------------|-----------------|-----------------------|
| Highest voltage for equipment   | Rated lightning impulse withstand voltage | Rated power-frequency short-duration withstand voltage for voltage test |
| \(kV_{\text{r.m.s.}}\) | List 1 | List 2 | \(kV_{\text{r.m.s.}}\) | Duration |
| \(kV_{\text{peak}}\) | \(kV_{\text{peak}}\) | \(kV_{\text{r.m.s.}}\) | Routine test | Type test |
| up to 0.66 | – | 15 | \{ Refer to Table 26.3 \} | \(\uparrow\) |
| 0.66 to 1.0 | – | 25 | 6 | \(\uparrow\) |
| 1.2 | – | 25 | 8 | \(\uparrow\) |
| 2.4 | – | 35 | 10 | \(\uparrow\) |
| 3.6 | 20 | 40 | 10 s | 1 min |
| 7.2 | 40 | 60 | 20 | \(\uparrow\) |
| 12 | 60 | 75 | 28 | \(\uparrow\) |
| 17.5 | 75 | 95 | 38 | \(\uparrow\) |
| 24 | 95 | 125 | 50 | \(\uparrow\) |
| 36 | 145 | 170 | 70 | \(\uparrow\) |

**Notes**

1. For a repeat test only 75% of the test voltage must be applied.
2. The power frequency voltage test refers to indoor units. The outdoor capacitor units must be subjected to a wet test as in IEC 60060-1.
3. The choice between list 1 and list 2 will depend upon the extent of exposure of the units to the internal and external voltage surges and the amount of surge protection, if provided.
4. It will also depend upon the condition of system grounding, i.e. whether effectively grounded, non-effectively grounded or isolated neutral etc. For systems other than effectively grounded, list 2 must be preferred.
5. For higher voltage systems, refer to the relevant Standards noted in the table of Standards provided at the end of the chapter.
discharge test and after the voltage test. The capacitance values thus measured should not be exceeded by more than 2% or breakdown of an element or blowing of an internal fuse.

(7) Partial discharge test (applicable to HV units)

There are invariably voids that will appear in an insulating system as a matter of process, irrespective of the type and procedure of impregnation adopted, as discussed in Section 9.6.1. For all practical purposes, a dielectric system may therefore be considered to be an imperfect capacitor. All such voids may cause internal discharges and lead to erosion and ultimate failure of the dielectric under the effect of the applied voltage. The applied voltage may be fluctuating too, aggravating the situation. This test is conducted to check the condition and suitability of the dielectric used to perform the required duties in service without causing an undue discharge (ionization). It is a means of detecting defects in the insulating system of a capacitor unit and is complementary to a dielectric test.

To perform this test, the rated voltage may be applied long enough for thermal equilibrium to be achieved. Then a test voltage of twice the rated voltage is applied only once for one second. The voltage is then reduced to 1.2 times the rated voltage and maintained for 10 minutes and then it is raised again to 1.5 times the rated voltage for 30 minutes. During the last 10 minutes, the discharge under such conditions should be less than 50 pc (picocoulombs). The capacitance should be measured both before and after the test. The change in capacitance should not exceed 2%.

One will appreciate that such tests are no guarantee of the minimum life of a capacitor unit. Moreover, it is not expected that such tests can predict the future of the capacitor units. They can, at best, suggest the compliance of the test requirements which should ensure a reasonably prolonged operating life of the capacitors, as envisaged. These tests do provide feedback to the manufacturer on the quality of the dielectric and the process of insulation adopted and if any improvements are required.

(8) Endurance test (process test for HV capacitors)

This is an alternative to the ageing test and is applicable for shunt capacitors of 1000 V and above. It is an in-house process test and is carried out on the capacitor elements before they are assembled into a capacitor unit to ascertain their dielectric stability against repeated over-voltages. For the test procedure refer to IEC 60871-2.

(9) Ageing test (applicable to LV units)

This test is conducted to estimate the working life of a capacitor. Briefly, the test can be conducted in three stages as follows:

(a) The capacitor is energized at 1.25 times the rated voltage for 750 hours.
(b) It is then subjected to 1000 discharges.
(c) After test (b), the test in (a) is repeated.

On conclusion of the test no permanent breakdown or flashover should be observed. The variation in the capacitance value as measured before and at the end of the test should not vary by more than 3%. The capacitor unit should withstand the voltage test between the terminals and the container as stated in test (4) above and the scaling test as in test (6) under routine tests.

(10) Self-healing test

This test is applicable to LV capacitors only, which are the self-healing type. The capacitor is subjected to a voltage of 2.15 $V_r$, for 10 seconds. If fewer than five breakdowns occur during this time, the voltage may be increased slowly until it reaches 3.5 times its rated value, or five breakdowns, whichever happens first. If five breakdowns have still not occurred, the test is continued until they do. The capacitance measured before and after the test should show no significant change.

(11) Destruction test

This test is also applicable to LV capacitor units only. The basic objective is to establish that the failure of a unit is within a safe zone and is not accompanied by the risk of a violent explosion or fire.

Concluding

These are only brief descriptions of the recommended tests and their procedures on a completed capacitor unit. For more details refer to the table of Standards provided at the end of the chapter.

26.3.3 Checking field operating conditions

On larger installations, particularly, it is recommended that the actual operating conditions be checked and compared with the assumed conditions for which the capacitor units were designed to ensure that they do not differ by more than the permissible limits. This is because a capacitor is highly susceptible to some operating conditions such as fluctuations in voltage and harmonic contents in the system. An excess of any of these or both $V$ and $V_h$ may shorten the life of the capacitor units and cause frequent failures of individual units. It may also lead to over-voltages across the units and increase harmonic contents. All this may cause failure of the capacitor units, leading to even a cascade failure, increasing the unbalance in voltage and kVAr across each phase and destabilize the entire capacitor network.

The effect of voltage and voltage fluctuations can be checked through the capacitor line current, $I_c$, which is a measure of the capacitance $C$ of the capacitor units. The capacitor current must correspond to the designed (rated) current plus the permissible variation. A higher current than this would mean a voltage variation or the presence of harmonics in the system or both. While the voltage may be measured through a voltmeter and the current through an ammeter in the three lines, the
悍然ics content may be checked by an oscilloscope. If the actual operating conditions differ from the designed parameters by more than permissible, suitable measures will be essential to restore the operating conditions within the permissible limits, say, by providing series reactors or filter circuits in the system as discussed already.

Relevant Standards

<table>
<thead>
<tr>
<th>IEC</th>
<th>Title</th>
<th>IS</th>
<th>BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>60110-2/2000</td>
<td>Power capacitors for induction heating installations – Ageing test, destruction test etc.</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>60831-2/1995</td>
<td>Shunt power capacitors of the self healing type for a.c. systems having rated voltage up to and including 1000 V. Ageing test, self-heating test and destruction test.</td>
<td>13341/1997</td>
<td>BS EN 60831-2/1996</td>
</tr>
</tbody>
</table>

Relevant US Standards ANSI/NEMA and IEEE

<table>
<thead>
<tr>
<th>Standard Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMA/CP-1/2000</td>
<td>Shunt capacitors, both LV and HV.</td>
</tr>
</tbody>
</table>

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

Voltage unbalance

\[ V_u = \frac{N \cdot V_{ph}}{3N_2 \cdot N_1 - 3N \cdot N_1 + 2N} \]  \hspace{1cm} (26.1)

\( V_u \) = Unbalanced voltage across the open delta. This is for grounded systems. For isolated systems, it will be three times this.

\[ V_{ph} = \frac{V_1}{\sqrt{3}} \]

\( N \) = number of units failed
\( N_1 \) = number of units in series per group per phase
\( N_2 \) = number of units in parallel per group per phase

Current unbalance

\[ I_u = \frac{3N \cdot N_2}{6N_2 \cdot N_1 - 6N \cdot N_1 + 5N} \times I_c \]  \hspace{1cm} (26.2)

\( I_u \) = Unbalanced current through the interconnected neutral
\( I_c \) = current per capacitor unit

Further Reading