Notes on

Thyristor and GTO thyristor

Controlled series Capacitors (TCSC and GCSC)

(Unit 3)

EE-8th Sem

Subject:- Flexible AC Transmission System

Content

4 Thyristor and GTO Controlled Series Capacitor

Chapter 4

Thyristor and GTO Controlled Series Capacitor

4.1 Introduction

Series Capacitors have been used in long distance EHV transmission lines for increasing power transfer. The use of series capacitors is generally the most economic solution for enhancing power flow. However, the problem of SSR has deterred system planners from going in a big way for series compensation. While the use of shunt capacitors don't have the problem of SSR, they have drawbacks of their effectiveness being dependent largely on their location. Even when a shunt capacitor is located at the midpoint of a long line, it requires much larger rating to achieve the same level of increase in power transfer as a series capacitor. It was shown in chapter 2 that the ratio of the two ratings is given by

$$\frac{Q_{se}}{Q_{sh}} = \tan^2\left(\frac{\delta_{\max}}{2}\right) \tag{4.1}$$

where Q_{se} and Q_{sh} are the ratings of the series and the shunt capacitor respectively, $\delta_{\max}$ is the maximum angular difference between the two ends of the line. For $\delta_{\max}$ in the range of 30°–40°, Q_{se} varies from 7% to 13% of Q_{sh}. Although the series capacitors tend to be twice as costly as shunt capacitors (per unit var), they are still cheaper to use. In addition, the location of a series capacitor is not critical.

The use of thyristor control to provide variable series compensation makes it attractive to employ series capacitors in long lines. A major advantage is that the SSR problem (Torsional Interaction) is significantly reduced. The feasibility of fast control of thyristor valves enables the improvement of stability and damping of oscillations using appropriate control strategies.

The first demonstration project of TCSC was commissioned in 1991 at a 345 kV Kanawha River Substation in West Virginia, U.S.A. under American Electric Power Company. This was a test installation of thyristor switches in one phase for rapid switching of series capacitor segment and was supplied by ABB, Sweden.

In October 1992, the first three phase TCSC was installed at 230 kV Kayenta Substation in Arizona under Western Area Power Administration (WAPA). Here a 15Ω capacitor bank is connected in parallel with a TCR and permits a smooth and rapid control of (capacitive) reactance between 15 and 60Ω through phase control of TCR.

A larger prototype three phase TCSC was installed in 1993 at 500 kV Slatt Substation in Oregon under Bonneville Power Administration (BPA). The project was sponsored by Electric Power Research Institute (EPRI) and the equipment was developed by General Electric in U.S.A. Here, six modules of TCSC are connected in series and controlled to provide a variation in impedance from $+1.4\Omega$ to -16Ω.

In Sweden, a long, series-compensated 400 kV transmission line connected to a nuclear power station was chosen to install TCSC by splitting the existing series capacitor into two parts – a fixed capacitor and a Thyristor Controlled Series Capacitor at Stode Station [23]. This was necessitated by an SSR problem that caused repeated triggering of protections. The TCSC allowed the existing level of compensation to be continued without any SSR problems.

4.2 Basic Concepts of Controlled Series Compensation

By controlled series compensation, we imply dynamic control of the degree of series compensation in a long line. This can be achieved in two ways as

1. Discrete control using TSSC (Thyristor Switched Series Capacitor)
2. Continuous control using
    (a) TCSC or
    (b) GTO thyristor Controlled Series Capacitor (GCSC)

The configuration using TSSC is shown in Fig. 4.1(a). Here, the thyristor switch is either off or on continuously. To insert the capacitor, the switch is turned off while it is turned on to bypass the capacitor. A major problem with this configuration is that the SSR characteristics of the TSSC are no different from that of the fixed capacitor. Also, the full line current flows through the thyristor switch when it is on. Thus, this configuration is not common.

The configuration using TCSC is shown in Fig. 4.1(b). Here, a TCR is used in parallel with a fixed capacitor to enable continuous control over the series compensation. Although harmonics are present in steady state with

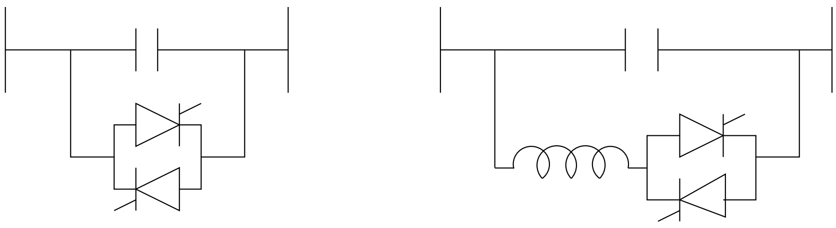


Figure 4.1: Configurations of series compensation

partial conduction of thyristor switches, the TCSC can be used to mitigate SSR. In addition, TCSC provides inherent protection against over voltages.

The configuration of GCSC in similar to what in shown in Fig. 4.1(a) except that the switch is made of GTO thyristors to permit turn off capability when current is flowing through the switch. This enables, phase control to be applied to the capacitor in a similar fashion as in a TCR. As a matter of fact, the GCSC is a dual of the TCR in that the voltage across the capacitor can be controlled by controlling the conduction (or turn-off) angle of the GTO thyristor switch.

Although continuous control of the capacitor is possible in both TCSC and GCSC, the latter is yet to be applied in practice. In comparing TCSC with GCSC, the former has the advantages of (a) lower costs due to the requirements of conventional thyristors as opposed to GTO and (b) boost in the capacitor voltage provided by the discontinuous conduction of the TCR (Note that TCSC is formed by the parallel combination of a fixed capacitor and a TCR in each phase). The TCSC was also labeled as RANI (Rapid Adjustment of Network Impedance) in a paper by Vithayathil *et al.* [6].

TCSC is a mature technology available for application in AC lines of voltage up to 500 kV. This chapter will concentrate mainly on TCSC except for a section on GCSC.

Consider the equivalent circuit of the TCSC modeled as a capacitor in parallel with a variable inductor (as shown in Fig. 4.2(a)). The impedance of TCSC (Z_{TCSC}) is given by

$$Z_{\text{TCSC}} = \frac{-jX_C \cdot jX_{TCR}}{j(X_{TCR} - X_C)} = \frac{-jX_C}{\left(1 - \frac{X_C}{X_{TCR}}\right)} \tag{4.2}$$

The current through the TCR (I_{TCR}) is given by

$$\hat{I}_{TCR} = \frac{-jX_C}{j(X_{TCR} - X_C)}\hat{I}_L = \frac{\hat{I}_L}{\left(1 - \frac{X_{TCR}}{X_C}\right)} \tag{4.3}$$

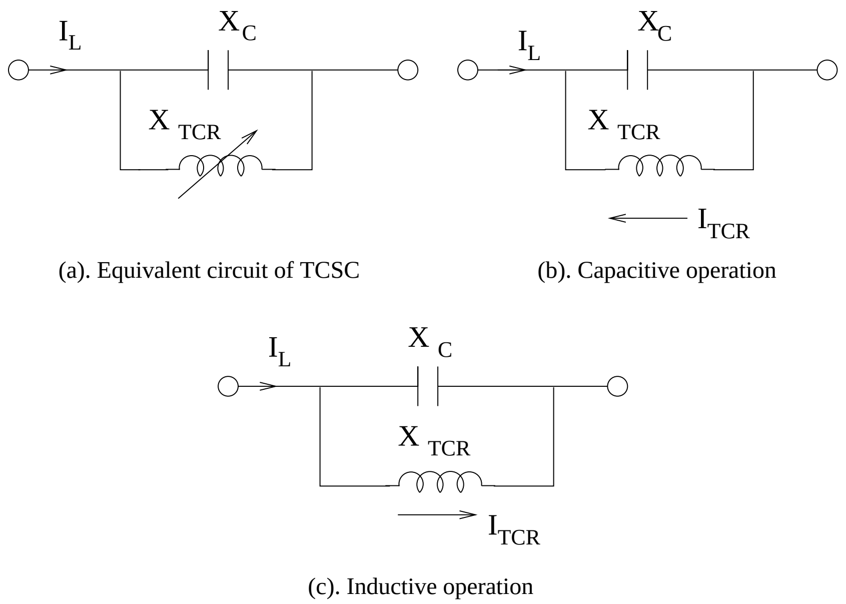


Figure 4.2: TCSC circuit representation

Since the losses are neglected, the impedance of TCSC is purely reactive. The capacitive reactance of TCSC is obtained from (4.2) as

$$X_{\text{TCSC}} = \frac{X_C}{\left(1 - \frac{X_C}{X_{TCR}}\right)} \tag{4.4}$$

Note that X_{TCSC} is capacitive as long as $X_C < X_{TCR}$. $X_{TCR} = \infty$ when the thyristors are blocked and $I_{TCR} = 0$. For the condition when $X_C < X_{TCR}$, $\hat{I}_{TCR}$ is 180° out of phase with the line current phases $\hat{I}_L$. In other words, $\hat{I}_L$ is in phase with $-\hat{I}_{TCR}$.

For the condition where $X_C > X_{TCR}$, the effective reactance of TCSC (X_{TCSC}) is negative implying that it behaves like an inductor. In this case, $\hat{I}_L$ and $\hat{I}_{TCR}$ are in phase. The capacitive and the inductive operation of TCSC is shown in Fig. 4.2(b) and (c) respectively.

Example 1

Compute $\frac{X_{\text{TCSC}}}{X_C}$ and $\frac{I_{TCR}}{I_L}$ if (a) $X_{TCR} = 1.5X_C$ and (b) $X_{TCR} = 0.75X_C$.

(a) From Eqs. (4.4) and (4.3), we get substituting the values

$$\begin{aligned} \frac{X_{\text{TCSC}}}{X_C} &= \frac{1}{1 - \frac{2}{3}} = 3.0 \\ \frac{I_{TCR}}{I_L} &= \frac{1}{1.5 - 1} = 2.0 \end{aligned}$$

(b) For $X_{TCR} = 0.75X_C$,

$$\begin{aligned}\frac{X_{\text{TCSC}}}{X_C} &= \frac{1}{1-\frac{4}{3}} = -3.0 \\ \frac{I_{TCR}}{I_L} &= \frac{1}{1-0.75} = 4.0\end{aligned}$$

It is interesting to observe that even though the magnitude of the TCSC reactance is same in both (capacitive and inductive) cases, the current through the TCR is more for the inductive operation (twice that for the capacitive operation). This indicates that thyristor ratings determine the maximum limit on the X_{TCSC} for the inductive operation.

The TCR injects also harmonics in addition to the fundamental frequency current. This distorts the capacitor voltage which does not remain sinusoidal even though the line current remains approximately sinusoidal. (Note that the presence of harmonics in the capacitor voltage can result in harmonics in the line current, but for long lines, these can be neglected). It is also obvious that inductive operation of the TCSC results in higher voltage harmonics across the capacitor.

The presence of the voltage harmonics invalidate the expression for the susceptance of TCR derived in chapter 3, (assuming sinusoidal voltage). This expression is repeated below for ready reference.

$$B_{TCR} = \frac{\sigma - \sin\sigma}{\pi X_L} \tag{4.5}$$

Eq. (4.5) cannot be used for the calculation of X_{TCSC} as a function of the conduction angle (σ). A new expression for X_{TCSC} will be derived in section 4.4.

It is to be noted that $X_L < X_C$. A typical value of $\frac{X_L}{X_C}$ is 0.16. This results in protection against over-voltages due to fault currents by increasing the conduction angle to 180°. It is obvious that there is a value of the conduction angle (σ_{res}) for which $X_{TCR} = X_C$ and the TCSC reactance is maximum (theoretically infinite when losses are neglected). It is necessary to ensure that the conduction angle stays within limits even during transient operation. The ratio of $\frac{X_{TCSC}}{X_C}$ is kept below a limit (say 3.0 in the capacitive region). The actual value of the limit is also a function of the line current to ensure that the capacitor voltage rating is not exceeded. In general, there are three voltage ratings based on the current ratings.

1. V_{rated} is the maximum continuous voltage across the TCSC. This must be more than $X_C * I_{\text{rated}}$ to allow for continuous modulation with vernier operation (typically with 15 % margin)

2. V_{temp} is the maximum temporary voltage ($X_C I_{\text{temp}}$) where I_{temp} is the temporary line current (typically $1.35 \times I_{\text{rated}}$) that has a typical duration of 30 minutes.
3. V_{tran} is the maximum voltage required during transient swings. This must be equal to or more than $X_C \times I_{\text{tran}}$ where I_{tran} is the maximum line current for which the thyristor control is not affected by protective considerations. Typically, $I_{\text{tran}} = 2 \times I_{\text{rated}}$ and lasts for a duration of 3 to 10 seconds.

4.3 Operation of TCSC

A single line diagram of a TCSC is shown in Fig. 4.3 which shows two modules connected in series. There can be one or more modules depending on the requirement. To reduce the costs, TCSC may be used in conjunction with fixed series capacitors.

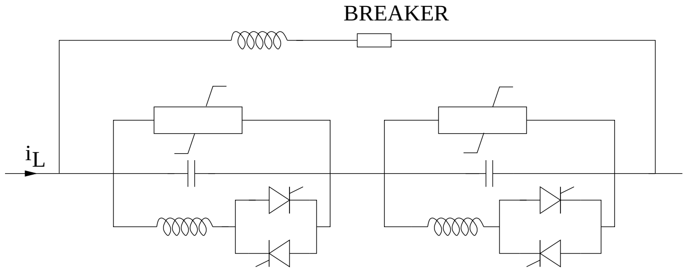


Figure 4.3: Single Line Diagram of a TCSC

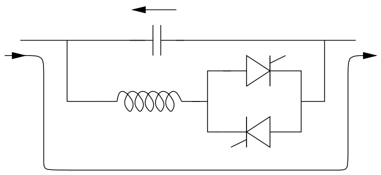
Each module has three operating modes (see Fig. 4.4).

(a) Bypassed

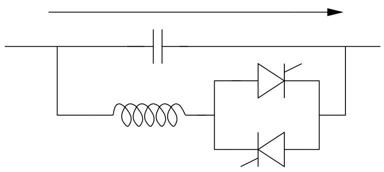
Here the thyristor valves are gated for 180° conduction (in each direction) and the current flow in the reactor is continuous and sinusoidal. The net reactance of the module is slightly inductive as the susceptance of the reactor is larger than that of the capacitor. During this mode, most of the line current is flowing through the reactor and thyristor valves with some current flowing through the capacitor. This mode is used mainly for protecting the capacitor against overvoltages (during transient overcurrents in the line). This mode is also termed as TSR (Thyristor Switched Reactor) mode.

(b) Inserted with Thyristor Valve Blocked

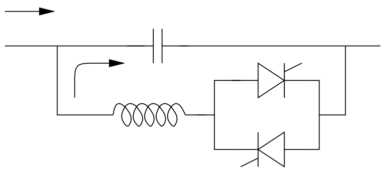
In this operating mode no current flows through the valves with the blocking of gate pulses. Here, the TCSC reactance is same as that of the fixed capaci-



(a) Bypassed



(b)Thyristor blocked



(c)Vernier operation

Figure 4.4: Operating Modes in a TCSC

tor and there is no difference in the performance of TCSC in this mode with that of a fixed capacitor. Hence this operating mode is generally avoided. This mode is also termed as waiting mode.

(c) Inserted with Vernier Control

In this operating mode, the thyristor valves are gated in the region of ($\alpha_{\min} < \alpha < 90°$) such that they conduct for the part of a cycle. The effective value of TCSC reactance (in the capacitive region) increases as the conduction angle increases from zero. $\alpha_{\min}$ is above the value of α corresponding to the parallel resonance of TCR and the capacitor (at fundamental frequency). In the inductive vernier mode, the TCSC (inductive) reactance increases as the conduction angle reduced from 180°.

Generally, vernier control is used only in the capacitive region and not in the inductive region.

4.4 Analysis of TCSC

To understand the vernier control operation of TCSC, it is necessary to analyze the TCSC circuit (see Fig. 4.5).

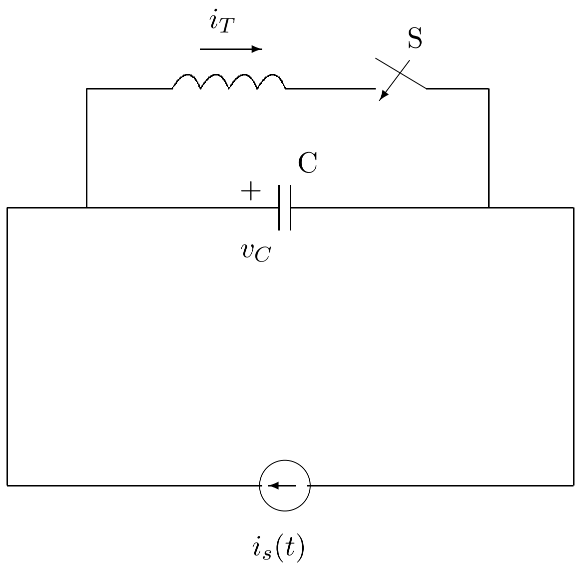


Figure 4.5: The TCSC Circuit

For simplicity, it is assumed that the line current is specified and can be viewed as a current source. The equations are

$$C\frac{dv_C}{dt} = i_s(t) - i_T \tag{4.6}$$

$$L\frac{di_T}{dt} = v_C u \tag{4.7}$$

where $u = 1$ when the switch is closed and $u = 0$ when it is open. The current in the thyristor switch and the reactor (i_T) is zero at the instant when the switch is opened. Note that when $u = 0$, and the initial current $i_T = 0$, it remains at the zero value until S is turned on and $u = 1$. The line current i_s is defined by,

$$i_s(t) = I_m \cos\omega t \tag{4.8}$$

It is convenient to measure the firing angle (α) form the zero crossing instant of the line current. It can be shown that the zero crossing of the capacitor voltage (v_C) coincides with the peak value of the line current in steady state. The range of α is from 0 to 90° corresponding to the conduction angle varying from 180° to 0°. The angle of advance (β) is defined as

$$\beta = 90^\circ - \alpha \tag{4.9}$$

which also varies from 0 to 90°. Fig. 4.6 shows the waveforms of $i_s(t), i_T(t)$ and $v_C(t)$ with delay angle (α), angle of advance (β) and conduction angle (σ) indicated.

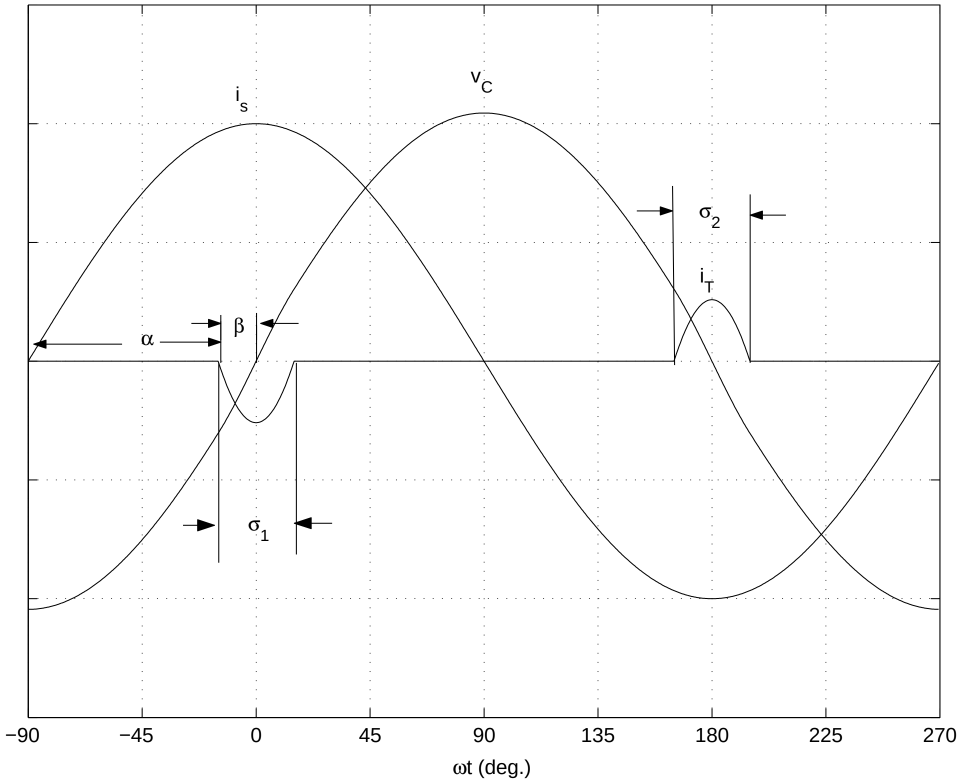


Figure 4.6: Waveforms of $i_s(t)$, $i_T(t)$, $v_c(t)$

The equations (4.6) and (4.7) can be solved if the switching instants are known. The switch, 'S' is turned on twice in a cycle (of the line current) at the instants (assuming equidistant gating pulses)

$$\left.\begin{array}{l} t_1 = \frac{-\beta}{\omega} \\ t_3 = \frac{\pi-\beta}{\omega} \end{array}\right\} \tag{4.10}$$

where $0 < \beta < \beta_{\max}$. The thyristor switch turns off at the instants t_2 and t_4 given by

$$\left.\begin{array}{l} t_2 = t_1 + \frac{\sigma_1}{\omega} \\ t_4 = t_3 + \frac{\sigma_2}{\omega} \end{array}\right\} \tag{4.11}$$

where σ_1 and σ_2 are the conduction angles in the two halves of the cycle. In steady state, $\sigma_1 = \sigma_2 = \sigma$ with half wave symmetry and

$$\sigma = 2\beta \tag{4.12}$$

Solution for the time interval $(-\beta \leq \omega t \leq \beta)$

During this interval, $u = 1$. From Eqs. (4.6) and (4.7) we obtain

$$LC\frac{d^2 i_T}{dt^2} + i_T = i_s(t) \tag{4.13}$$

The solution of this differential equation is given by

$$i_T(t) = \frac{\lambda^2}{\lambda^2 - 1} I_m \cos\omega t + A\cos\omega_r t + B\sin\omega_r t \tag{4.14}$$

where

$$\omega_r = \frac{1}{\sqrt{LC}}, \quad \lambda = \frac{\omega_r}{\omega} = \sqrt{\frac{X_C}{X_L}}, \quad X_C = \frac{1}{\omega C}, \quad X_L = \omega L \tag{4.15}$$

The constants A and B are determined from the boundary conditions. From Eq, (4.7) and (4.14), we obtain

$$v_C(t) = L\frac{di_T}{dt} = -\frac{\lambda^2}{\lambda^2 - 1} I_m X_L \sin\omega t - A\lambda X_L \sin\omega_r t + B\lambda X_L \cos\omega_r t \tag{4.16}$$

In steady state, due to half wave (odd) symmetry,

$$v_C(\omega t = -\beta) = -v_C(\omega t = \beta) \tag{4.17}$$

The above condition leads to the conclusion that the constant $B = 0$. This also shows that the zero crossing of the capacitor voltage occurs at $\omega t = 0$. Since $i_T(t) = 0$ at $\omega t = -\beta$, we get

$$A = -\frac{\lambda^2}{\lambda^2 - 1} I_m \frac{\cos\beta}{\cos\lambda\beta} \tag{4.18}$$

and we can express $i_T(t)$ and $v_C(t)$ as

$$i_T(t) = \frac{\lambda^2}{\lambda^2 - 1} I_m \left[\cos\omega t - \frac{\cos\beta}{\cos\lambda\beta}\cos\omega_r t\right] \tag{4.19}$$

$$v_C(t) = \frac{I_m X_C}{\lambda^2 - 1}\left[-\sin\omega t + \frac{\lambda\cos\beta}{\cos\lambda\beta}\sin\omega_r t\right] \tag{4.20}$$

It can be shown that

$$i_T(\omega t = \beta) = 0 \tag{4.21}$$

and

$$v_{C1} = -v_{C2} \tag{4.22}$$

where

$$v_{C1} = v_C(\omega t = -\beta), \quad v_{C2} = v_C(\omega t = \beta)$$

The expression for v_{C2} is given by

$$v_{C2} = \frac{I_m X_C}{\lambda^2 - 1}[-\sin\beta + \lambda\cos\beta\tan\lambda\beta] \tag{4.23}$$

Solution for the time interval $(\beta < \omega t < \pi - \beta)$

For this interval, $u = 0$. Also $i_T(t) = 0$. The capacitor voltage (v_C) is given by

$$\begin{aligned} v_C(t) &= v_{C2} + \frac{1}{C}\int_{\beta}^{\omega t} i_s(t) d\omega t \\ &= v_{C2} + I_m X_C[\sin\omega t - \sin\beta] \end{aligned} \tag{4.24}$$

Note that the current through the capacitor (i_C) is given by

$$i_C(t) = i_s(t) - i_T(t) \tag{4.25}$$

The waveforms of $i_s(t), i_T(t)$ and $v_C(t)$ over a cycle are shown in Fig. 4.6 for $\lambda = 2.5$, $\beta = 15°$.

Computation of the TCSC Reactance (X_{TCSC})

The TCSC reactance corresponding to the fundamental frequency, is obtained by taking the ratio of the peak value of the fundamental frequency component (V_{C1}) to the peak value of the sinusoidal line current. From Fourier analysis, the fundamental frequency component (V_{C1}) is calculated from

$$V_{C1} = \frac{4}{\pi}\int_0^{\pi/2} v_C(t)\sin\omega t d(\omega t) \tag{4.26}$$

The above equation follows from the fact that v_C has half-wave odd symmetry about the axis $\omega t = 0$. Substituting (4.20) and (4.24) in Eq. (4.26), we get

$$V_{C1} = \frac{4}{\pi}\left[\int_0^{\beta} v_C^1(t)\sin\omega t d\omega t + \int_{\beta}^{\pi/2} v_C^2(t)\sin\omega t d\omega t\right]$$

where

$$v_C^1(t) = \frac{I_m X_C}{\lambda^2 - 1}\left[-\sin\omega t + \frac{\lambda\cos\beta}{\cos\lambda\beta}\sin\omega_r t\right] \tag{4.27}$$

$$v_C^2(t) = v_{C2} + I_m X_C(\sin\omega t - \sin\beta) \tag{4.28}$$

The reactance (X_{TCSC}) is usually expressed in terms of X_C. By defining,

$$X_{TCSC} = \frac{V_{C1}}{I_m} \tag{4.29}$$

we can derive the ratio $\frac{X_{TCSC}}{X_C}$ as

$$\frac{X_{TCSC}}{X_C} = 1 + \frac{2}{\pi}\frac{\lambda^2}{(\lambda^2 - 1)}\left[\frac{2\cos^2\beta}{(\lambda^2 - 1)}(\lambda\tan\lambda\beta - \tan\beta) - \beta - \frac{\sin 2\beta}{2}\right] \tag{4.30}$$

The above expression can be simplified as

$$\frac{X_{TCSC}}{X_C} = 1 + \frac{2}{\pi}\frac{\lambda^2}{(\lambda^2-1)}\left[-\left(\frac{\lambda^2+1}{\lambda^2-1}\right)\frac{\sin 2\beta}{2} - \beta + \frac{2\cos^2\beta\cdot\lambda\tan\lambda\beta}{(\lambda^2-1)}\right] \tag{4.31}$$

The capacitor voltage also contains odd harmonics of the order

$$n = 2k-1, \quad k = 1,2,3,\ldots \tag{4.32}$$

Remarks

1. The fundamental frequency component and the harmonics in the capacitor voltage can also be obtained from the calculation of harmonics in the TCR current $i_T(t)$.

   The peak value of the fundamental component I_{T1} can be found from

$$\begin{aligned} I_{T1} &= \frac{4}{\pi}\int_0^{\pi/2} i_T(t)\cos\omega t d\omega t \\ &= \frac{4}{\pi}\left[\int_0^{\beta}\frac{\lambda^2}{\lambda^2-1}I_m\left[\cos\omega t - \frac{\cos\beta}{\cos\lambda\beta}\cos\lambda\omega t\right]d\omega t\right] \end{aligned} \tag{4.33}$$

   The fundamental component of the capacitor voltage is obtained from

$$V_{C1} = (I_m - I_{T1})X_C \tag{4.34}$$

   The peak value of the nth harmonic (I_{Tn}) in the TCR current is obtained from

$$I_{Tn} = \frac{4}{\pi}\int_0^{\pi/2} i_T(t)\cos n\omega t d\omega t \tag{4.35}$$

$$\begin{aligned} &= \frac{2}{\pi}\frac{I_m\lambda^2}{(\lambda^2-1)}\left\{\frac{\sin(n-1)\beta}{n-1} + \frac{\sin(n+1)\beta}{n+1}\right. \\ &\left. -\frac{\cos\beta}{\cos\lambda\beta}\left[\frac{\sin(n-\lambda)\beta}{n-\lambda} + \frac{\sin(n+\lambda)\beta}{n+\lambda}\right]\right\} \end{aligned} \tag{4.36}$$

   The peak value of the n^{th} harmonic in the capacitor voltage (V_{Cn}) is given by

$$V_{Cn} = I_{Tn}\frac{X_C}{n} \tag{4.37}$$

   The ratio $\left(\frac{V_{Cn}}{I_m X_C}\right)$ is obtained as

$$\begin{aligned} \frac{V_{Cn}}{I_m X_C} &= \frac{2}{\pi}\frac{\lambda^2}{(\lambda^2-1)}\left[\frac{\sin(n-1)\beta}{n-1} + \frac{\sin(n+1)\beta}{n+1}\right. \\ &\left. -\frac{\cos\beta}{\cos\lambda\beta}\left[\frac{\sin(n-\lambda)\beta}{n-\lambda} + \frac{\sin(n+\lambda)\beta}{n+\lambda}\right]\right], \quad n = 3,5,7,\ldots \end{aligned} \tag{4.38}$$

2. $\frac{X_{TCSC}}{X_C} \to \infty$ at $\beta_{\text{res}} = \frac{(2k-1)\pi}{2\lambda}$ where k is an integer. Since the range of β is limited to 90°, if $\lambda < 3$, there will be only one value of β_{res} at which the TCR and the capacitor will be in resonance at the fundamental frequency. Typically, $\lambda = 2.5$. The variation of $\frac{X_{TCSC}}{X_C}$ as a function of β for $\lambda = 2.5$ is shown in Fig. 4.7. The negative value of $\frac{X_{TCSC}}{X_C}$ indicate that the reactance is inductive.

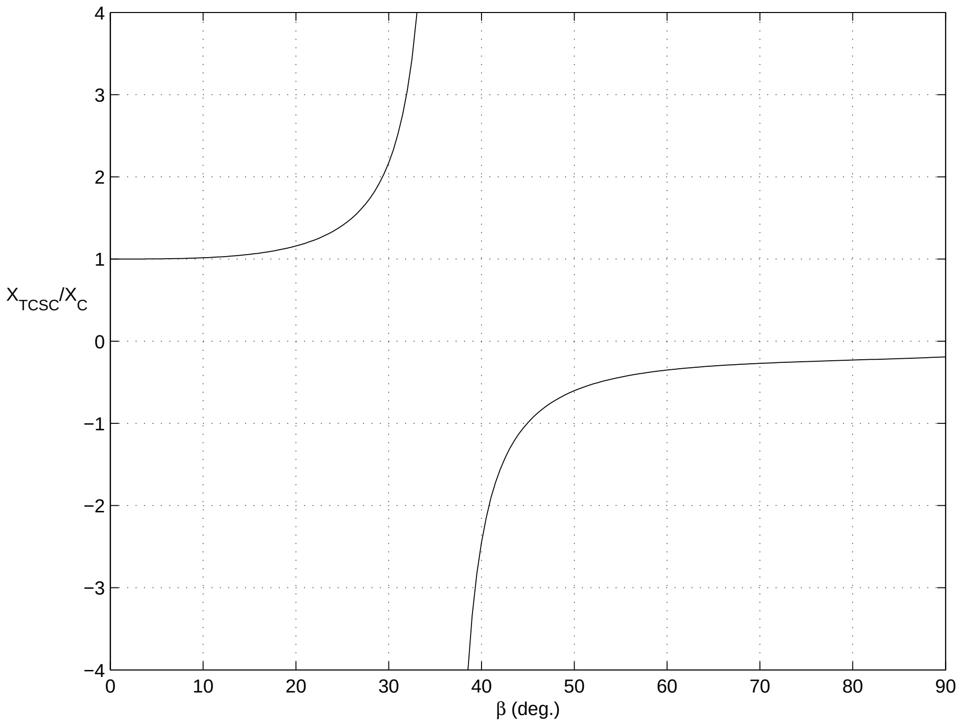


Figure 4.7: Variation of (X_{TCSC}/X_C) as a function of β

The variation of $\left(\frac{|V_{Cn}|}{I_m X_C}\right)$ as a function of β is shown in Fig. 4.8. The capacitor voltage wave forms for (i) $\beta = 20°$ and (ii) $\beta = 70°$ are shown in Fig. 4.9.

3. As the TCSC impedance is very high at resonance (β_{res}) given by

$$\beta_{\text{res}} = \frac{\pi}{2\lambda} \tag{4.39}$$

the operation of TCSC must ensure that the upper limit on $\beta(\beta_{\max})$ should be strictly enforced even under transient conditions. Generally $\frac{X_{TCSC}}{X_C} < 4$ to ensure that the voltage ratings on the capacitor are not exceeded.

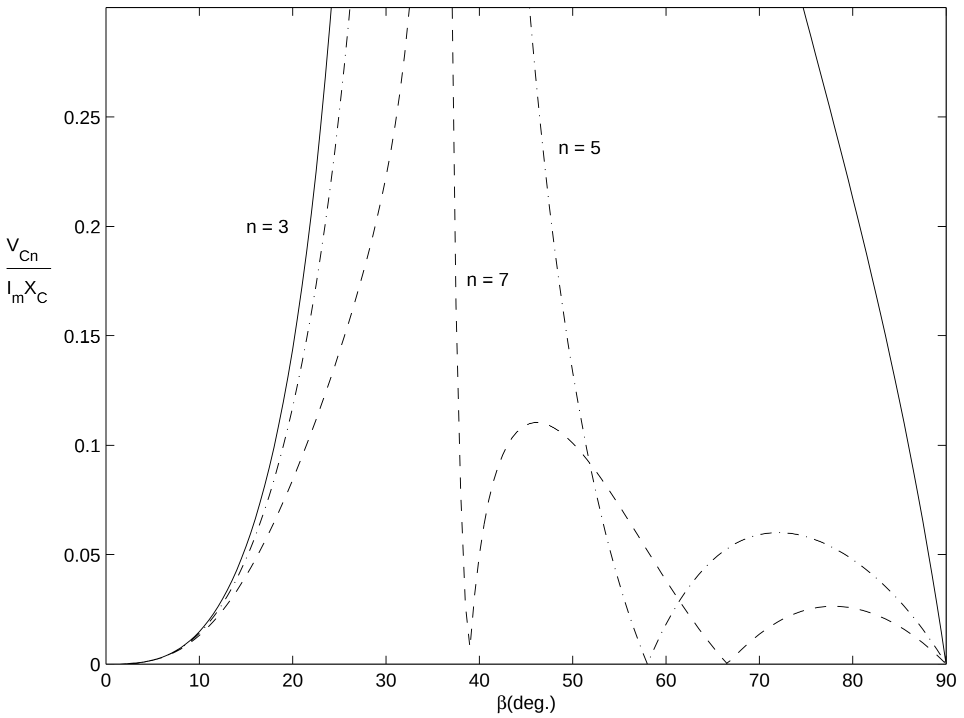


Figure 4.8: Variation of $(V_{cn}/I_m X_c)$ as a function of β

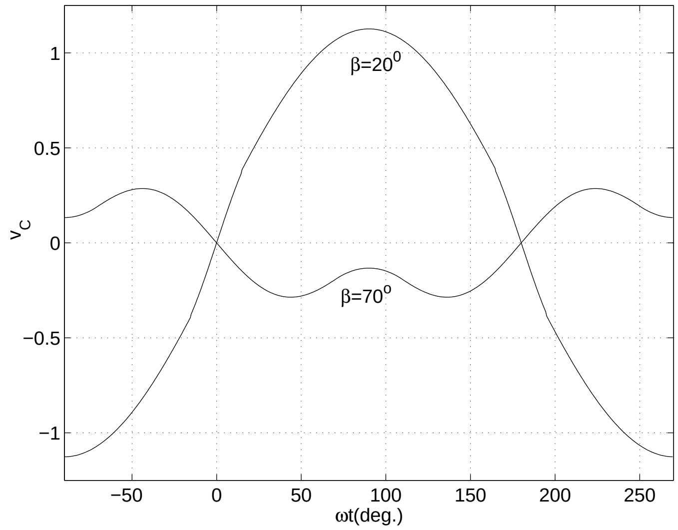


Figure 4.9: Capacitor voltage waveforms for $\beta = 20^0$ $\beta = 70^0$

4.5 Control of TCSC

The control of TCSC also includes protective functions (protective bypass). The control functions are partitioned into two levels - common (to all modules) and the module (level). Commands for the control flow from the common level to the module levels while the status information is sent back from each module level.

Module Control Functions

There are three basic functions at each module level. These are

(a) reactance control

(b) SSR damping control (involving modulation of the reactance) and

(c) Bypass (for protection)

The controller also ensures that the transients associated with mode transitions are minimized. The module controller executes the ordered change to reactance within one half cycle. This includes bypassing, reinsertion and setting the vernier without overshoot.

The protective bypass (TSR mode) is initiated in response to

(i) line overcurrent

(ii) arrester overcurrent

(iii) arrester energy exceeding a limit.

The line overcurrent protection detects fault currents in the line and rapidly implements thyristor bypass to reduce duty on MOV (metal oxide varistors) and capacitors. The bypass is performed on all the three phases simultaneously. When the line current returns and stays within limits for a preset time, the bypass is removed. The arrester overcurrent protection detects overcurrents in the arrester and implements thyristor bypass in the affected phase(s) to reduce varistor duty. The bypass is removed when the arrester currents reduce and stay below limits for a preset time.

The arrester energy protection initiates a bypass when $\int i^2 dt$ in the arrester exceeds its rating. In this case, the bypass is not removed automatically because of the long thermal time constants associated with excessive arrester energy.

Common Control Functions

The common level receives signals of line current and TCSC voltage to generate feedback signals for closed-loop control functions. It also receives commands from energy management centre for setting power order. The major control functions in a TCSC are described below.

Power Scheduling Control

The simplest type of power scheduling control adjusts the reactance order (or setpoint) slowly to meet the required steady-state power flow requirements of the transmission network. The adjustment may be done manually or by a slow acting feedback loop.

An alternative approach is to use a closed-loop current control in which the measured line current is compared to a reference current (which may be derived from the knowledge of the required power level).

An interesting approach to power scheduling is one where during a transient, the line in which TCSC is situated carries the required power so that the power flow in parallel paths is kept constant. This is equivalent to maintaining the angular difference across the line a constant and has been termed as Constant Angle (CA) control. Assuming the voltage magnitudes at the two ends of the line are regulated, maintaining constant angle is equivalent to maintaining constant voltage difference between two ends of the line.

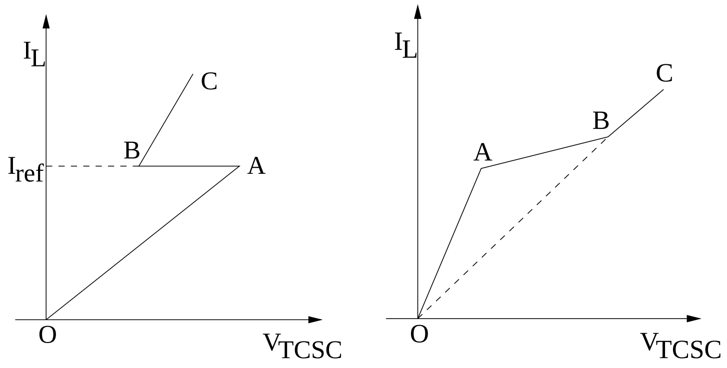
Both CC (Constant Current) and CA controllers can be of PI type with dynamic compensation for improving the response. The steady state control characteristics of both CC and CA control are shown in Fig.4.10(a) and (b) respectively. Assuming V_{TCSC} to be positive in the capacitive region, the characteristics have three segments OA, AB and BC. The control range is AB. OA and BC correspond to the limits on X_{TCSC}. In Fig.4.10(b), the control range AB is described by the equation

$$V_{TCSC} = I_L X_{LR} - V_{Lo} \tag{4.40}$$

where I_L is the magnitude of the line current, X_{LR} is the net line reactance (taking into account the fixed series compensation if any), V_{Lo} is the constant (regulated) voltage drop across the line (including TCSC). Thus, the slope of the line AB is the reciprocal of X_{LR}. OA in Fig.4.10(b), corresponds to the lower limit on TCSC reactance while BC corresponds to the higher limit on TCSC reactance.

Power Swing Damping Control (PSDC)

This is designed to modulate the TCSC reactance in response to an appropriately chosen control signal derived from local measurements. The objective is to damp low frequency swing modes (corresponding to oscillation of generator rotors) of frequencies in the range of 0.2 to 2.0 Hz. One of the signals that is easily accessible is the line current magnitude. Alternatively, the signal corresponding to the frequency of Thevenin (equivalent) voltage of the system across the TCSC can be used. This signal can be synthesized from the knowledge of voltage and current measurements.



(a) CC Control

(b) CA Control

Figure 4.10: Control Characteristics

Transient Stability Control (TSC)

This is generally a discrete control in response to the detection of a major system disturbance.

The discrete or bang-bang control of TCSC in response to signals from locally measured variables is described in [16]. The controller is activated immediately after a major disturbance such as clearing of a fault and is deactivated when the magnitude of frequency deviation is below threshold. This type of control is beneficial not only in reducing the first swing but also for damping subsequent swings.

Subsynchronous Damping Control (SSDC)

The use of vernier control mode at the module level by setting the reactance setpoint at the requisite (minimum) level is often adequate to damp subsynchronous oscillations caused by series resonance in the line and sustained due to torsional interaction. However in some cases, the constant reactance control may not be adequate. In such cases, a damping control is added. The control signal is based on the synthesis of speed of remote turbo-generators. The control signal can be derived from the locally measured current and voltage signals.

The coordination of control actions of all modules in a TCSC is carried out by devising a suitable logic. For example, at Slatt substation, the highest priority is given to the need to tackle SSR, which determines the minimum number of modules to be inserted and their minimum reactance. The power scheduling control has next priority. Even here, there are two options - one based on minimizing the losses and other based on maximizing smooth operation (avoiding stepped variation in reactance order). It is to be noted that vernier operation results in increased losses in a module.

Power swing damping control has the next priority in modulating the set point for reactance. This can be replaced by TSC whenever required.

Under normal operational conditions, all the modules may not be required. To ensure balanced long term duty for each module in a TCSC, the control logic also incorporates a rotation feature, according to which, the modules in series are rotated if no insert/bypass operations occur for some preset time (say an hour). The rotation is performed without changing the net reactance.

4.6 Modelling of TCSC for Stability Studies

For stability studies it is not necessary to model the gate pulse unit and the generation of gate pulses. It is adequate to assume that the desired value of TCSC reactance is implemented within a well defined time frame. This delay can be modelled by first order lag as shown in Fig.4.11. The value of T_{TCSC} is from 15 to 20 ms. X_{ref} is determined by the power scheduling controller or in its absence, by manual control based on order from load dispatch.

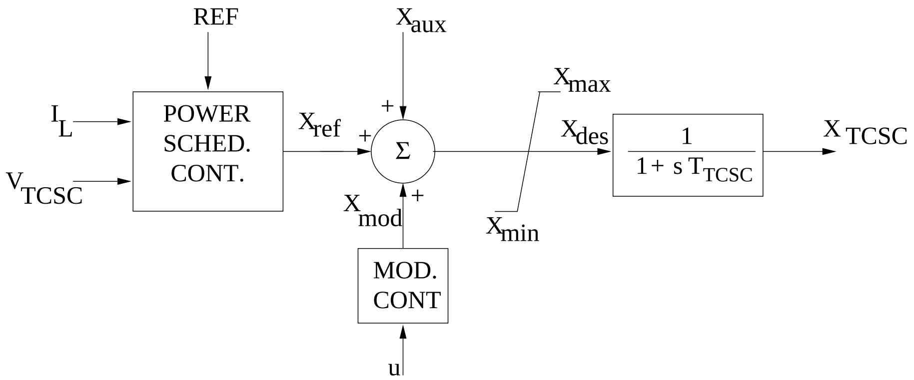


Figure 4.11: Block diagram of TCSC

The block diagram of constant current (CC) or constant angle (CA) controller is shown in Fig.4.12. T_m is the time constant of first order low pass filter associated with the measurement of line current I_L and the TCSC voltage. $S = 0$ for CC control and $S = \frac{1}{X}$ for CA control. X is the net reactance of line given by

$$X = X_{Line} - X_{FC} \tag{4.41}$$

where X_{Line} is the line reactance and X_{FC} is the reactance of the fixed series capacitor if any. Generally, TCSC will be used in conjunction with fixed series capacitor to minimize overall cost of compensation while providing effective control for stability improvement.

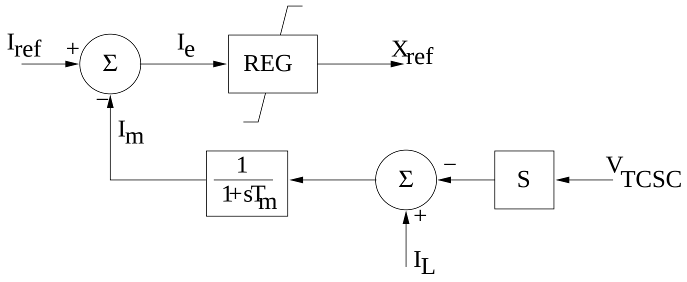


Figure 4.12: Block diagram of CC or CA controller

The regulator block diagram is shown in Fig.4.13. This consists mainly PI controller and phase lead circuit if required. K_P, the proportional gain can be set to zero if only integral control is used. The gain K_I is positive in the case of current control and negative in case of CA control. In the latter case I_{ref} is actually the voltage reference divided by X. Hence positive error signal implies the net voltage drop in the line is less than the reference and X_{TCSC} (assumed to be positive in capacitive region) is to be reduced. On the other hand for current control, if the error is positive, the controller has to increase X_{TCSC} to raise the line current to reduce the error.

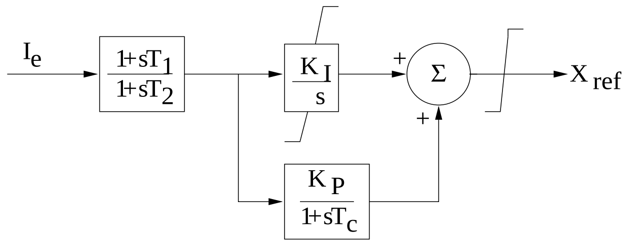
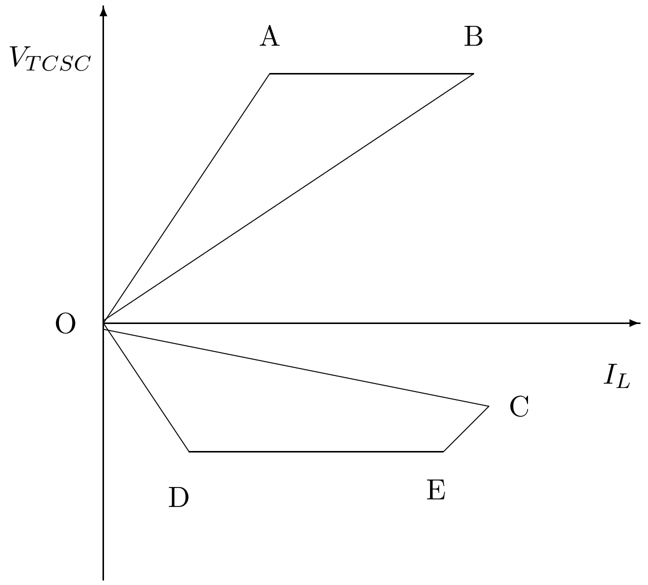


Figure 4.13: Block diagram of the Regulator

The modulation controller is designed to damp power swings in the line by using a control signal derived from local measurement. A convenient signal to use is the magnitude of line current. The control configuration is similar to the SMC used in SVC. X_{aux} could represent the increase in the reactance order required for mitigating SSR or improving transient stability.

The limits on the total reactance order X_{des} are based on the TCSC capability. For a single module, the operational region of TCSC in the

(a) V-I Plane



(b) X-I Plane

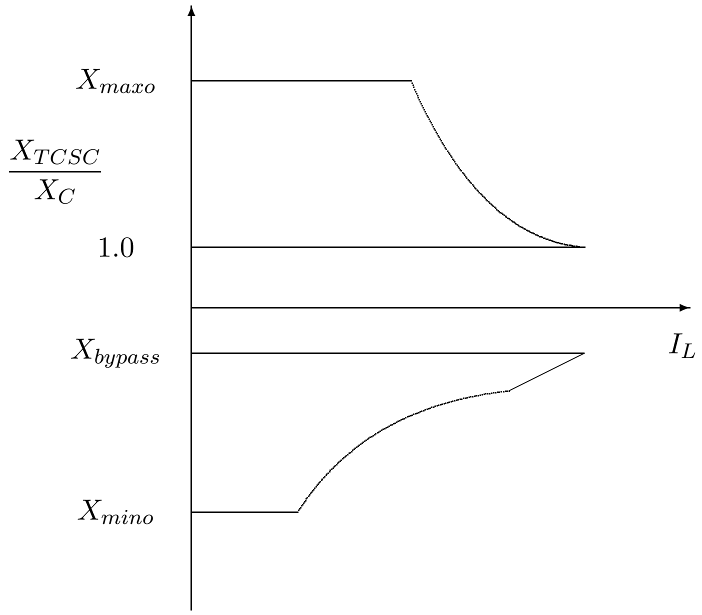


Figure 4.14: TCSC capability curves for a module

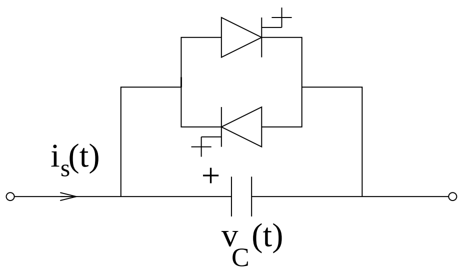


Figure 4.15: GTO Controlled Series Capacitor (GCSC)

$V_{TCSC} - I_L$ plane is shown in Fig.4.14(a). The operation region in $(\frac{X_{TCSC}}{X_C}) - I_L$ plane is shown in Fig.4.14(b). The voltage and reactances are considered to be positive when TCSC is in the capacitive region.

The line OA in Fig.4.14(a) corresponds to the constant reactance of TCSC at its limit X_{max0}. This is selected based on the TCSC design and should be such that the TCSC does not operate close to the resonance point which would be inherently unstable. A typical value of X_{max0} (in pu of X_C) is 3.0. Line AB corresponds to maximum voltage rating of TCSC. Line OB corresponds to the operation of TCSC with thyristors blocked. Here $X_{TCSC} = 1$ pu.

The line OC has negative slope corresponding to X_{bypass} (which is negative) in the bypass mode of TCSC. Line OD corresponds to the upper limit on the inductive reactance (X_{min0}). Line DE corresponds to trhe voltage limit of TCSC in the inductive region. EC corresponds to limit imposed on the thyristor current in the inductive vernier mode. Under normal conditions, the TCSC operates only in the first quadrant of both $V_{TCSC} - I_L$ plane and $X_{TCSC} - I_L$ plane.

The operation at constant maximum voltage (across TCSC) implies that X_{TCSC} is reduced in inverse ratio of the line current.

The equations for TCSC can be written down from the block diagrams shown in Fig.4.11 to Fig.4.13.

4.7 GTO Thyristor Controlled Series Capacitor (GCSC)

A single phase GCSC is shown in Fig. 4.15. It consists of a fixed capacitor in parallel with a bidirectional switch made up of a pair of GTO thyristors. In contrast to a thyristor, a GTO thyristor can be turned off upon command.

A GCSC is a dual of a TCR which is connected across a voltage

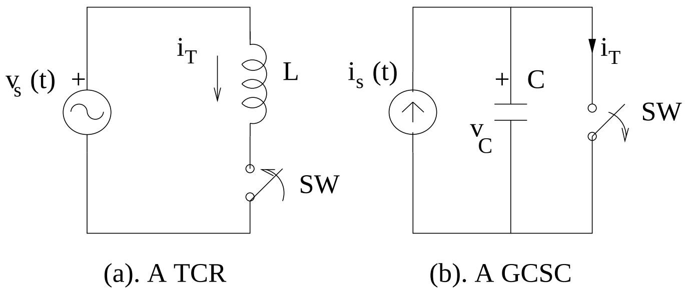


Figure 4.16: Representation of a TCR and a GCSC

source which is assumed to be sinusoidal. By phase control (varying the delay angle α measured from the instant corresponding to peak value of the source voltage), the current through a TCR can be controlled. See Fig. 4.16 (a) which represents the thyristor valve as a switch that can be turned on at controllable delay angle (α) in the range from 0 to 90°. A GCSC is connected in series with a sinusoidal current source. The controllable switch is connected in parallel with the capacitor (see Fig. 4.16(b)) while the thyristor switch is connected in series with the reactor. The switch in a GCSC is *turned off* at an angle (γ) measured with reference to the peak value of the sinusoidal line current (i_s). When the switch across the capacitor is turned off at an angle γ, the current $i_s(t)$ is forced to flow through the capacitor and the voltage (v_C) starts building up according to the relation given by

$$\begin{aligned} v_C(t) &= \frac{1}{C}\int_{\gamma}^{\omega t} i_s(t)d(\omega t) = \frac{1}{C}\int_{\gamma}^{\omega t} I_m \cos\omega t d(\omega t) \\ &= \frac{I_m}{\omega C}[\sin\omega t - \sin\gamma] \end{aligned} \tag{4.42}$$

The GTO switch is closed when $v_C(t) = 0$ and this occurs at the instant when $\omega t = \pi - \gamma$. The switch remains off for the duration δ given by

$$\delta = \pi - 2\gamma = 2\left(\frac{\pi}{2} - \gamma\right) = 2\beta \tag{4.43}$$

δ may be called the hold off angle (as opposed to the conduction angle in a TCR). β is the angle of advance defined as

$$\beta = \frac{\pi}{2} - \gamma \tag{4.44}$$

Both γ and β vary in the range 0 to 90°. When $\gamma = 0$, the capacitor is continuously conducting and $\delta = 180°$. When $\gamma = \frac{\pi}{2}, \delta = 0$ and the capacitor voltage remains at zero as the capacitor is continuously bypassed by the GTO switch. The instantaneous capacitor voltage is maximum corresponding to

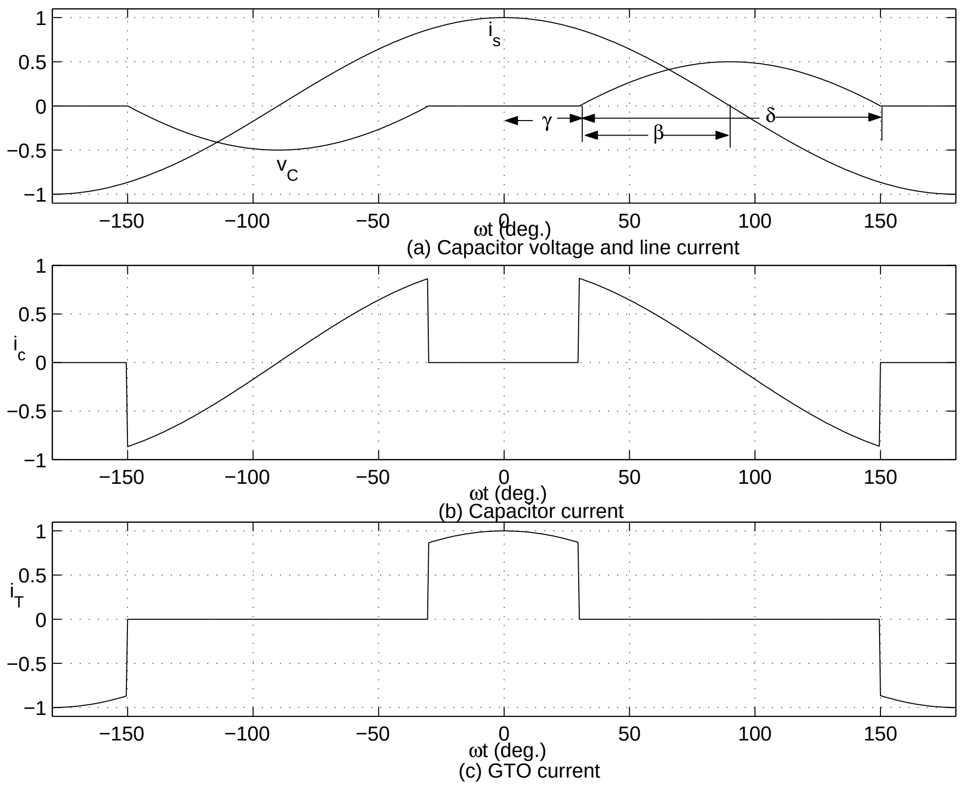


Figure 4.17: Current and voltage waveforms

the instant when the line current is zero. The capacitor voltage and the line current waveforms are shown in Fig. 4.17 along with the currents through the capacitor and the GTO switch. By comparing the TCR quantities (given in chapter 3) with those shown in Fig. 4.17, it can be observed that the TCR current is analogous to the capacitor voltage, the voltage across the thyristor switch (in a TCR) is analogous to the current in the GTO switch and the voltage across the reactor (in a TCR) is analogous to the current through the capacitor. It is to be noted that the firing (delay) angle in a TCR (α) corresponds to the blocking angle (γ) in a GCSC, while the conduction angle (σ) in a TCR corresponds to the hold off angle δ in a GCSC.

The capacitor voltage waveform is not sinusoidal. The fundamental frequency component is given by

$$\begin{aligned} V_{C1} &= \frac{4}{\pi}\int_0^{\pi/2} v_C(t)\sin\omega t d(\omega t) \\ &= \frac{4}{\pi}\frac{I_m}{\omega C}\int_\gamma^{\pi/2}[\sin\omega t - \sin\gamma]\sin\omega t d(\omega t) \end{aligned}$$

$$= \quad I_m X_C \left[1 - \frac{2\gamma}{\pi} - \frac{\sin 2\gamma}{\pi}\right] \tag{4.45}$$

The effective reactance of the GCSC is given by

$$\begin{aligned} X_{GCSC} &= \frac{V_{C1}}{I_m} = X_C \left(1 - \frac{2\gamma}{\pi} - \frac{\sin 2\gamma}{\pi}\right) \\ &= \frac{X_C}{\pi}(\delta - \sin\delta) \end{aligned} \tag{4.46}$$

As δ varies from 0 to 180°, X_{GCSC} varies from 0 to X_C. (Note that in a TCR, B_{TCR} varies from 0 to B_L as σ varies from 0 to 180°.)

The amplitude of the harmonics voltage (V_{cn}) across the capacitor, is given by

$$V_{cn} = I_m X_C \frac{4}{\pi} \left[\frac{\sin\gamma\cos(n\gamma) - n\cos\gamma\sin(n\gamma)}{n(n^2-1)}\right], \quad n = 2k+1, k = 1, 2, 3, \ldots \tag{4.47}$$

The third harmonic component has a peak value of 13.8% of ($I_m X_C$) at a value of γ around 35°. Unlike in a three phase TCR, there is no provision of connecting the GCSC in a delta to eliminate the triplen harmonics (unless an insertion transformer is used). The GCSC would normally be inserted directly (without any magnetics) in series with the line. Fortunately, the line impedance (inductive) would be sufficiently high to limit the triplen (zero sequence) current harmonics to values that would not create problems. Further, just as a segmented TCR (made of multiple modules connected in parallel) can be operated with all (except one module) in the TSR mode, a GCSC made up of multiple, identical modules connected in series, can be operated with all (except one) in a GSSC (GTO Switched Series Capacitor) mode. However, in comparison with TSR operation it should be noted that a GTO switch in a GSSC is called upon to turn-off and on at the instant when the line current is maximum and the capacitor voltage is zero. A thyristor switch in a Thyristor Switched Series Capacitor (TSSC) can be turned on at the voltage zero, but has to wait until the instant of current zero to turn-off. At this instant, the capacitor voltage is maximum and results in dc offset for the capacitor voltage which is 100% of ($I_m X_c$).

4.8 Mitigation of Subsynchronous Resonance with TCSC and GCSC

4.8.1 Description of SSR

The turbo generators have several rotors corresponding to steam turbines (High Pressure, Intermediate Pressure and Low Pressure) in addition to the generator and rotating exciter (if any), all connected by elastic shafts