CHAPTER-3

3.1 SERIES REACTIVE POWER COMPENSATION

Series reactive power compensation consists of controlling the reactive impedance of a transmission line to control line power flow. Series capacitive impedance was initially introduced to decrease the total line reactance and thus increases the power on the line, by which total or effective utilization of the transmission line can made during general operation and during contingencies.

In the Late 1980's, the basic Thyristor Controlled Series Capacitor (TCSC) controller based on semiconductor switches was proposed to allow controllable series reactive power compensation. In this controller, one or more capacitor banks, each shunted with a thyristor-controlled reactor, are employed. The thyristor-controlled reactor variable current circulates through the capacitor bank affecting the compensating voltage, this current is a function of the conduction angle of the thyristor switch.

In Late 1980's, the use of the VSC in series reactive power compensation was proposed, leading to the SSSC controller. The SSSC can generate a controllable compensating capacitive or inductive voltage, which implies that the amount of transmittable power can be increased or decreased from the natural power flow. The SSSC output voltage is independent of the line current, as opposed to the voltage across the TCSC, which is a function of the line current that is a function of the transmission angle. Therefore, when the transmission angle changes, which varies in a power system, the compensating voltage of the TCSC also changes.

A voltage in series with the transmission line can be introduced to control the current flow and thereby the power transmissions from the sending end to the receiving end [44]. An ideal series compensator is represented by the voltage source Vc which is connected in the middle of a transmission line as shown in Fig. 3.1

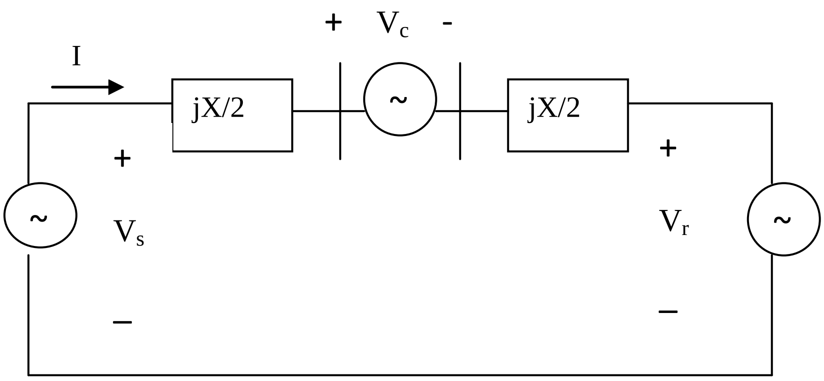

Fig 3.1 Two-Machine Power System

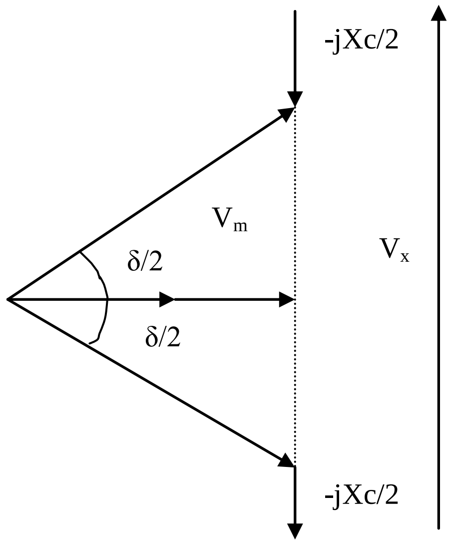

Fig 3.2 Phasor diagram of Series compensated Two machine Power System

From Fig 3.1

Let Vs = per phase sending end voltage magnitude

Vr = per phase receiving end voltage magnitude

Vc = per phase midpoint voltage magnitude which is applied in series

X = Transmission line impedance

δ = Phase angle between sending and receiving end voltage

Assuming Vs = Vr = Vc = V

The current flowing through transmission line is given by

$$I = \frac{Vs - Vr - Vc}{jX} \tag{3.1}$$

If the series applied voltage Vc is in quadrature with respect to the line current, the series compensator cannot supply or absorb active power. This is because phase angle between voltage and line current is 90^0 (i.e. cos 90^0=0). Thus the power at the source Vc terminal can be only reactive. This means that capacitive or inductive equivalent impedance may replace the voltage source Vc.

So equivalent transmission line impedance of compensated line can be represented by

$$X_{eq} = X - X_{comp} = X(1-r) \qquad (3.2)$$

Where $r = \frac{X_{COMP}}{X}$

and r is the degree of series compensation and its range is $0 \leq r \leq 1$ and X_{comp} is the series equivalent compensation reactance which is positive if it is capacitive and negative if it is inductive.

The magnitude of the current through the line is given by

$$I = \frac{Vs - Vr}{X_{eq}}$$

$$I = \frac{2V}{(1-r)X} \sin \delta / 2 \qquad (3.3)$$

The reactive power Qc at the source Vc terminal is given by

$$Qc = I^2 X_{comp} = \frac{2V^2}{x} \, x \, \frac{r}{(1-r)^2} (1 - \cos \delta) \qquad (3.4)$$

For capacitive compensation the line current leads the voltage Vc by 90^0 whereas for inductive compensation the line current lags the Vc by 90^0. Series capacitive impedance decreases the overall transmission line impedance and thereby increases the transmittable power. Whereas series inductive impedance increases the overall transmission line impedance, thus decreases the transmittable power.

3.2 INTRODUCTION

The TCSC varies the electrical length of the compensated transmission line with little delay [4]. Owing to this characteristic, it may be used to provide fast active power flow regulation. It also increases the stability margin of the system and has proved very effective in damping Sub-Synchronous Resonance (SSR) and power oscillation. The TCSC is the parallel combination of Thyristor Controlled reactor (TCR) and a fixed capacitor.

IMPACTS:

- **Balancing of load flows:** This enables the load flow on parallel circuits and different voltage levels to be optimized, with a minimum of power wheeling, the best possible utilization of the lines, and a minimizing of overall system losses at the same time.
- **Increasing of first swing stability, power oscillation damping, and voltage stability:** This enables a maximizing of system availability as well as of power transmission capability over existing as well as new lines. Thus, more power can be transmitted over fewer lines, with a saving of money as well as of environmental impact of the transmission link.
- **Mitigation of sub synchronous resonance risk:** Sub synchronous resonance (SSR) is a phenomenon which can be associated with series compensation under certain adverse conditions. The elimination of the risk of SSR even for the most onerous conditions means that the series compensation concept can be utilized in situations where it would otherwise not have been undertaken, thereby widening the usefulness of series compensation.
- **Power system interconnection:** Interconnecting of power systems is becoming increasingly widespread as part of power exchange between countries as well as regions within countries in many parts of the world. Such are found in the Nordic countries, Argentina, and Brazil.

3.3 PRACTICAL INSTALLATIONS OF TCSC WORLD WIDE

There are Nine TCSC installed in different locations around the world these are the major ones, five of them implemented in Asia making it maximum user of TCSC and Three in India. Table 3.1 shows the list of locations where TCSC are installed and the purpose [13], [19].

Table 3.1 List of TCSC installation

Year	Country	KV	Purpose	Place
1992	USA	230	To increase power transfer capability	Kayenta substation, Arizona
1993	USA	500	Controlling line power flow and increased loading	C.J.Slatt substation, Northern Oregon
1998	Sweden	400	Sub Synchronous Resonance mitigation	Stode substation

Year	Country	KV	Purpose	Place
1999	Brazil	500	To damp inter-area low freq (0.2 Hz) oscillation	Imperatriz and Sarra de Mesa
2002	China	500	Stability improvement, low frequency oscillation mitigation	Pinguo substation, State power south company, Guangzhou
2004	India	400	Compensation, Damping interregional power oscillation	Raipur substation
2004	China	220	Increase Stability margin, suppress low frequency oscillation	North-West China Power System
2001	India	400	Sub Synchronous Resonance mitigation	Kanpur - Ballabhgarh
2006	India	400	To increase power transfer capability, To enhance the transient stability	Purnea-Gorakhpur

3.3.1: Raipur substation, India [19]:

Power Grid Corporation of India Ltd (PGCIL) installed Two Thyristor Controlled Series Compensators (TCSC). The banks were installed on the Rourkela-Raipur double circuit 400 kV power transmission interconnector between the Eastern and Western regions of the grid. The length of the interconnector amounts to 412 km. The main purpose of this major AC interconnector is to enable export of surplus energy from the Eastern to the Western regions of India during normal operating conditions, and also during contingencies. The TCSC are located at the Raipur end of the lines. The TCSC enable damping of inter-area power oscillations between the regions, which would otherwise have constituted a limitation on power transfer over the interconnector. Dynamic simulations performed during the design stage, and subsequently confirmed at the commissioning and testing stage, have proved the effectiveness of the Raipur TCSC as power oscillation dampers. Furthermore, system studies performed showed no risk for Sub-Synchronous Resonance (SSR) in the Indian network. As a solution to these inter-area low frequency power swings, the studies proposed two fixed Series Capacitors, each rated at 40% degree of compensation of the Rourkela-Raipur line, and two TCSCs, each rated at 5% degree of compensation of the Rourkela-Raipur line. For power oscillation damping (POD), by control of the boost factor, the TCSCs introduce a component of modulation of the effective reactance of the power lines. By suitable system control, this modulation of reactance counteracts the oscillation of active power, thereby quickly damping it out. The Rourkela- Raipur TCSCs have proven effective as power oscillation dampers.

3.3.2: Imperatriz, Brazil [19]:

Since spring of 1999, Brazil has been operating a Thyristor-controlled Series Capacitor (TCSC) and five fixed Series Capacitors in the 500 kV interconnector between its northern and southern power systems. All in all, about 1.100 MVAR of series capacitors have been installed. The TCSC is located at Imperatriz at the northern end of the power corridor connecting the two systems which were previously not interconnected. Feasibility studies had been performed regarding the interconnection of the two systems, and a decision was made to go ahead and build the transmission corridor. Both AC and DC alternatives were assessed, and decided in favor of the AC option. It consists of a single 500 kV compact circuit (subsequently doubled), more than 1.000 km long and series compensated in several places along the line. Operation began in 1998. The power transmission capability of the corridor is 1.300 MW. The TCSC at Imperatriz, the first of its kind to be installed in Latin America, has the task of damping low-frequency inter-area power oscillations between the power systems on either side of the interconnection. These oscillations (0,2 Hz) would otherwise have constituted a hazard to power system stability and thereby to power transmission capability. The TCSC efficiently eliminates this obstacle to power transmission.

3.3.3: Bheramara, Bangladesh [19]:

Bangladesh's installed electric generating capacity in 2009 was 4000 MW, of which 94% was thermal (mainly natural-gas-fired), and the remainder hydroelectric, at 18 power stations. The Padma-Jamuna-Meghna river system divides Bangladesh into two zones, East and West. The East contains nearly all of the country's electric generating capacity, while the West, with almost no natural resources, must import power from the East. Electricity interconnection from the East to the West was accomplished in 1982 by a new, 230-kilovolt (kV) power transmission line. The vast majority of Bangladesh's electricity consumption takes place in the East, with the entire region west of the Jamuna River accounting for only 22% of the total Greater Dhaka alone consumes around half of Bangladeshi electricity.

Series compensation can be a useful tool for the power interconnection corridors between East and West Zones of Bangladesh. Analysis and survey by experts followed by proper placement of TCSC in the power grid of Bangladesh will improve the power transmission capacity as well as steady-state and dynamic stability of the long AC power transmission system. Bangladesh is also going to buy 500 MW power from different power plants of India. The power will be transmitted through a 400 KV switching station and a 400 KV single circuit line. Power Grid Corporation of India Ltd (PGCIL) will also construct a 400KV double circuit line stretching from India's Bahrampur to Bheramara in Bangladesh. If Two TCSC are installed on the double circuit 400 kV power transmission interconnector between the sending and receiving end of the grid, it will enable surplus energy during normal operating conditions, and also during contingencies.

3.5 OPERATING PRINCIPLE OF TCSC

The basic thyristor-controlled series capacitor scheme consists of the series compensating capacitor shunted by a thyristor-controlled reactor. In practice, several TCSC modules may be connected in series to obtain the desired voltage rating and operating characteristic as shown in Figure 3.3. Another common configuration is to use a hybrid of a conventional series capacitor and TCSC module connected in series. Under this arrangement, the conventional series capacitor is used for line compensation and the TCSC is only utilized during contingencies [25].

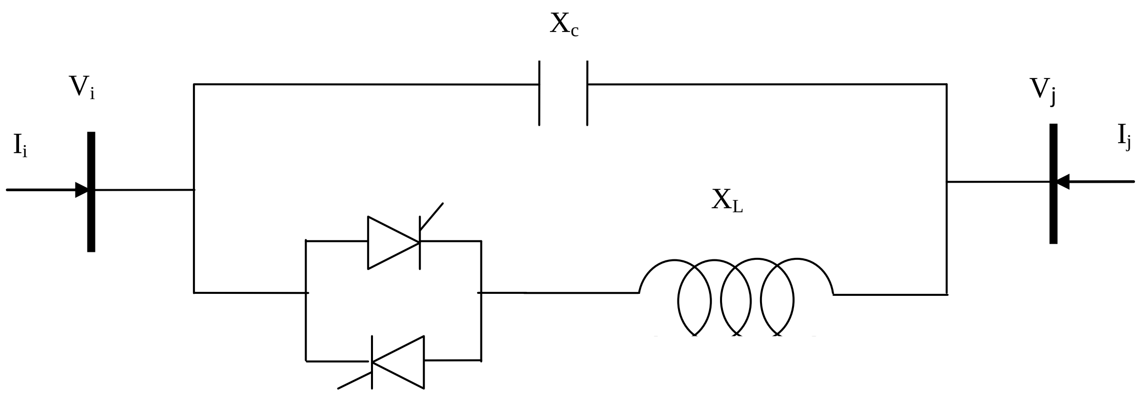

Fig 3.3 A Basic TCSC Module

The variable reactance of the TCSC is achieved by varying the firing angle (α) of the thyristor-controlled reactor. The figure 3.4 shows the typical operating region of the TCSC with the resonance point between inductive and capacitive region .The number of resonance points possible and the method to increase the capacitive region is described in TCSC Reactance analysis. The reactance equation when observed shows that the denominator becomes zero for some values of frequency thereby causing capacitive and inductive reactance to be same and hence resonance condition occurs .The number of resonance points is governed by the selection of 'K' value in the X_{TCSC} expression which is derived in next sections.

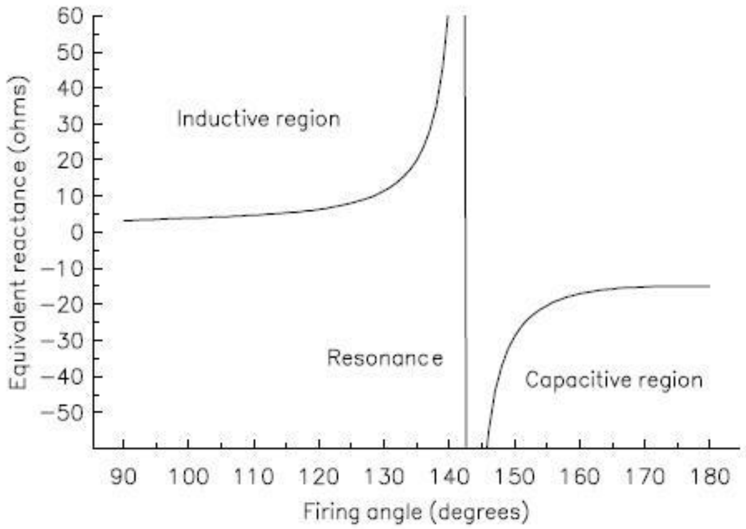

Fig 3.4 Operating region of TCSC Reactance

3.5.1 DIFFERENT OPERATING MODES OF TCSC

The TCSC has three basic modes of operation:

- Thyristor blocked,
- Thyristor bypassed and
- Vernier operation.

Thyristor blocked:

Under this mode of operation, the thyristors valves are not conducting any current (hence, the term blocked). The TCSC net reactance is effectively the capacitive reactance of the capacitor, $-jX_C$. This mode occurs when the firing angle is $180^{0,}$ Figure 3.5 shows that no current passes through the thyristors, hence $I_{LINE} = I_{TCSC}$ and $I_{TCR}=0$.

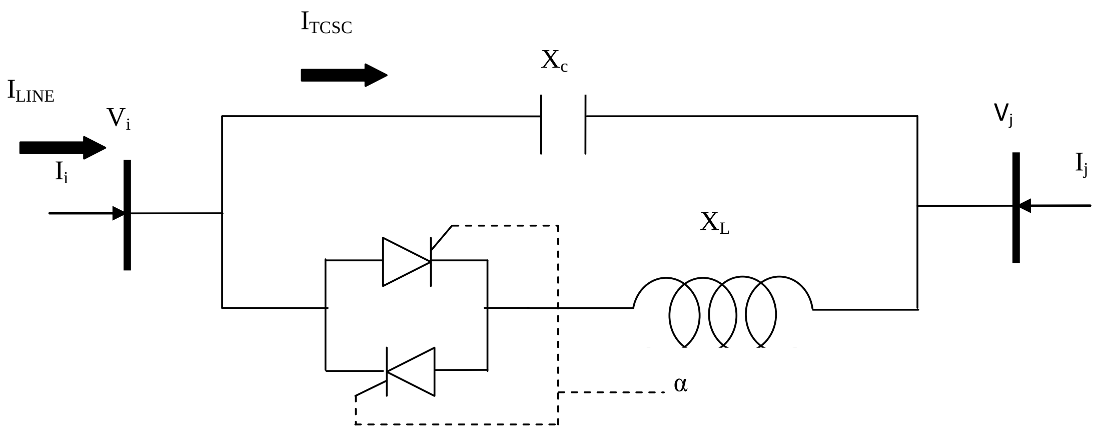

Fig 3.5 TCSC operating under Thyristor blocked mode

Thyristor bypassed:

Under this mode of operation, the thyristor valves are gated for full conduction. The resulting net TCSC reactance is effectively the parallel combination of $-jX_C$ and jX_{TCR}. This mode occurs when the firing delay angle α, is equal to 90°. In practice, some current also flows through the Capacitor during bypassed operation, but most flows through the thyristor valves and reactor because it is a much lower impedance path. Figure 3.6 shows the flow of current under this mode. Depending on the design of the TCSC, most of the line current flows through the TCR branch and hence $I_{LINE} = I_{TCR}$ and $I_C=0$.

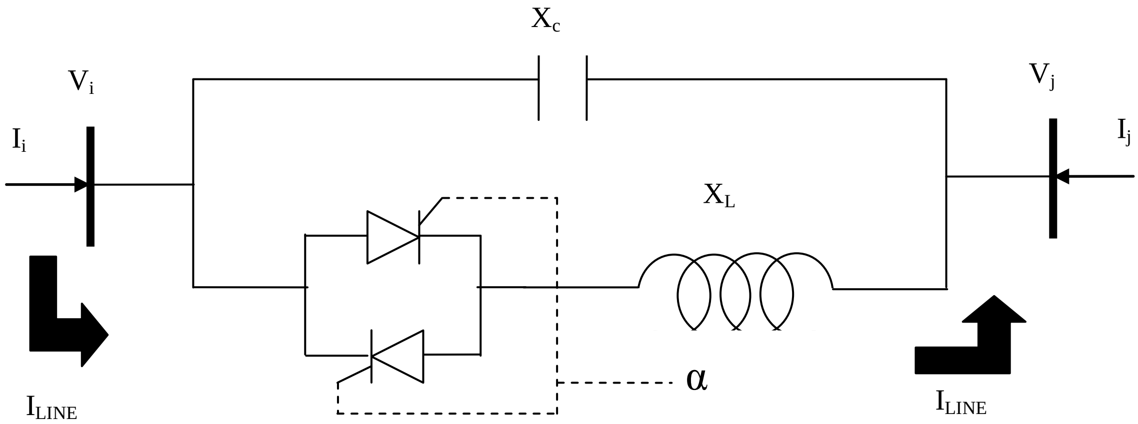

Fig 3.6 TCSC operating under Thyristor bypassed mode

Vernier Operation:

This is the most common mode of operation. The vernier operation mode is subdivided into two categories, namely: inductive vernier mode and capacitive Vernier mode. Under vernier mode, the TCSC reactance can be calculated for each firing angle based on the equation below, equation 3.5, which defines the TCSC circuit reactance as a function of the firing angle:

$$X_{TCSC} = \frac{\pi X_{TCR}}{(\sigma - \mathrm{Sin}\sigma) + \pi \frac{X_{TCR}}{X_C}} \qquad (3.5)$$

Where

$\sigma = 2\pi - 2\alpha$ (conduction angle)

X_{TCR} = TCR reactance

X_C = fixed capacitor bank reactance

In this mode, the thyristor valves are gated near the end of each half cycle in a manner that can circulate a controlled amount of inductive current through the capacitor, thereby increasing the effective capacitive reactance of the module. Figure 3.7 shows the distribution of currents under capacitive vernier operation mode. From the same figure above, the circuit appears somewhat like that of a parallel L-C tank circuit with variable inductance, such a circuit has a reactance as seen by the AC system at the TCSC terminals

$$X_{TCSC}(\alpha) = \frac{jX_{TCR}(\alpha) * jX_C}{jX_C - jX_{TCR}(\alpha)} \tag{3.6}$$

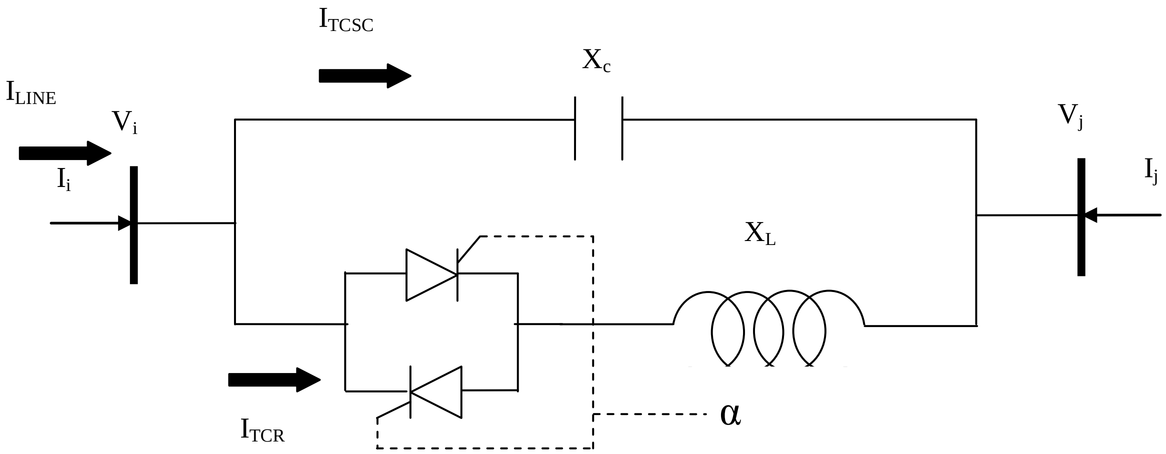

Figure 3.7: TCSC module under capacitive vernier operation mode

3.6 ANALYSIS OF TCSC

The TCSC varies the electrical length of the compensated transmission line with little delay. Owing to this characteristic, it may be used to provide fast active power flow regulation. It also increases the stability margin of the system and has proved very effective in damping Sub-Synchronous Resonance (SSR) and power oscillation. The TCSC is the parallel combination of Thyristor Controlled reactor (TCR) and a fixed capacitor. So before discussing in details about TCSC, let us discuss about TCR.

3.6.1 THYRISTOR-CONTROLLED REACTOR (TCR) [1, 2]

It consists of a fixed reactor of inductance L and a bidirectional thyristor switch SW as shown in Fig 3.8. The current through the reactor can be controlled from zero (when the switch is open) to maximum (when the switch is closed) by varying the firing angle α of the thyristor. Thus the conduction angle of the thyristor is $\sigma = \pi - 2\alpha$. If the switch is permanently closed when α =0, then it has no effect of the inductor current.

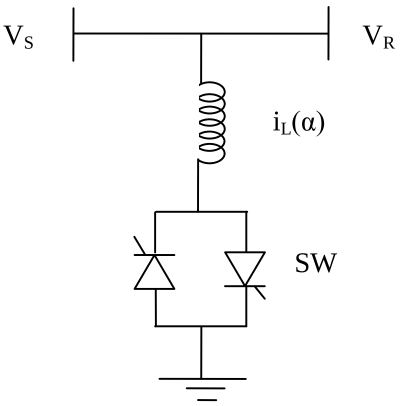

Fig 3.8 Thyristor Controlled Reactor (TCR)

Let the supply voltage v (t) = Vm cos wt = $\sqrt{2}V\cos wt$.

Where Vm = peak voltage of supply voltage

Thus instantaneous inductor current can be expressed as a function of α as follows:

$$i_L(t) = \frac{1}{L}\int_{\alpha}^{wt} v(t)dt = \frac{1}{wL} Vm \,|\sin wt\,|_{\alpha}^{wt} = \frac{Vm}{wL}(\sin wt - \sin\alpha) \qquad (3.7)$$

This is valid for $\alpha \le wt \le \pi - \alpha$

From the equation (6.1) it is clear that $i_L(t)$ is maximum when α =0 and it is zero when α = $\pi/2$.

The fundamental root-mean-square (rms) current of the reactor can be found as

$$I_{Lf}(\alpha) = \frac{V}{wL}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right) \qquad (3.8)$$

Which is α (firing angle) dependent

Thus admittance for the shunt compensator for fundamental current is given by

$$Y_L(\alpha) = \frac{I_{LF}}{V} = \frac{1}{wL}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right) \qquad (3.9)$$

The impedance of compensator which is dependent on α.

$$Z_L(\alpha) = 1/Y_L(\alpha) = \frac{V}{I_{LF}} = \frac{wL}{\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)} \qquad (3.10)$$

3.6.2 ANALYSIS OF THE TCSC EQUIVALENT CIRCUIT

The analysis of TCSC operation [3, 21] in the vernier-control mode is performed based on the simplified TCSC circuit as shown in Fig. 3.9.

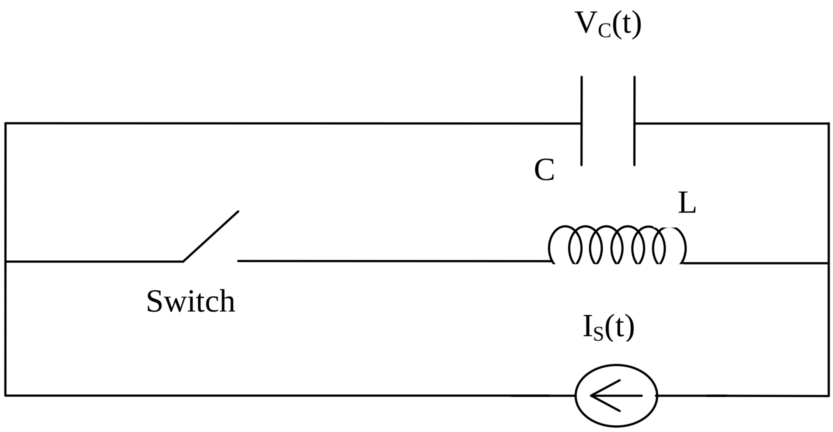

Fig 3.9 Simplified TCSC Circuit

From the above Fig

Is (t) = Transmission line current which is modeled as an external current source and assumed to be sinusoidal current.

$I_T(t)$ = Thyristor-valve current

u = switching variable

when u = 1, thyristor is conducting i.e. switch S is closed

when u = 0, thyristor is blocked i.e. switch S is open

C = Fixed capacitor used in parallel with TCR circuit

L = Inductance used in series with Thyristor bidirectional switch

Vc (t) = voltage across the capacitor C

The current through the fixed capacitor C is expressed as

$$C\frac{dV_C}{dt} = I_S(t) - I_T(t).u \quad (3.11)$$

The current through thyristor is given by

$$L\frac{dI_T}{dt} = V_C.u \quad (3.12)$$

Let the line current Is(t) be represented by

$$I_S(t)=I_m \cos t\, wt \quad (3.13)$$

In equidistant firing-pulse control, for balanced TCSC operation, the thyristors are switched on twice in each cycle of the line current at instants t_1 and t_3 and these are given by

$$t_1 = -\frac{\beta}{w}$$
$$t_3 = \frac{\pi - \beta}{w}$$

Where β is the angle of advance (before the forward voltage becomes zero) or,

$$\beta = \pi - \alpha; \qquad 0 < \beta < \beta_{max}$$

where α is the firing angle of the thyristor. This angle is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instants t_2 and t_4, defined as

$$t_2 = t_1 + \frac{\sigma}{w}$$
$$t_4 = t_3 + \frac{\sigma}{w}$$

where σ is the conduction angle, which is assumed to be the same in both the positive and the negative cycle of conduction. Also

$$\sigma = 2\beta$$

Solving the TCSC equations (3.11) – (3.12) result in the steady state thyristor current I_T.

$$i_T(t) = \frac{K^2}{K^2 - 2} I_m \left[\cos wt - \frac{\cos\beta}{\cos K\beta} \cos w_r t\right]; -\beta \leq wt \leq \beta \qquad (3.14)$$

where w_r is called resonance frequency and is given by

$$w_r = \frac{1}{\sqrt{LC}}$$

$$K = \frac{w_r}{w} = \sqrt{\frac{X_C}{X_L}}$$

where X_c and X_L are capacitive reactance and inductive reactance respectively.

The steady state capacitor voltage at the instant $wt = -\beta$ is expressed as

$$V_{C1} = \frac{ImX_C}{K^2 - 1}(\sin\beta - K\cos\beta \tan K\beta)$$

At $wt = \beta$, $i_T = 0$, the capacitor voltage is given by

V_c (wt = β) v_{c2} = -vc1

Finally the capacitor voltage is given by

$V_C(t) = \frac{Im X_C}{K^2-1}\left(-\sin wt + K\frac{\cos\beta}{\cos K\beta}\sin w_r t\right)$;-β≤wt≤β

$V_C(t) = V_{C2} + ImX_C(\sin wt - \sin\beta);\ \beta < wt < \pi - \beta$

Because the non-sinusoidal capacitor voltage, Vc, has odd symmetry about the axis wt = 0, the fundamental component, V_{CF}, is obtained as

$$V_{CF} = \frac{4}{\pi}\int_0^{\pi/2} vc(t)\sin wtd(wt) \qquad (3.15)$$

The equivalent TCSC reactance is computed as the ratio of V_{CF} to I_m :

$$X_{TCSC} = \frac{V_{CF}}{Im} - X_C - \frac{X_C^2}{X_C - X_L}\frac{2\beta + \sin 2\beta}{\pi} + \frac{4X_C^2}{X_C - X_L}\frac{\cos^2\beta}{K^2-1}\frac{(K\tan K\beta - \tan\beta)}{\pi}$$

(3.16)

If we apply $\beta = \pi - \alpha$, in equation (3.16) the reactance of TCSC becomes as :

$$X_{TCSC} = -X_C + C_1\{2(\pi-\alpha) + \sin[(\pi-\alpha)]\} - C_2\cos^2(\pi-\alpha)\{K\tan[K(\pi-\alpha)] - \tan(\pi-\alpha)\} \qquad (3.17)$$

Where

$$C_1 = \frac{X_C + X_{LC}}{\pi}$$

$$C_2 = \frac{4X_{LC}^2}{\pi X_L}$$

$$X = \sqrt{\frac{X_C}{X_L}}$$

$$X_{LC} = \frac{X_C * X_L}{X_C - X_L}$$

The above mentioned equation can also be written as shown below by eliminating the term X_L and Substituting the other values as usual.

$$X_{TCSC} = -X_C + \frac{K^2 X_C}{\pi(K^2-1)}[2(\pi-\alpha) + Sin2(\pi-\alpha)] + \frac{4K^2 X_C Cos^2(\pi-\alpha)}{\pi(K^2-1)^2}[K \tan\{K(\pi-\alpha)\} - Tan\,(\pi-\alpha)] \quad (3.18)$$

In the above expression Selection of 'K' value is of critical importance while modeling the TCSC and the range is between 2.4-2.7 , maximum K value for a system can be 3[37].fig 3.10 and Fig 3.11 show the occurrence of multiple resonance points.

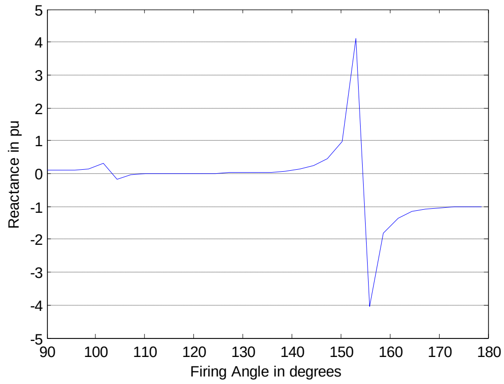

Fig 3.10 plot for K=3.5

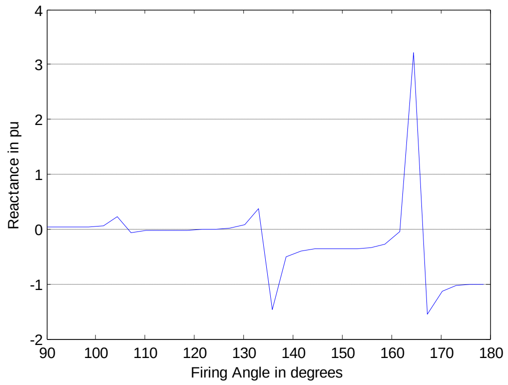

Fig 3.11 plot for K=6