CHAPTER 6

SIMULATION STUDIES ON DISTRIBUTION FEEDER WITH SHUNT COMPENSATOR
6.1 Introduction:

This chapter deals with representation of a typical distribution feeder with the proposed shunt compensator to carry out simulation studies using MATLAB and SIMULINK. It is possible to have a clear idea of control strategy to be employed on the practical system with this study. One of the major problems faced by the power system engineers is the switching transient, whenever the capacitor switching operations are taking place. This aspect is thoroughly investigated for optimum selection of parameters for the inrush current limiting reactors. The objective is to minimize the starting current and reduce the frequency as well as transient duration. This chapter also deals with the replacement of contactors with thyristors for switching operations for fast control.

6.2 Representation of Distribution Network:

A typical distribution feeder from a sub-station to load centers is shown in figure 6.1. A three-phase 11Kv/433V, Dy11 transformer is employed in most complexes for catering to the loads locally.

![Fig.6.1 Single Line Diagram of a Distribution Feeder](image)

Single phase equivalent diagram representing the feeder is given in figure 6.2 with actual values as calculated below:HT
1. Source Reactance = \( X_s \)
   
   Short circuit level on 11KV bus-bar = 20 KA
   
   \[
   X_s = \frac{11}{\sqrt{3}} \times \frac{20KA}{11} = 0.3175 \, \Omega
   \]

2. Transformer’s parameters
   
   The shunt path is neglected.
   
   The percentage impedance for 125 KVA transformer is 4.25%.
   
   \[
   I_p = \frac{125}{11\sqrt{3}} = 6.56 \, \text{Amps},
   \]
   
   \[
   Z_p = \frac{0.0425 \times \frac{11}{\sqrt{3}} \times 1000}{6.56} = 41.1 \, \Omega
   \]
Copper losses in the transformer = 2000 Watts

Equivalent resistance $R_p = \frac{2000}{3 \times 6.56^2} = 15.49 \, \Omega$

\[ \therefore X_p = \sqrt{Z_p^2 - R_p^2} = \sqrt{41.1^2 - 15.49^2} \]

\[ = 38.069 \, \Omega \]

3. Feeder parameters

Distance = 5 Km; \hspace{1em} R_f/Km = 0.49\Omega; \hspace{1em} X_f/Km = 0.365 \, \Omega

\[ \therefore R_f = 0.49 \times 5 = 2.45 \, \Omega \hspace{1em} \text{and} \hspace{1em} X_f = 0.365 \times 5 = 1.825 \, \Omega \]

Equivalent values referring to H. V. side

Total resistance \hspace{1em} = 2.45 + 15.49 \hspace{1em} = 17.94 \, \Omega

Total equivalent reactance \hspace{1em} = 0.365 + 1.825 + 38.069

\hspace{1em} = 40.259 \, \Omega

The equivalent values referring to L. V. sides are

\[ R_{LV} = 0.0287 \, \Omega \]

\[ X_{LV} = 0.06431 \, \Omega; \hspace{1em} (X_{LV} = 0.2047 \, \text{mH}) \]

All the parameters are shown in the equivalent diagram fig. 6.3.

The $R_L$ and $X_L$ values will depend on the loading level and there are six sets of values for the cases considered.
6.3.1 Reactor Parameter Selection Based on Switching Transient:

Whenever a shunt capacitor is switched ON/OFF there is a transient of inrush current/outflow current due to charging/discharging phenomenon. The size of the capacitor, source impedance, switching instant, whether isolated capacitor or in parallel with already existing bank, the instant of supply voltage waveform at which the switching operation is taking place, will decide the magnitude of inrush current, its frequency and duration. Hence the capacitors are provided with inrush current limiting reactors. A large inductance for the choke reduces the magnitude of starting current but increases the effective voltage across the capacitor under steady-state. The resistance of choke if large damping is effective, transient duration is small but gives rise to more losses in steady state condition. This necessitates optimum choice of R and L values for the choke. So that the inrush current is not large, frequency is not high and the transient duration is small. It is in this perspective the simulation study is carried out for switching instant at $0^\circ$, $30^\circ$, $60^\circ$ and $90^\circ$ in the supply voltage waveform. When the capacitor banks are switched ON/OFF using contactors the instant at which the switching ON/OFF is not known. The schematic diagram for quite general in nature study is shown in figure 6.4.
The switching transient obtained for the above instants on the voltage waveform as obtained from the simulation study are depicted. A particular case of instant of switching operation at $90^\circ$ on the supply voltage waveform is shown in figure. Different resistance and inductance parameters of the inrush current limiting choke are considered.

Appropriate values are chosen for every capacitor bank step, with low starting current, reduced frequency and for least duration of transients.

### 6.3.2 Derivation of Inrush Current:

Switching transient phenomenon for a capacitor bank is of considerable importance, particularly when contactors/circuit breakers are employed for switching operations. A typical capacitor switching ON operation is shown in figure 6.4. The highest magnitude of transient inrush current occurs when the contacts of capacitor switch are closed at
the peak of voltage curve [40]. The voltage and current relationship for
this RLC circuit is

\[ E_m \cos(\omega t) = iR + L \frac{di}{dt} + \frac{1}{C} \int idt \] ........ [6.1]

This integro-differential gives the current as a sum of two Steady
state and transient component. The steady state components of the current
is

\[ I_s = \frac{E_m}{Z} \times \cos(\omega t - \phi) \] ......................... [6.2]

Where,

\[ E_m = \frac{\sqrt{2}E}{\sqrt{3}} = \sqrt{\frac{2}{3}}E \]

Where, \( E \) is line voltage

\[ Z = \sqrt{R^2 + (X_L - X_C)^2} \]

The maximum transient current occurs at a time \( t_m \) and steady state

current at this time \( t_m \) is

\[ i_s(t_m) = -\frac{E_m}{Z} \times \sin(\omega t_m) \] ..........................[6.3]

This transient component of inrush current depends on the
resistance and inductance of the feeder circuit and has a natural frequency
\( f_n \) given by

\[ \omega_n = 2\pi f_n = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \] ..........................[6.4]

It is possible to adjust the resistance \( R \) such that

\[ \frac{1}{LC} = \frac{R^2}{4C^2} \]

This resistance is called as the critical resistance given by
For any other resistance \( R \), the expression in terms of \( RC \) will be

\[
R = nR_c = 2n\sqrt{X_L X_C} \quad \text{...........................}[6.5]
\]

Where, \( n = \frac{f_n}{f_0} \), \( f_0 \) is rated frequency of system

The transient dies out if \( R < R_C \) and will rise to a certain maximum value and dies out without oscillations if \( R > R_C \).

In case thyristors are employed for switching operations, it is possible to make it transient free. For this purpose, in the simulation network, two thyristors in anti-parallel mode are considered to carry out the switching either in positive half cycle or negative half cycle of the supply voltage. It is possible to have a control on switching instants. Simulation studies are carried out by using thyristors as switches in place of contactors and the switching transients for all the above cases are presented[41, 42].

### 6.3.3 Scheme of Thyristor Switched Capacitor:

![Basic TSC Configuration](image)
It is possible to switch the capacitor with minimum transients, if the transistor is turned ON at the instant when the capacitor voltage and the network voltages are equal. The current that flows through a capacitor at a given time \( t \) is given by the following expression.

\[
i(t) = \frac{V_m}{X_C - X_L} \cos(\omega t + \alpha) - \frac{V_m}{X_C - X_L} \cos(\alpha) \cos(\omega t) \\
+ \left[ \frac{X_C V_m \sin(\alpha)}{\omega L (X_C - X_L)} - \frac{V_{co}}{\omega L} \right] \sin(\omega t)
\]

\[\text{[6.6]}\]

Where,

\( X_C = \) Capacitor reactance
\( X_L = \) Inductive reactance
\( V_m = \) Source maximum instantaneous voltage
\( \alpha = \) Phase shift angle
\( \omega_r = \) System resonant frequency
\[\omega_r = \frac{1}{\sqrt{LC}}\]
\( V_{co} = \) Capacitor voltage at \( t = 0^- \)

This expression is derived under the assumption that system equivalent resistance is negligible.

6.4 Schematic Diagram for Different Cases of Study:

The load on a distribution feeder on a typical complex varies throughout the day depending on the activities. Six different cases are undertaken for study at different load levels covering the entire range of operation. The source side voltage is held constant and six different load
levels are considered. A capacitor bank is arranged in 5 binary sequential steps. The distribution network simulated for the study is shown in figure 6.6 with source, load and capacitor bank in 5 steps along with inrush current limiting reactors.

![Fig.6.6 Simulated Electrical Equivalent Diagram of a Feeder](image)

**6.5.1 Bank to Bank (Back to Back) Capacitor Switching**

In typical compensation scheme of capacitor banks are arranged in five binary sequential steps as shown in figure 6.6. While if a single capacitor bank is to be considered, it is as shown in fig.6.4. The arrangement of two capacitor banks in parallel for back to back switching operation is as shown in fig. 6.7. In this kind of capacitor switching only local capacitor dominates the inrush current for few milliseconds. Therefore, $R_s$ and $L_s$ have very less role as for as transients are concerned [43].
The expression for the current at the instant of closing the switch is given by

\[ i_2(t) = \frac{v_m \sin(\omega_2 t)}{z_T} \] ..............................[6.7]

Where, \( \omega_2 = \sqrt{\frac{1}{LC}} = \sqrt{\frac{1}{L_0 + L_1 \left( \frac{1}{C_0} + \frac{1}{C_1} \right)}} \)

And,

\[ z_T = Z_0 + Z_1 = \sqrt{(x_{L0} - x_{C0})^2 + (x_{L1} - x_{C1})^2} \]

(Neglecting resistance \( R_0 \) and \( R_1 \))

\[ Z_T = x_{L0} + x_{L1} - (x_{C0} + x_{C1}) \]

\[ Z_T = 2\pi f (L_0 + L_1) - \frac{1}{2\pi f} \left( \frac{1}{C_0} + \frac{1}{C_1} \right) \]

\[ Z_T = \omega(L_0 + L_1) - \frac{1}{\omega} \left( \frac{1}{C_0} + \frac{1}{C_1} \right) \] ..............................[6.8]
Because of low impedance, the transient inrush current is very high. This high transient current circulates in the local parallel capacitor circuits and does not affect the rest of the circuit.

6.5.2 Limiting the Transient Currents:

To limit the magnitude, frequency and duration of the inrush current and frequency, following remedial measures are to be taken.

1. At the switching instant momentarily closing resistor may be inserted and then subsequently bypassed.
2. By permanently placing a fixed reactance in the capacitor circuit. Remembering that the reactance will increase the energy loss in this system and also reduce effectiveness of capacitor.
3. Synchronizing the closing of the circuit. In this case ensure that closing of the switch takes place at very nearer to zero voltage (zero voltage switching). This can be done more effectively with the help of thyristors as a controlled switch. A comparison of synchronized (thyristor) and non synchronized (contactors) transients are dealt in the subsequent sections.

6.6 Non-synchronized (Contactor based) Switching of Capacitor Banks:

In this case of study, there are five capacitor banks along with small resistors and inductors to limit the inrush current and transient frequency are considered as shown in fig. 6.6 (simulated electrical equivalent diagram). Its equivalent SIMULINK model is shown in fig. 6.8. The different values of capacitor banks used along with inrush limiting reactors and critical resistances are as given in the table No.6.1
Table No.6.1 Capacitor values with series reactor and resistance values

<table>
<thead>
<tr>
<th>Capacitor Bank</th>
<th>KVAr Value</th>
<th>$X_c$ (Ohm)</th>
<th>Microfarad Value</th>
<th>Series Reactor (mH)</th>
<th>Series Resistor (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_0$</td>
<td>2.5</td>
<td>75</td>
<td>42.44</td>
<td>2.39</td>
<td>0.075</td>
</tr>
<tr>
<td>$C_1$</td>
<td>5.0</td>
<td>37.5</td>
<td>84.88</td>
<td>1.19</td>
<td>0.0375</td>
</tr>
<tr>
<td>$C_2$</td>
<td>10.0</td>
<td>18.75</td>
<td>169.76</td>
<td>0.573</td>
<td>0.01875</td>
</tr>
<tr>
<td>$C_3$</td>
<td>20.0</td>
<td>9.375</td>
<td>339.52</td>
<td>0.298</td>
<td>0.01475</td>
</tr>
<tr>
<td>$C_4$</td>
<td>40.0</td>
<td>4.687</td>
<td>679.04</td>
<td>0.149</td>
<td>0.01075</td>
</tr>
</tbody>
</table>

For studying the limiting values of transient voltages, currents and frequencies for various loading conditions are as shown in the Table No. 6.2
## Table No. 6.2 Switching of capacitor bank for six loading conditions

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Load Current</th>
<th>P.F</th>
<th>Kw.</th>
<th>KVAR</th>
<th>Load voltage</th>
<th>Capacitor ON/OFF Switching Instances</th>
<th>Total Capacitance</th>
<th>TCR value</th>
<th>Required Lag. VARS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C0</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.5 KVAR</td>
<td>5.0 KVAR</td>
<td>10KVAR</td>
<td>20KVAR</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>0.7</td>
<td>15.6</td>
<td>15.9</td>
<td>430.1</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=[0 0.05]</td>
<td>Control=[0 1]</td>
<td>t=[0 0.1]</td>
<td>Control=[0 1]</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>.72</td>
<td>31.9</td>
<td>30.8</td>
<td>427.25</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=[0 0.05]</td>
<td>Control=[0 1]</td>
<td>t=[0 0.1]</td>
<td>Control=[0 0]</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>0.74</td>
<td>48.9</td>
<td>44.5</td>
<td>424.9</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=[0 0.05]</td>
<td>Control=[0 1]</td>
<td>t=[0 0.1]</td>
<td>Control=[0 0]</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>.76</td>
<td>61.2</td>
<td>52.3</td>
<td>422.78</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=[0 0.05]</td>
<td>Control=[0 1]</td>
<td>t=[0 0.1]</td>
<td>Control=[0 0]</td>
</tr>
<tr>
<td>5</td>
<td>135</td>
<td>.78</td>
<td>76.7</td>
<td>61.5</td>
<td>420.69</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=[0 0.05]</td>
<td>Control=[0 1]</td>
<td>t=[0 0.1]</td>
<td>Control=[0 0]</td>
</tr>
<tr>
<td>6</td>
<td>165</td>
<td>.8</td>
<td>95.6</td>
<td>71.7</td>
<td>418.27</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T=[0 0.05]</td>
<td>Control=[0 1]</td>
<td>t=[0 0.1]</td>
<td>Control=[0 0]</td>
</tr>
</tbody>
</table>
This table gives the following information.

- For all the six loading conditions: load current, power factor, active and reactive power required by the load.
- Capacitor bank steps switched ON.
- Capacitor bank steps switched OFF.
- Time delay between switching operations.
- Switching instant i.e. instant at which closing signal applied.
- Total capacitance injected (KVAr leading) in the system.
- The required VARs lagging which is to be injected by TCR so as to maintain unity power factor.
SIMULINK Model for Switched Capacitor Bank at PCC:

Fig. 6.8 SIMULINK Model for Switched Capacitor Bank at PCC
### 6.6.1 Switching Transient Waveforms Obtained by Simulink:

The transient current and voltage waveforms for all the six loading conditions are as shown in subsequent plots.

#### Table 6.3 Switching transient parameters for various loading and switching conditions

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Load Current</th>
<th>P.F.</th>
<th>Real Power Kw.</th>
<th>Reactive Power Kvar</th>
<th>Volt age</th>
<th>Fig. No</th>
<th>Switching Angle</th>
<th>Peak V&lt;sub&gt;L&lt;/sub&gt;</th>
<th>Peak I&lt;sub&gt;L&lt;/sub&gt;</th>
<th>Peak I&lt;sub&gt;C&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Before Switching</td>
<td>Transient Peak</td>
<td>Steady state</td>
<td>Before Switching</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>7</td>
<td>5.25</td>
<td>5.35</td>
<td>248.3</td>
<td>Fig.6.13</td>
<td>0</td>
<td>350.86</td>
<td>356.77</td>
<td>351.19</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>.72</td>
<td>10.8</td>
<td>10.4</td>
<td>246.7</td>
<td>Fig.6.14</td>
<td>0</td>
<td>348</td>
<td>352</td>
<td>351</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>0.74</td>
<td>16.65</td>
<td>15.13</td>
<td>245.1</td>
<td>Fig.6.15</td>
<td>0</td>
<td>345</td>
<td>362</td>
<td>351</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>.76</td>
<td>20.9</td>
<td>17.87</td>
<td>244.1</td>
<td>Fig.6.16</td>
<td>0</td>
<td>343</td>
<td>363</td>
<td>350</td>
</tr>
</tbody>
</table>
6.6.2 Performance evaluation of mechanically switched capacitor bank and TCR for incremental load model

An incremental load model is shown in fig. 6.9. It is considered for joint performance evaluation of capacitor bank switching in binary sequential with TCR. A SIMULINK model fig. 6.10 has been developed and different performance parameters are evaluated.

The following performance parameters are evaluated through simulation.

1. Switching transients of the capacitor currents $I_{C_0}$, $I_{C_1}$, $I_{C_2}$, $I_{C_3}$ and $I_{C_4}$ are shown in fig. 6.11
2. The plot of phase voltages as load increases
3. Line currents
4. Line losses
5. Active power
6. Reactive power
The parameters listed 2 to 6 are shown in fig. 6.12. The subsequent fig. 6.13 to 6.18 gives following information for 6 different loading conditions.

1. Switching ON/OFF conditions of different capacitors
2. Different loading conditions
3. KVAr leading injected
4. TCR value required in KVAr lagging

![Incremental Load Model](image)

Fig. 6.9 Incremental load model
Fig. 6.10: Simulation of mechanically switched capacitor bank and TCR with incremental load model.
Fig. 6.11 Switching transients of capacitor bank with TCR
Fig. 6.12 Performance of system w.r.t. active, reactive powers, line losses and line voltages
Fig. 6.13 Switching transients for case study No.1
Fig. 6.14 Switching transients for case study No.2

<table>
<thead>
<tr>
<th>Case-2</th>
<th>Load Current (A)</th>
<th>P.F.</th>
<th>Kw.</th>
<th>KVAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
<td>0.72</td>
<td>31.9</td>
<td>30.8</td>
</tr>
</tbody>
</table>

ON — C0, C2, C3; OFF — C1, C4
KVAR injected 32.5; TCR required = 0.6
Fig. 6.15 Switching transients for case study No.3
Fig. 6.16 Switching transients for case study No.4
Case 5 Capacitor Charging Current
Ic1, Ic4, Ic5

ON – C1, C4, C5; OFF – C2, C3
KVAR injected 62.5; TCR

Fig. 6.17 Switching transients for case study No. 5
Fig. 6.18 Switching transients for case study No.6

Case 6 Capacitor Charging Current
Ic3, Ic4, Ic5

Case 6 Ic1

Case 6 Ic2

Case 6 Ic3

Case 6 Ic4

Case 6 Ic5

Case 6 Load Current
I65

ON – C1, C3, C4, C5
OFF—C2

KVAR injected 72.5; TCR required=0.8

ON – C1, C3, C4, C5
OFF—C2

KVAR injected 72.5; TCR required=0.8

P.F 0.8
Kw. 95.6
KVAR 71.7

Fig. 6.18 Switching transients for case study No.6
6.7 Synchronized Switching of the Capacitor Banks

(Thyristor Switched Capacitor Banks TSC):

As discussed earlier, static compensator can be replaced as synchronous condenser. It has lesser disadvantages, over other methods of compensation. It gives fine control over the range and gives faster response [44, 45, and 46]. Standard static compensator consists of controlled shunt elements. These elements are switched shunt capacitors and controllable reactor. This class of compensation is grouped into two basic categories such as TSC – TCR and MSC – TCR. In case of TSC and MSC capacitor bank is arranged in binary sequential switching.

![Fig.6.19 Binary sequential switching arrangement of capacitor bank](image)

Fig.6.19 shows the thyristor switched capacitor in binary sequential mode with five steps. The objective in the switching strategy is to be
developed through the simulation, such that in reactors to be employed must be of minimum size and to make the switching operation transient free for all combinations. The sequence employed for switching operation is as follows –

*Step - 1*: Capacitor $C_0$ is brought ON for two cycles and OFF for two cycles.

*Step – 2*: Capacitor $C_1$ is brought in when step 1 is OFF and kept ON for four cycles.

*Step – 3*: Capacitor $C_2$ is switched ON after 1 and 2 are kept ON for eight cycles.

*Step – 4*: Capacitor $C_3$ is kept ON at the instant when 1, 2, 3 are OFF and kept ON for 16 cycles.

*Step – 5*: Capacitor $C_4$ is kept ON at the instant when 1, 2, 3, and 4 are OFF and kept ON for 32 cycles.

The simulated results are shown in the fig. 6.20 and 6.21. for the various currents that are flowing in branches $B_0$, $B_1$, $B_2$, $B_3$ and $B_4$. And the total system compensating current

$$I_{TC} = I_{C0} + I_{C1} + I_{C2} + I_{C3} + I_{C4} \ldots \ldots \ldots [6.9]$$

is shown in Fig. 6.22

This simulation experiment gives smooth transition to make the resulting system compensating current practically transient free. In case the above switching conditions are completely satisfied, the inrush current limiting inductor $L$ may be minimized or even eliminated.

The above steps indicated for switching operation are incorporated version of the mode of switching reported in reference [41]. Absolutely
transient free switching operation could be achieved as can be seen from the aggregate waveform. The transition is smooth with no device being subjected to undue stresses.

Fig. 6.20 Switching of the capacitor current $I_{C0}$, $I_{C1}$ and $I_{C2}$
Fig. 6.21 Switching of the capacitor current $I_{C3}$ and $I_{C4}$

Fig. 6.22 Total current $I_{C0} + I_{C1} + I_{C2} + I_{C3} + I_{C4}$
6.7.1 TCR – Thyristor Controlled Reactor:

The fig. 6.23 shows the basic configuration of static compensator FC-TCR. In this case capacitor represents a switched capacitor bank either as mechanically switched or thyristor switched in binary sequential steps as explained earlier and \( L \) represents reactor with phase angle control [37, 42, 47].

The controllable range of TCR firing angle \( \alpha \) extends from \( 90^0 \) to \( 180^0 \). In case of ideal reactor of \( L \) Henry firing angle of \( 90^0 \) results in full conduction with continuous sinusoidal current flow. Also, as firing angle is varied from \( 90^0 \) to \( 180^0 \) current flows in discontinuous pulses symmetrically located in positive and negative half cycles as shown in the TCR, line and phase current waveforms. Once the conduction of thyristor starts, it can be stopped only when current reaches its natural zero called as line commutation. This is the case of ideal reactor with negligible resistance. Practically air cored reactors designed have an average resistance of \( 10 \) \( \Omega \) and inductance of 230 mH.
Considering resistance and inductance in the TCR circuit, the voltage distribution is shown in the fig. 6.24.

Source voltage \( v_s = V_m \sin(\omega t) \)

The TCR current equation is given by

\[
L \frac{di}{dt} + Ri - V_m \sin(\alpha t) = 0
\]

\[ \text{..........................}[6.10] \]

Solving this TCR current is

\[
i = \frac{V_m}{Z} \sin(\alpha t - \theta) + Ae^{-\frac{Rt}{L}}
\]

\[ \text{..........................}[6.11] \]

Where, \( Z = \sqrt{R^2 + X_L^2} \) and \( \theta = \tan^{-1} \frac{\omega L}{R} \)

The constant \( A \) can be found out from initial conditions i.e. \( i = 0 \) at \( \omega t = \alpha \) (thyristor firing angle)

\[
\therefore \quad i = 0 = \frac{V_m}{Z} \sin(\alpha - \theta) + Ae^{-\frac{Rt}{L}}
\]

\[
\therefore \quad A = -\frac{V_m}{Z} \sin(\alpha - \theta)e^{-\frac{R(\alpha)}{L(\omega)}}
\]

\[
\therefore \quad i = \frac{V_m}{Z} \sin(\alpha t - \theta) - \frac{V_m}{Z} \sin(\alpha - \theta) \times e^{\frac{R\alpha}{L(\omega)}} \times e^{-\frac{Rt}{L}}
\]

\[
= \frac{V_m}{Z} \left[ \sin(\omega t - \theta) - \sin(\alpha - \theta) \times e^{\frac{R(\alpha)}{L(\omega)}} \right]
\]

\[ \text{..........}[6.12] \]

The current \( i \) becomes zero at \( \angle \beta \) known as extinction angle.

Therefore, substituting \( i=0 \) and \( \alpha t = \beta \) we get,

\[
0 = \frac{V_m}{Z} \left[ \sin(\beta - \theta) - \sin(\alpha - \theta) \times e^{\frac{R(\alpha + \beta)}{L(\omega)}} \right]
\]

\[
\therefore \quad \sin(\beta - \theta) = \sin(\alpha - \theta) \times e^{\frac{R(\alpha + \beta)}{L(\omega)}}
\]
\[ \sin(\beta - \theta) = \sin(\alpha - \theta) \times e^{\frac{R}{\omega L}(\beta - \alpha)} \]

\[ (\beta - \theta) = \sin^{-1}\left[ \sin(\alpha - \theta) \times e^{\frac{R}{\omega L}(\beta - \alpha)} \right] \]

\[ \beta = \theta + \sin^{-1}\left[ \sin(\alpha - \theta) \times e^{\frac{R}{\omega L}(\beta - \alpha)} \right] \] ..........................[6.13]

Therefore, conduction period of each thyristor is \((\beta - \alpha)\).

The average value of thyristor current is \(I_A\)

\[ I_A = \frac{1}{2\pi} \int_{\alpha}^{\beta} i_t d(\omega t) \]

\[ I_A = \frac{V_m}{2\pi Z} \left[ \sin(\omega t - \theta) - \sin(\alpha - \theta) e^{\frac{R}{\omega L}(\omega t - \alpha)} \right] d(\omega t) \]

\[ I_{rms} = \left[ \frac{1}{2\pi} \int_{\alpha}^{\beta} i_t^2 d(\omega t) \right]^{0.5} \]

\[ I_{rms} = \frac{V_m}{2\pi Z} \left[ \int_{\alpha}^{\beta} \left( \sin(\alpha - \theta) - \sin(\alpha - \theta) e^{\frac{R}{\omega L}(\omega t - \alpha)} \right)^2 d(\omega t) \right]^{0.5} \] ..........................[6.14]

The currents through Th1 and Th2 are same and have the same rms value.

The rms value of the load current

\[ I_L = \left( 2I_r^2 \right)^{0.5} = \sqrt{2} I_r \]

The rms output voltage across inductor is given by

\[ V_L = \frac{1}{\pi} \int_{-\alpha}^{\beta} \left[ V_m^2 \sin^2(\omega t) \right]^{0.5} d(\omega t) \] ..........................[6.15]

\[ = \left[ \frac{V_m^2}{\pi} \int_{-\alpha}^{\beta} \left\{ \frac{1 - \cos 2\omega t}{2} d(\omega t) \right\} \right]^{0.5} \]
\[ V_m \left[ \frac{1}{2\pi} \left\{ (\beta - \alpha) + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2} \right\} \right]^{0.5} \]

and

\[ I_L(\alpha) = \frac{V_L}{Z} = \frac{V_m}{\sqrt{R^2 + X_L^2}} \left[ \frac{1}{2\pi} \left\{ (\beta - \alpha) + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2} \right\} \right]^{0.5} \]

The following observations are important.

i) If \( \alpha = \theta \) i.e. firing angle = phase angle

\[ \sin(\beta - \theta) = \sin(\beta - \alpha) = 0 \]

and conduction angle = \( \beta - \alpha = \pi \)

ii) Conduction angle should not exceed \( \pi \)

The range of control angle \( \alpha \) is \( \theta \leq \alpha \leq \pi \)

\[ I_1(\alpha) = \frac{V_L}{Z} = V_m Y_{TCR(\alpha-\theta)} \]

Where, \( Y_{TCR(\alpha-\theta)} = Y_{Max} \left[ \frac{1}{2\pi} \left\{ (\beta - \alpha) + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2} \right\} \right]^{0.5} \)  \[\text{[6.17]}\]

Thus the TCR acts like a variable admittance. By varying the firing angle \( \alpha \) the admittance changes and consequently fundamental current component which in turn gives rise to variation of reactive power absorbed by reactor. Hence if \( \alpha = \theta = 85.5 \) continuous conduction of current take place. However, if firing angle is increased beyond this, non-sinusoidal currents are generated and hence harmonics get introduced. The rms value of \( n^{th} \) order harmonic is expressed as a function of \( \alpha \) in the following equation.
\[ I_1(\alpha) = \frac{V}{Z} \times \frac{2}{\pi} \left[ -\frac{2 \cos(\alpha - \theta)}{n} \sin(n(\alpha - \theta)) + \frac{\sin(n-1)(\alpha - \theta)}{n-1} + \frac{\sin(n+1)(\alpha - \theta)}{n+1} \right] \]

Where, \( n = 2k+1 \) and \( k = 1, 2, 3, \ldots \).

\[ \text{.................}[6.18] \]

### 6.7.2 Three Phase TCR:

A three phase delta connected TCR with SSR is shown in the Fig. 2.5. With six different coils as follows. (Design data as given in section 2.2.2)

- \( L_1 = 310 \text{ mH} \)
- \( L_2 = 325 \text{ mH} \)
- \( L_3 = 329 \text{ mH} \)
- \( L_4 = 332 \text{ mH} \)
- \( L_5 = 316 \text{ mH} \)
- \( L_6 = 332 \text{ mH} \)

- \( R_1 = 10.6 \)
- \( R_2 = 11.23 \)
- \( R_3 = 10.7 \)
- \( R_4 = 10.9 \)
- \( R_5 = 10.87 \)
- \( R_6 = 11.5 \)

The reactor coil in the phase is split in two halves as shown in the Fig. 2.5. to prevent the full AC voltage appearing across the SSR. The entire Simulink model has been shown in the Fig. 6.32. The display of all the line and phase currents waveforms are carried out for firing angles \( \alpha = 99^0, 117^0, 135^0 \) and \( 153^0 \). Since all the inductors do not have exactly the same magnitudes, it results in slight asymmetrical operation. The Table 6.4 shows the various fundamental rms magnitudes as well as percentage of harmonic current generated with respect to fundamental component of the current for firing angle \( \alpha \) varying from \( 85^0 \) to \( 171^0 \). The plot of
magnitude of the entire harmonics Vs firing angle is depicted in Fig. 6.25 to 6.31.

The fig. 6.25 shows the fundamental line and phase current magnitude variation with respect to the firing angle $\alpha$. Due to this current KVAr compensation can be controlled.

From the Table 6.4 and Fig. 6.29(a) to 6.29(d) it is observed that because of asymmetrical operation all triplen harmonics are not cancelled but their magnitudes are reduced considerably. These are insignificant in normal circumstances. This asymmetrical operation results in generating a DC component which has been listed in the Table 6.4 also and shown in the fig. 6.26.

In addition to the harmonics, small in phase component of current (approximately 0.5 to 2%) of fundamental frequency flows in TCR which represents copper losses in TCR winding. The quality factor for TCR coil $Q_F = \frac{\omega L}{R} = 72$ is accounting for these losses which are listed in Table 6.4. The plot of active and reactive power variation with respect to firing angle $\alpha$ is also considered in fig. 6.28.

Fig. 6.27 shows the percent THD component variation with respect to firing angle $\alpha$. As the angle $\alpha$ approaches to $180^0$, the THD goes on increasing. It is observed that the safest region of TCR operation without significant harmonics is in between $90^0$ to $130^0$.

The fig. 6.30 shows all the line and phase odd harmonics. These odd harmonics have a significant magnitude beyond the firing angle $\alpha$ is equal to $130^0$. 

Fig. 6.31 shows all the even harmonics having a small magnitude upto $\alpha$ is equal to $130^0$. While beyond this angle even harmonics goes on increasing abruptly.

Also, all the phase and line current waveforms are plotted for various firing angle $\alpha = 90^0$ to $180^0$. These waveforms are shown in fig. 6.33, 6.35, 6.39 and 6.42. Also for same firing angle active and reactive power flows are shown in fig. 6.34, 6.36 and 6.43. It is observed that beyond angle $\alpha = 130^0$, these power waveforms are highly oscillated. Also, fig. 6.37, 6.38,, 6.40, 6.41, 6.44 and 6.45 gives FFT analysis for line and phase currents.

Considering all above aspects it can be concluded that TCR can be operated safely without generating much harmonics is in the range of $90^0$ to $130^0$. 
<table>
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<tr>
<th>Sr. No.</th>
<th>Firing Angle ($\alpha$)</th>
<th>Fundamental Current</th>
<th>D. C. Current Component</th>
<th>THD</th>
<th>H2%</th>
<th>H3%</th>
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<td>Phase</td>
<td>Line</td>
<td>Phase</td>
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<td>Line</td>
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Table 6.4 Simulated Results of TCR for various firing angle (\( \alpha \)) (Continued …)

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<th>Phase</th>
<th>Line</th>
<th>Phase</th>
<th>Line</th>
<th>Phase</th>
<th>Line</th>
<th>Phase</th>
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<th>Reactive Power</th>
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<td>0.8</td>
<td>0.59</td>
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<td>1.9</td>
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Fig. 6.25 Fundamental component of line & phase current for TCR

Fig. 6.26 D. C. components of TCR
Fig. 6.27 Total THD components of TCR

Fig. 6.28 Active & Reactive power of TCR
Fig. 6.29(a) Triplen harmonics of TCR for H3

Fig. 6.29(b) Triplen harmonics of TCR for H6
Fig. 6.29(c) Triplen harmonics of TCR for H9

Fig. 6.29(d) Triplen harmonics of TCR for H12
Fig. 6.30(a) Odd harmonics of TCR for H5

Fig. 6.30(b) Odd harmonics of TCR for H7
Fig. 6.30(c) Odd harmonics of TCR for H11

Fig. 6.31(a) Even harmonics of TCR for H2
Fig. 6.31(b) Even harmonics of TCR for H4

Fig. 6.31(c) Even harmonics of TCR for H8
Fig. 6.31(d) Even harmonics of TCR for H10
Fig. 6.32 TCR simulation model

Fig. 6.33 Line and phase current for $\alpha = 99^0$
Fig. 6.34 Active and reactive power of TCR for $\alpha = 99^0$

Fig. 6.35 Line and phase current for $\alpha = 117^0$
Fig. 6.36 Active and reactive power for $\alpha = 117^0$

Fig. 6.37 Harmonic spectrum of line current for $\alpha = 117^0$
Fig. 6.38 Harmonic spectrum for phase current at $\alpha = 117^0$

Fig. 6.39 Line currents and phase currents at $\alpha = 135^0$
Fig. 6.40 Harmonic spectrum for line currents at $\alpha = 135^0$

Fig. 6.41 Harmonic spectrum for phase currents at $\alpha = 135^0$
Fig. 6.42 Line and phase current at $\alpha = 153^\circ$

Fig. 6.43 Active reactive power at $\alpha = 153^\circ$
Fig. 6.44 Harmonic Spectrum for phase currents at $\alpha = 133^0$.

Fig. 6.45 Harmonic spectrum for line current at $\alpha = 153^0$. 
6.8 Conclusions:

In this chapter extensive simulation studies, carried out on distribution feeder with the proposed shunt compensator are dealt with using MATLAB and SIMULINK. The distribution network is represented on equivalent basis referring to LV side. The choice of reactor parameters for minimizing the switching transient is considered by deriving the inrush current phenomenon and from the scheme of thyristor switched capacitor. In order to limit the transient currents for the 5 capacitor bank steps, values for resistor and series reactor are fixed based on the considerations for minimizing magnitude, the frequency and duration of the transient. An innovative switching mode is prescribed for switching of the entire capacitor bank steps one after the other practically transient free and the waveforms are presented. The thyristor controlled reactor in its three phase mode of operation for a continuously variable lagging reactive power is considered and the harmonic spectra for both line and phase current for $\alpha = 117^0, 135^0$ and $153^0$ have been presented. The TCR is connected in delta and hence the line side odd tripplen harmonics are minimum, as can be seen from the values given in Table 6.4.

The variation of reactive power using capacitor bank in 5 binary sequential steps in conjunction with TCR is analyzed. Variations in phase and line currents and real and reactive powers for selected values of firing angles are studied. The author in a latest paper [48] has reported the results for FC-TCR in a single phase case. On the other hand the study carried in this thesis is work deals with reactive power control over the full range using the combination of TCR and capacitor bank is binary sequential steps for a three phase balanced system. As can
be seen from the graphical portraits for line and phase currents, and active and reactive powers for different values of $\alpha = 99^0, 117^0, 135^0 \text{ and } 153^0$ the values are steady up to $135^0$, more stable at $117^0$ and somewhat fluctuating at $153^0$. Other notable features of a study are: switching operations are transient free, line side harmonics minimized; transition from one state to another takes place within half cycle and complete flexibility in the reactive power variation.