Power Flow Control in Power System using FACT Device Thyristor Controlled Series Capacitor (TCSC): A Review

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Abstract: ***In a modern day's power system have been growing due to increase of demand and loads, it's getting more and more difficult to provide stability and control. In this paper an overview to general type of FACTS controller and performance of TCSC is given. The FACTS devices play an important role to improve the performance of power system. This paper the study of TCSC with various mode of operation is investigated and applications, advantages of FACTS. TCSC controller can be designed to control the power flow, increase the transmission limit or improve the stability and also increase synchronization of power and provide the continuous variable reactance and impedance. This paper proposed the control scheme of TCSC for power flow control, benefits of FACTS controller, VAR compensation and TCSC module. TCSC consist of back to back thyristor. By changing the firing angle of this back to back thyristor it is possible to vary the reactance of the TCSC as per TCSC characteristics. In inductive region power flow decreases and in capacitive region power flow increasing.***

Keywords: FACTS controller, Flexible AC Transmission System (FACTS), Power system analysis, VAR compensation.

1. Introduction

Now a day's power system are undergoing numerous changes and becoming more complex from operation, control and stability maintenance standpoints when they meet ever-increasing load demand [1]. Voltage stability is concerned with the ability of a power system to maintain acceptable voltage at all buses in the system under normal conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand or change in system condition causes a progressive and uncontrollable decline in voltage [2]. Power flow in Electrical Power System can be improved by adjusting reactance parameter of the transmission line. It can also be enhanced by adding a new transmission line in parallel with the existing one [2]. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power [3]-[5]. In power system applications the equivalent impedance control that maintains the equivalent impedance of the transmission line may be the preferred method from the operating stand point Figure 1. Shown a single line diagram of a simple transmission line with an inductive transmission reactance X_L, connecting to sending end (S.E.) voltage source Vs and receiving end (R.E.) voltage source Vr, respectively [6].

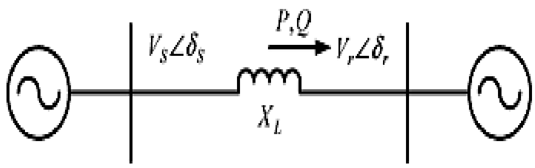

Figure 1. Two bus transmission system [6].

The real and reactive powers (P and Q) flows at the receiving end as shown in equation 1 and equation 2.

$$P = VsVr\,Sin(\delta s- \delta r)/X_L = V^2\,Sin\delta/X_L \quad (1)$$

$$Q = VsVr\,[1-Cos(\delta s- \delta r)]/X_L = V^2\,(1-Cos\delta)/X_L \quad (2)$$

$$\delta = \delta s- \delta r \quad (3)$$

Where,
Vs and Vr are the magnitudes and δs and δr are the phase angles of the voltage sources Vs and Vr, respectively, for simplicity, the voltage magnitudes are chosen such that Vs= Vr = V and the difference between the phase angles is
δ = δs – δr [6].

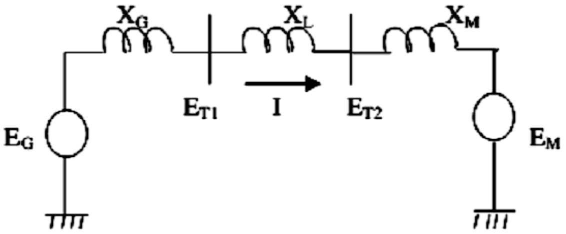

Figure 2. Idealised model of power system [7].

The VAR compensation is defined as the management of reactive power to improve the performance of ac power systems. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most of power quality problems can be attenuated or solved with an adequate control of reactive power [8]. In general, the problem of reactive power compensation is viewed from two aspects: load compensation and voltage support. In load compensation the objectives are to increase the value of the system power factor to balance the real power drawn from the ac supply, compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads [9], [10]. Voltage support is generally required to reduce voltage fluctuation at a given terminal of a transmission line. Reactive power compensation in transmission systems also improves the stability of the ac system by increasing the maximum active power that can be transmitted. It also helps to maintain a substantially flat voltage profile at all levels of power transmission, it improves HVDC (High Voltage Direct Current) conversion terminal performance, increases transmission efficiency, controls the steady state, temporary over voltages [11] and can avoid blackouts [12], [13]. Series and shunt VAR compensation are used to modify the natural electrical characteristics of ac power systems. Series compensation modifies the transmission or distribution system parameters, while shunt compensation changes the equivalent impedance of the load. In both cases, the reactive power that flows through the system can be effectively controlled improving the performance of the overall ac power system [8], [14].

2. Introduction of Flexible AC Transmission System (FACTS)

The series devices are compensating reactive power with their influence on the effective impedance on the line they have an influence on stability and power flow [15].The SSSC is a device which has so far not been builds on transmission level because Series Compensation and TCSC are fulfilling all the today's requirements more cost efficient. But series applications of Voltage Source Converters have been implemented for power quality applications on distribution level for instance to secure factory in feeds against dips and flicker. These devices are called Dynamic Voltage Restorer (DVR) or Static Voltage Restorer (SVR) [15]. A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide smoothly variable series capacitive reactance [16].

The basic applications and advantages of FACTS devices are [15]:

1. Power flow control.
2. Increase of transmission capability.
3. Voltage control.
4. Reactive power compensation.
5. Stability improvement.
6. Power quality improvement.
7. Power conditioning.
8. Flicker mitigation.
9. Interconnection of renewable and distributed generation and storages [15].
10. Rapid, continuous control of the transmission line reactance [17].

3. FACTS Controller

Now, for maximum utilization of any FACTS device in power system planning, operation and control. Power flow solution of the network that contains any of these devices is a fundamental requirement [18]-[22]. In general, FACTs controller can be divided into main four categories as shown in figure 3 [16].

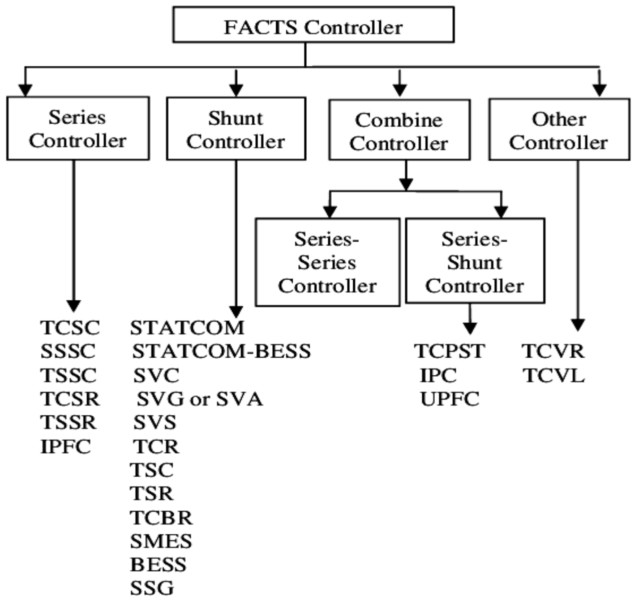

Figure 3. Classification of FACTS controllers [16].

It is important to appreciate that the series connected controller impact the driving voltage and hence the current and power directly. Therefore, if the of the application is to control the current/power flow and damp oscillation, the series controller for a given MVA size is several time more powerful than the shunt controller. FACT controller may be based on thyristor devices with no gate turn off (only with turn on) [16].

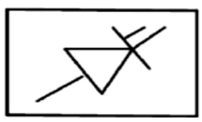

Figure 4. General symbol of fact controller [16].

In principle all the series controllers inject voltage in series with the line shown in figure 5. Series connected controller impacts the driving voltage and hence, the current and power flow directly. Static Synchronous Series Compensator (SSSC) and Thyristor Controlled Series Compensator (TCSC) etc. are the examples of series controllers [23].

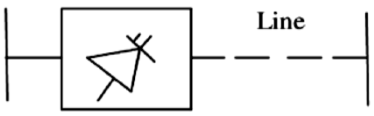

Figure 5. Series controller [16]

Table 1 Constraint equation and control variables for FACTS controllers [24].

Controller	Constraint Equation	Control Variable
SVC	Vp = 0, Vr = 0, Ip = 0, Ir = -B_{SVC} V_1	B_{SVC}
TCSC	Vp = 0, Ip = 0, Ir = 0, Vr = X_{TCSC} I_2	X_{TCSC}
STATCOM	Vp = 0, Vr = 0, Ip = 0,	Ir
STATCOM (With Energy Source)	Vp = 0, Vr = 0	Ip, Ir
TCPAR (SPAT)	$E = V_1(e^{j\Phi}-1) \sim jV_1\Phi$, $V_1Ip = VpI_2$, $V_1Ir = I_2Vr$	Φ
SSSC (S^3C) (SSC)	Vp = 0, Ip = 0, Ir = 0,	Vr
SSSC (With Energy Source)	Ip = 0, Ir = 0,	Vp, Vr

4. TCSC and Power Flow Control

Active and reactive power injections represent all features of the steady state FACTS device; it is rational to take the power injections as independent control variables for power flow control. In order to develop a versatile approach to power flow control with FACTS devices, firstly based on the PIM (Power injection model) shown in figure 6 [25].

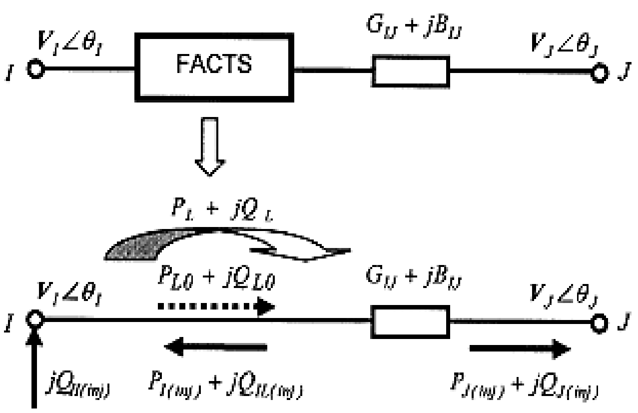

Figure 6. Power injection model for power flow control [25].

The basic conceptual TCSC module consists of a fixed series capacitor (FC) in parallel with a thyristor controlled reactor (TCR). The TCR is formed by a reactor in series with a bidirectional thyristor valve that is red with an angle ranging between 90^0 and 180^0 with respect to the capacitor voltage [26]. In Figure 7. Shown capacitor C parallel with a thyristor controlled reactor LS as shown in figure 8. However, a practical TCSC module also includes protective equipment normally installed with series capacitors, as shown in Figure 8 [27]. Capacitive mode can be XL<XC and inductive mode can be XL>XC. In this case, TCSC works either as inductive or capacitive. This mode is the mode in which TCSC is used dynamically [28], [29]. It consists of three components: capacitor banks C, bypass inductor L and bidirectional thyristors T1 and T2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations [30].

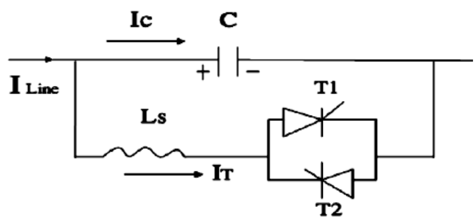

Figure 7. A TCSC basic module [27].

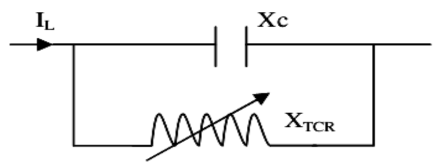

Figure 8. Equivalent circuit of TCSC [27].

A simple understanding of TCSC functioning can be obtained by analysing the behaviour of a variable inductor connected in parallel with an FC as shown in Figure 9. The equivalent impedance Zeq of this LC combination is expressed as [31].

$$Zeq = (j/\omega c) \,\big|\big|\, (j\omega L) = -j / (\omega c - 1/\omega L) \qquad (4)$$

The impedance of the FC alone, however, is given by $-j(1/\omega C)$. If $\omega C - (1/\omega L) > 0$ or, in other words, $\omega L > (1/\omega C)$, the reactance of the FC is less than that of the parallel-connected variable reactor and that this combination provides a variable-capacitive reactance are both implied. Moreover, this inductor increases the equivalent-capacitive reactance of the LC combination above that of the FC [31]. If $\omega C - (1/\omega L) = 0$, a resonance develops that results in an infinite capacitive impedance an obviously unacceptable condition. If $\omega C - (1/\omega L) < 0$, the LC combination provides inductance above the value of the fixed inductor. This situation corresponds to the inductive vernier mode of the TCSC operation [31].

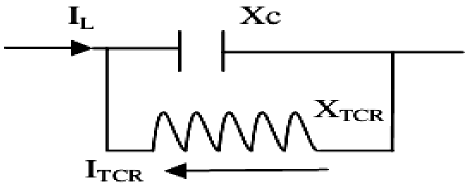

Figure 9. Capacitive operation [27]

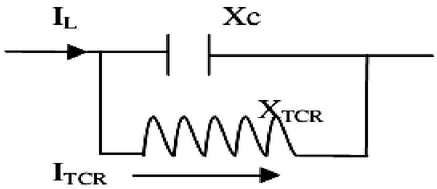

Figure 10. Inductive operation [27].

TCSC is a FACT device available for application in AC line of voltage up to 500 kv. In Figure 8 Shown equivalent circuit of the TCSC model as a capacitance in parallel with a variable inductor [27]. The impedance of TCSC (Z_{TCSC}) is given by [27].

$$Z_{TCSC} = (-jXc)\,(jX_{TCR}) / j(X_{TCR} - Xc) \quad (5)$$

$$Z_{TCSC} = (-jXc) / (1 - Xc / X_{TCR}) \quad (6)$$

The current through the TCR (I_{TCSC}) is given by [32].

$$I_{TCSC} = (-jXc)\, I_L / j(X_{TCR} - Xc) \quad (7)$$

$$I_{TCSC} = I_L / (1 - X_{TCR} / Xc) \quad (8)$$

Since the losses are neglected, the impedance of TCSC is purely reactive [27]. The capacitive reactance of TCSC is obtained from figure 9.

$$X_{TCSC} = Xc / (1 - Xc / X_{TCR}) \quad (9)$$

A TCSC is a series controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. From the system viewpoint, the principle of variable series compensation is simply to increase the fundamental frequency voltage across a fixed capacitor (FC) in a series compensated line through appropriate variation of the firing angle α [33]. This enhanced voltage changes the effective value of the series capacitive reactance [31].

5. TCSC Module

A practical TCSC module also includes protective equipment normally installed with series capacitors, as shown in Figure 11. A metal oxide varistor (MOV), essentially a nonlinear resistor is connected across the series capacitor to prevent the occurrence of high capacitor over voltages. Not only does the MOV limit the voltage across the capacitor, but it allows the capacitor to remain in circuit even during fault conditions and helps improve the transient stability [24].

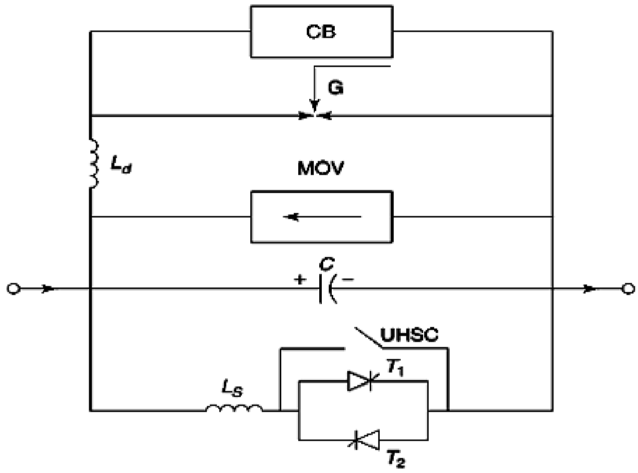

Figure 11: A TCSC basic module [24].

Also installed across the capacitor is a circuit breaker (CB) for controlling its insertion in the line. In addition, the CB bypasses the capacitor if severe fault or equipment malfunction events occur. A current limiting inductor Ld, is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor bypass operation. If the TCSC valves are required to operate in the fully "on" mode for prolonged durations, the conduction losses are minimized by installing an ultra high speed contact (UHSC) across the valve. This metallic contact offers a virtually lossless feature similar to that of circuit breakers and is capable of handling many switching operations. The metallic contact is closed shortly after the thyristor valve is turned on and it is opened shortly before the valve is turned off. During a sudden overload of the valve and also during fault conditions, the metallic contact is closed to alleviate the stress on the valve [24].

6. Modes of TCSC

There are essentially three modes of TCSC operation [16], [17], [23], [34]; these are illustrated in Figure 12,13,14,15.

1. Bypassed Thyristor mode.
2. Blocked Thyristor Mode (Waiting Mode).
3. Partially Conducting Thyristor or Vernier Mode: Capacitive and Inductive Vernier Mode.

1. Bypassed Thyristor Mode: In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 180^0. Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the thyristor valves. The TCSC module behaves like a parallel capacitor inductor combination. This mode is employed for control purposes and also for initiating certain protective functions [31].

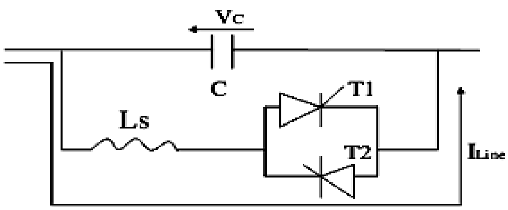

Figure 12. Operating modes of a TCSC: The bypassed thyristor mode [31].

2. Blocked Thyristor Mode: This mode also known as the waiting mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing [31]. The TCSC module is thus reduced to a fixed series capacitor, and the net TCSC reactance is capacitive. In this mode, the dc offset voltages of the capacitors are monitored and quickly discharged using a dc offset control without causing any harm to the transmission system [31].

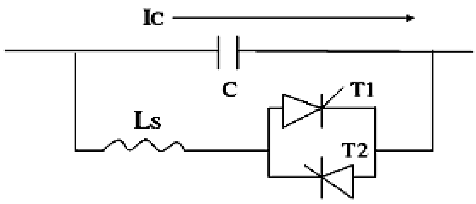

Figure 13. Operating modes of a TCSC: The blocked thyristor mode [31].

3. Partially Conducting Thyristor or Vernier Mode: This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor pair firing angle in an appropriate range. However, a smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes. The loop current increases the voltage across the FC, is constrained in the range $\alpha min \leq \alpha \leq 180^0$. This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases as α is decreased from 180^0 to α min [31]. Another variant is the inductive vernier mode, in which the TCSC can be operated by having a high level of thyristor conduction. In this mode, the direction of the circulating current is reversed and the controller presents a net inductive impedance Based on the three modes of thyristor valve operation [31].

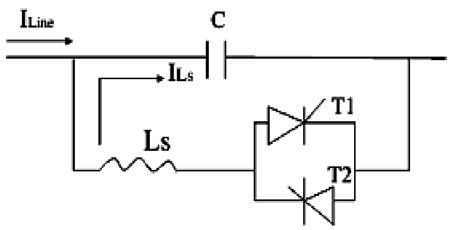

Figure 14. Operating modes of a TCSC: The partially conducting thyristor (capacitive vernier) mode [31].

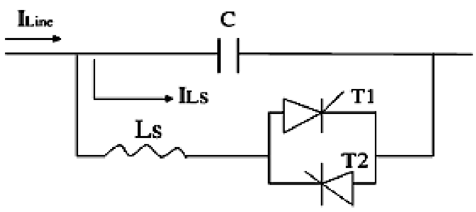

Figure 15. Operating modes of a TCSC: The partially Conducting thyristor (inductive vernier) mode [31].

7. Operation of TCSC

The basic operation of TCSC can be easily explained from circuit analysis. It consists of a series compensating capacitor shunted by a Thyristor controlled reactor (TCR). TCR is a variable inductive reactor X_L shown in figure 17, controlled by firing angle α. Here variation of X_L with respect to α is given by

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} \tag{10}$$

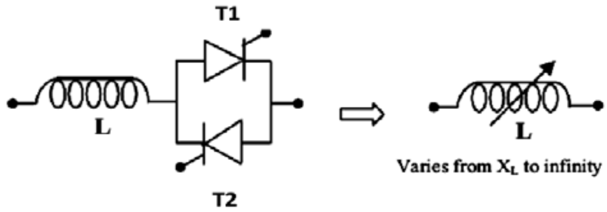

Figure 16. Equivalent circuit of TCR

For the range of 0 to 90^0 of α, X_L (α) start vary from actual reactance X_L to infinity. This controlled reactor is connected across the series capacitor, so that the variable capacitive reactance shown in figure 18 is possible across the TCSC to modify the transmission line impedance. Effective TCSC reactance X_{TCSC} with respect to firing angle alpha (α) is [36]-[39].

$$X_{TCSC}(\alpha) = -Xc + C1[\,2(\pi-\alpha) + \sin 2(\pi-\alpha)\,] - C2[\cos^2(\pi-\alpha)\,\overline{W}\tan\{\overline{W}(\pi-\alpha)\}] - \tan(\pi-\alpha) \tag{11}$$

Where,

$$X_{LC} = \frac{Xc\,X_L}{Xc - X_L},\quad C_1 = \frac{Xc+XL}{\pi},\quad C_2 = 4\,X^2Lc/\,\pi\,X_L,$$

$$\overline{W} = \sqrt{Xc/XL}$$

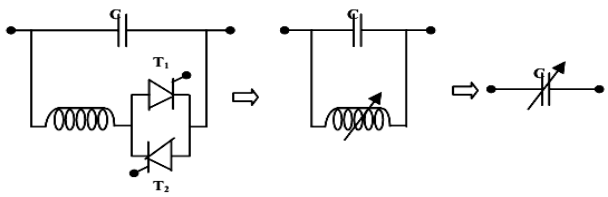

Figure 17. Equivalent circuit of TCSC

The impedance characteristics curve of a TCSC device is shown in Figure 18, that is drawn between effective reactance of TCSC and firing angle α [40], [41]. Impedance characteristics of TCSC shows, both capacitive and inductive region are possible through varying firing angle (α) as follows:

1. $90^0 < \alpha < \alpha_{Llim}$ Inductive region.
2. $\alpha_{Llim} < \alpha < \alpha_{Clim}$ Capacitive region.
3. $\alpha_{Clim} < \alpha < 180^0$ Resonance region

While the maximum and minimum value of firing angles should be selected in such a way as to avoid the TCSC operating in high impedance region (at resonance) which results in high voltage drop across the TCSC.

This limitation can be used as a constraint during load flow analysis [42].

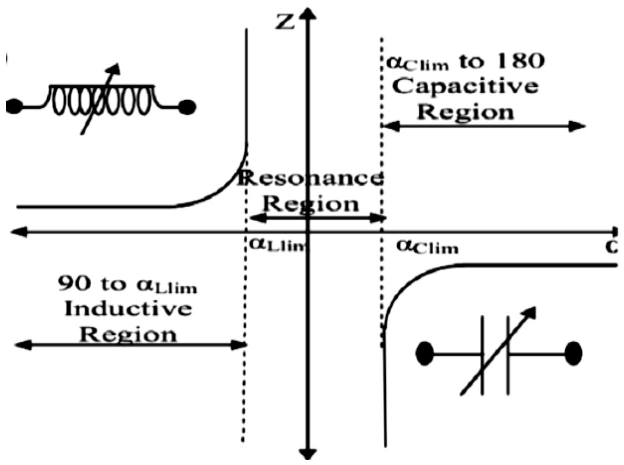

Figure 18. Impedance Versus firing angle characteristic of a TCSC [42].

8. Control Operation of TCSC

The two basic control approach scheme for the TCSC based on first is the synchronization to the fundamental component of the line current. Second approach is synchronized the line current for the generation of the basic timing reference. In this method the actual zero crossing of the capacitor voltage is estimated from the prevailing capacitor voltage and line current by an angle correction circuit the delay angle is then determine from the desired angle and the estimated correction angle so as to make to TCR conduction symmetrical with respect to the excepted zero crossing. The control circuit performances are usually heavily dependent on the actual implementation, this approach is theoretically more likely to provide faster response for those application requiring such response as shown in figure 19 [16].

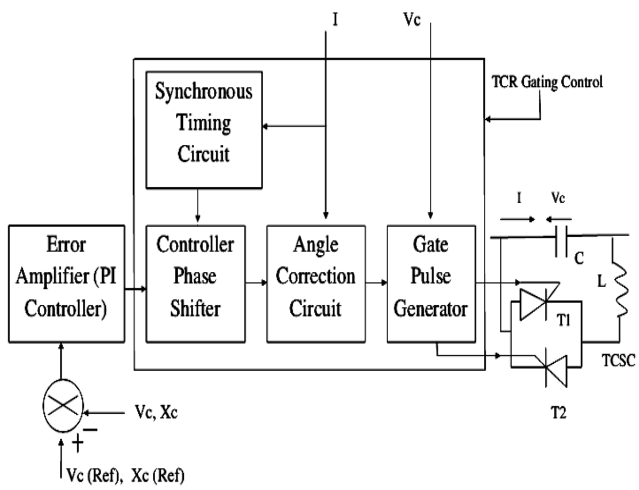

Figure 19. A functional internal control scheme for the TCSC based on prediction of the capacitor voltage zero crossing [16].

9. Voltage Collapse Prevention

Voltage collapse problems are a serious concern for power system engineers and planners. Voltage collapse is mathematically indicated when the system Jacobian becomes singular. The collapse points are indicative of the maximum load ability of the transmission lines or the available transfer capability (ATC) [43]. The TCSCs can significantly enhance the load ability of transmission networks, thus obviating voltage collapse at existing power transfer levels. While the TCSC reduces the effective line reactance, thereby increasing the power flow, it generates reactive power with increasing through current, thus exercising a beneficial influence on the neighboring bus voltage. The system faces voltage collapse or a maximum loading point corresponding to a 2120 MW increase in the net load. If a TCSC is installed to provide 50% compensation of the line experiencing the highest increase in power at the point of collapse, the maximum load ability will be enhanced to 3534 MW. The in fluencies of the TCSC on the voltage profile of a critical bus are illustrated in Figure 20 [43].

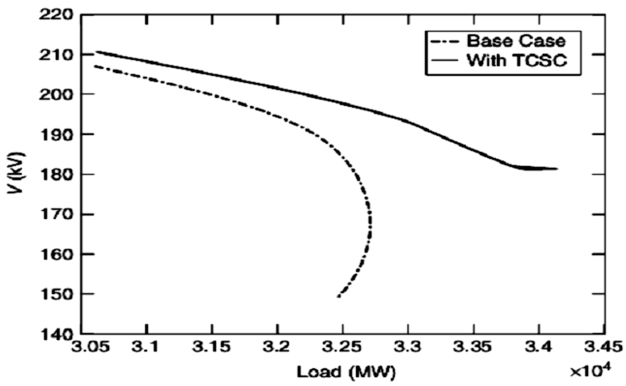

Figure 20. The voltage profile of the critical bus employing 50% TCSC compensation [43].

10. Conclusion

In this paper, the analysis of power flow control between two ends of the transmission line to maintain the voltage magnitude, phase angle and line impedance. The study of VAR, Series compensation and TCSC device controlling the power flow through the transmission line by changing the reactance of the system. The TCSC can be operated in capacitive and an inductive mode is rarely used in practice. The FACTS controller with its classification and performance of TCSC are included in this paper. The advantages of FACTS devices and various operating modes of TCSC are specified. This paper work can be extended in future for TCSC modelling with a number of bus system and determine the method for controlling the power flow.

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