CHAPTER – 2

ELEMENTS OF SHUNT COMPENSATOR
Introduction:

A typical shunt compensator to be employed in a distribution system primarily consists of capacitor units, series and shunt reactors for inrush current limiting purpose and to provide variable inductive reactive power respectively, thyristors for control purpose and switchgear for protection. The switchgear could be CBs / MCCBS, contactors and relays. A compensator installation has to be provided with conventional over current protection, under voltage detection and disconnection, unbalance and earth fault. These things are dealt in this chapter in brief as applicable both for LT and HT systems.

2.1 Capacitor Banks

2.1.1 Preliminary Considerations:

Capacitor is the most indispensable static device in a power system. It can be connected either in series form or shunt form for power frequency applications. Below 650 volts the capacitors are categorized as LT and above 650 volt as HT. It is possible to design and manufacture capacitor units of standard sizes and banks can be formed with series parallel combinations of units for the required capacities. Capacitors are relatively cheap; no foundations are required for installations, most efficient due to very low losses (0.3 to 1.5% of the rating), least maintenance and incur low annual charges. Their limitations are: incapable of providing step less variation in Q, the reactive power is proportional to the square of mains supply voltage, associated with switching transients and resonance problems.
Since 1940’s the voltage stress has increased from 18 volts per micron to 70 volts per micron, loss got reduced from 0.5% to 0.01%, the size of individual unit from a few KVAR up to 600 KVAR, voltage few volts to 11 KV and the volume got reduced from 600 cm$^3$ per KVAR to about 100 cm$^3$ per KVAR. These figures are indicative of technological advancement in the manufacture of capacitor units for both LT and HT applications.

The LT capacitors are manufactured with metalized poly-propylene (MPP) in either three phase single units or single phase units. The capacitors are designed and built for delta connection in LT applications. On the other hand they are connected in star for HT applications. HT capacitors are manufactured making use of bi-axially oriented poly-propylene (BOPP) of small sizes. They are connected in series-parallel combinations forming banks to suit the voltage and KVAR requirements.

A capacitor subjected to switching operations is invariably associated with the transient phenomenon. The voltage across a capacitor cannot be changed abruptly and when switched on at $t = 0^+$ it acts like a short circuit. In their application as a shunt compensator, they are provided with current limiting reactors. However, in LT applications the problem is not that severe. A shunt capacitor connected across a load injects reactive power and directly compensates the load reactive power. Shunt capacitors are widely employed in both LT and HT systems, on account of their attractive features. Numbers of advances have taken place in the design and manufacture of both LT and HT capacitors. Once they are installed in a system, they are long lasting, give trouble free service and highly reliable if they are provided with requisite protection.
A capacitor bank can be formed with capacitors in steps, more number of steps gives reduced resolution but the cost of switch gear will increase in order to get a continuously variable reactive power, a thyristor controlled reactor is connected across it so as to obtain step less variation of reactive power. The LT capacitors employed for experimental set up are of the following rating:

<table>
<thead>
<tr>
<th>Capacitor Bank</th>
<th>KVAR Value</th>
<th>Xc (Ohm)</th>
<th>Microfarad Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>2.5</td>
<td>75</td>
<td>42.44</td>
</tr>
<tr>
<td>C1</td>
<td>5.0</td>
<td>37.5</td>
<td>84.88</td>
</tr>
<tr>
<td>C2</td>
<td>10.0</td>
<td>18.75</td>
<td>169.7</td>
</tr>
<tr>
<td>C3</td>
<td>20.0</td>
<td>9.375</td>
<td>339.5</td>
</tr>
<tr>
<td>C4</td>
<td>40.0</td>
<td>4.687</td>
<td>679.1</td>
</tr>
</tbody>
</table>

2.1.2 Discharge Device:

Every capacitor unit is provided with a discharge resistor in both LT and HT applications to bring down the voltage up to or below 50 volts within 2 or 5 minutes respectively. The discharge time can be calculated from the formulae[26].

\[ t = 2.3 \times 10^{-6} CR (\log_{10} V_n - 1.5) \text{ seconds} \quad [2.1] \]

Where,

\[ t = \text{time to discharge to 50 volts} \]
R = measured value of discharged resistance in ohms.

C = capacitance in microfarads of the capacitors across which

the discharge resistor R is connected.

Vn = r.m.s. value of the voltage at rated frequency between the terminals, which the capacitor is designed to withstand continuously.

### 2.1.3 Capacitor Bank Switching:

A capacitor bank when energized or d-energized by switching on or off, it is subjected to both voltage and current transients. In order to understand this phenomenon consider the electrical circuit energizing an isolated capacitor bank as shown in fig 2.1

In fig 2.1 shows electrical equivalent circuit for energizing an isolated capacitor bank from a predominantly inductive source. Immediately following the closure of switch, a high frequency and large magnitude current flows into the capacitor, so as to equalize capacitor voltage with the system voltage. The voltage surge and the inrush current depend on the instant at which the switch is closed on the supply wave
form. The voltage surge for an isolated grounded star bank can reach a maximum of 1.8/2.0 per unit as shown in fig-2.2

2.1.4 Energisation of Back to Back Capacitor Bank:

In the distribution system the capacitor banks are arranged in steps and switching operations are carried out to obtain the reactive power required to match with the prevailing load requirement so as to maintain the power factor at desired level. This necessitates parallel operations and capacitor bank arrangement in steps. A typical back to back switching arrangement is shown in fig-2.3, where in C1 and C2 are already in the circuit and C3 being switched on[27].

![Back to back switching of capacitor bank in steps](image)

Consider C₁ and C₂ are in energized condition and C₃ with NIL / least charge is switched on. At, t=0⁺ a high frequency inrush current flows due to energisation of capacitor C₃. This switching operation is associated with two types of transient oscillations, (i) very high natural frequency by which the C₃ has to be brought to the same potential level of that of C₁ and C₂ and, (ii) with a considerable lower natural frequency by which all the three capacitors should be brought to the same potential level of the source. The first phenomenon given rise to large magnitude
of inrush current at very high frequency and the second one is associated with relatively smaller transient current at low frequencies in KHz lasting for a longer duration.

2.1.5 Capacitor Energising Transient:

It is an established fact that when a capacitor bank is connected to supply, a high frequency and large magnitude transient current flows for a short period. The peak value of this inrush current for a single capacitor bank can be calculated using the formula[27].

\[
I_{\text{max}} = 1.15 I_o \left(1 + \frac{\text{shortKVA}}{\text{capacitorKVAR}} \right)
\]  \hspace{1cm} \text{---------------- [2.2]}

Where \( I_o = \) nominal steady state power frequency peak current

The inrush current for purely reactive network has the following frequency

\[
f = f_o \sqrt{\frac{\text{shortcircuitKVAR}}{\text{capacitorKVAR}}} \]  \hspace{1cm} \text{------------------------ [2.3]}

Where \( f_o = \) rated power frequency of the system.

At the instant of switching \( t = 0^+ \) an uncharged capacitor exhibits zero impedance to the flow of current. The inrush current during switching of the single capacitor bank is limited by the series resistance and inductance of the circuit. The frequency of the large magnitude transient oscillatory current depends on the resistance, inductances & capacitance of the circuit. In the above formulae resistance is neglected.
As dealt above high frequency voltage and current oscillations occur during the energizing period. In respect of both single and parallel banks it is necessary to limit the voltage to less than twice, line to neutral value under normal switching conditions. The capacitors are capable of withstanding a high voltage in excess of two times rated value for very short durations. Thus in parallel operation of bank the following things must be given due consideration:

- Continuous voltage rating and transient voltage rating for short duration of time.
- Continuous current rating with adequate margin (1.43 times capacitor bank rating)
- Interrupting rating required for handling the short circuit current which may occur on capacitor side.
- Momentary current rating must be large enough to withstand both short circuit current during faults and inrush current associated with energization.
- Frequency of operating the switching device must be mechanically robust enough & electrically simple to withstand repetitive switching operations.

2.2 Reactors: General

Reactors are employed in power systems for various purposes both in series and shunt forms in LT and HT systems. There exists number of types designed and manufactured to serve variety of applications. In this section air cored reactor is introduced, design considerations are dealt the
operating principle of thyristor controlled reactor and its use in static VAR compensator is are explained.

2.2.1 Application of Reactors:

Most commonly the capacitors are invariably provided with reactors in series on line side or neutral side. Small value chokes in LT, 6% reactors on line or 0.2% reactors on neutral side in HT applications, 13% reactors at 25 KV traction substations and specially designed tuned reactors in filter circuits, are in use. They can be of air cored, air/oil cooled, dry type or of gaped core type, with or without shielding. In majority cases the role of a reactor is somewhat limited; the cost is relatively high and is also associated with high percentage losses. In the specific application of static VAR compensator in LT distribution systems, the thyristor controlled reactor is arranged across a shunt capacitor to obtain continuously variable reactive power. The design of an air cored reactor is dealt in the next section.

2.2.2 Air Cored Reactor:

Air cored coils are preferred as the inductance remains constant over the entire range of operation. This is most suitable for static VAR applications. Its design is given bellow [28] making use of formula given for a multi layer reactor,

\[
L = \frac{0.8a^2n^2}{6a + 9b + 10c} \quad \text{Micro-Henry’s} \quad [2.4]
\]

Where \( n = \) no. of turns
a = mean radius of the coil

b = length of the coil

c = thickness of the winding

All dimensions are in inches

Each air cored coil is rated for 220 volts, 2 Amps and single phase with approximately 700mH Inductance. This is suitable for thyristor controlled reactor to be connected in delta form with coils on either side of two thyristors in anti parallel mode in each phase. 17 SWG super enamelled wire is used for the reactor. Following are the dimensions obtained as per the above mentioned formula.

a = 4.5 inches

b = 6 inches

c = 2.5 inches

n = 1500 turns, number of layers = 14, turns per layer = 107/108
ID = 6.5 inches

OD = 11.5 inches

MD = 9 inches

Weight of copper 15.25 kg per coil

Dimensions of super enameled wire employed are 17 SWG, 1.589 mm², 1.42 mm diameter, 14.13 Kg. weight per Km length.

Total length of wire used is approximately 1.07 km / coil.

There are thirteen gaps between layers each approximately 4 mm thick, separated by strips for insulation purpose.

Total number of six such coils are built and tested in the laboratory for their inductance values. It has been found that they all have the following inductance, resistance and impedance values in close proximity.

Table 2.1 Test results of the six reactor coils designed

<table>
<thead>
<tr>
<th>Coil No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance Z₁ to Z₆ Ohms.</td>
<td>98.25</td>
<td>102.8</td>
<td>104.0</td>
<td>105</td>
<td>100</td>
<td>105</td>
</tr>
<tr>
<td>Resistance R₁ to R₆ Ohms.</td>
<td>10.6</td>
<td>11.23</td>
<td>10.7</td>
<td>10.9</td>
<td>10.87</td>
<td>11.5</td>
</tr>
<tr>
<td>Inductance L₁ to L₆ mH.</td>
<td>310</td>
<td>325</td>
<td>329</td>
<td>332</td>
<td>316</td>
<td>332</td>
</tr>
</tbody>
</table>
2.3 Thyristor Controlled Reactor (TCR):

A typical TCR scheme with two thyristors connected in anti-parallel mode in each phase for phase control is shown in fig 2.5

It is possible to vary the reactive power level from zero to the KVAR rating of the coil by controlling the delay angle through appropriate triggering. The TCR circuit and the associated wave forms for both voltage and current are shown in fig 2.6(a) & (b)[29, 30]

As shown in fig 2.6(a) & (b) the current in a TCR can be continuously varied from zero (corresponding to $\sigma = 0$) to maximum (corresponding to conduction angle of 180°) by phase control in which the firing angle $\alpha$ (with respect to zero crossing of voltage is varied from 180° to 90°. The instantaneous current $i_{TCR}$ over a half cycle is given by

$$i_{TCR} = \frac{\sqrt{2}V}{X_L} (\cos \alpha - \cos(\omega t)) \quad \alpha < \omega t < (\alpha + \sigma)$$

$$= 0 \quad (\alpha + \sigma) < \omega t < (\alpha + \pi) \quad \ldots \ldots \quad [2.5]$$

![Fig 2.5 Schematic Arrangement for Thyristor Controlled Reactor](image)
Where \( V \) is RMS voltage applied, \( X_L \) is the reactance at fundamental frequency. The conduction angle \( \sigma \) is related to \( \alpha \) by

\[
\sigma = (\pi - 2\alpha)
\] 

The amplitude \( I_L(\alpha) \) of the fundamental reactor current \( i_{tcr}(\alpha) \) can be expressed as a function of angle \( \alpha \):

\[
I_L(\alpha) = \frac{V}{X_L} \left(1 - \frac{2}{\pi} \alpha - \frac{1}{\pi} \sin 2\alpha\right)
\] 

The variation of amplitude \( I_L(\alpha) \) normalized to the maximum current

\[
I_{LMAX}(\alpha) = \frac{V}{X_L}
\]

is shown against delay angle \( \alpha \) in fig 2.7

It is clear from the fig 2.7 that TCR can control the fundamental current from zero (valve closed) to a maximum (valve opened) amounting to continuously variable reactive admittance, \( B_L(\alpha) \).

\[
B_L(\alpha) = \frac{V}{\alpha X_L} \left(1 - \frac{2}{\pi} \alpha - \frac{1}{\pi} \sin(2\alpha)\right)
\]
Thus the admittance $B_L(\alpha)$ varies with $\alpha$ is the same manner as the fundamental current $I_L(\alpha)$.

When TCR is in operating condition in conjunction with a switched capacitor bank, it is necessary to adjust $B_L$ continuously to get the requisites KVAr. The reactor must be linear in the entire range and unsusceptible to differ in inductance value with voltage / current spikes. Hence air cored reactors are preferred for static VAR compensator proposed in this work.

2.4 Conclusions:

The preliminary considerations on capacitors, energisation and associated transient phenomenon are introduced. The design of air cored reactors for the six coils to be used in TCR is presented. TCR operation for continuously variable reactive power is explained.