Chapter-4

MODELING OF SERIES FACTS DEVICES

4.1 Introduction

Series FACTS devices are powerful controllers recognized for power flow, power oscillation damping and improving transient stability [22] [33]. Normally series FACTS devices are used for power flow control in transmission lines and also used to damp the power system oscillations. Because of slow response of proportional and integral power flow (PIPF) controller series FACTS devices are not in a position to effectively damp the power system oscillations [17]. It needs some auxiliary signal to improve the performance of series FACTS devices to damp the power system oscillations. In this work fuzzy logic power oscillation damping (FLPOD) controller along with PIPF controller is proposed to achieve this.

In this work most popular two series FACTS devices –TCSC and SSSC are considered

4.2 Thyristor Controlled Series Capacitor (TCSC)

4.2.1 Introduction

Thyristor Controlled Series Capacitor (TCSC) provides powerful means of controlling and increasing power transfer level of a system by varying the apparent impedance of a specific transmission line. A TCSC can be utilized in a planned way for contingencies to enhance power system stability. Using TCSC, it is possible to operate stably at
power levels well beyond those for which the system was originally intended without endangering system stability [17]. Apart from this, TCSC is also being used to mitigate SSR (sub synchronous resonance).

4.2.2 Configuration

TCSC is a series compensating FACTS device using to control power flow in transmission lines and improves transient stability in power system. TCSC controls the power flow in transmission lines by varying the impedance of TCSC by controlling the delay angle of thyristor valves. The basic scheme of TCSC [5] [19] [33] is shown in Fig. 4.1. It consists of the series controlled capacitor shunted by a Thyristor controlled Reactor.

The impedance ($X_{TCSC}$) of TCSC for different values of delay angle ($\alpha$) of thyristor valves is shown in Fig.4.2. The TCSC has two operating ranges around its internal circuit resonance ($\alpha_r$): One is the $\alpha_{Clim} \leq \alpha \leq 180^\circ$ Where $X_{TCSC}(\alpha)$ is capacitive, and the other is the $90^\circ \leq \alpha \leq \alpha_{Llim}$ where $X_{TCSC}(\alpha)$ is inductive. The internal circuit resonance depends on the ratio between Inductor and Capacitor reactance of TCSC. Different ratios of reactance yield different resonance points ($\alpha_r$) [26].

![Basic scheme of TCSC](image)
4.2.3 Modes of operation

TCSC can operate in three modes [24]. They are

(i) Thyristor blocked (no gating and zero thyristor conduction) shown in Fig.4.3 (a).

(ii) Thyristor bypassed (continuous gating and full thyristor conduction) shown in Fig.4.3 (b).

(iii) Vernier operation with phase control of gating signals shown in Fig.4.3(c) and 4.3(d).

- In case of blocked operating mode, the TCSC net impedance is just capacitive reactance.
- In case of bypass mode, as the thyristors are fully conducting, most of the line current flows through thyristors and hence TCSC has small net inductive reactance.
In Vernier control, thyristors are conducted in such a manner that a controlled amount of inductive current can circulate through the capacitor, thereby increasing effective capacitive/inductive reactance of the module.

![Diagram](image)

**Fig. 4.3.** Modes of TCSC operation

### 4.2.4 TCSC model

The basic scheme of TCSC is shown in Figure 1. The overall reactance of the TCSC is given in terms of delay angle (α) as [19]

\[
X_{TCSC} (\alpha) = B_1 (X_C + B_2) - B_4 B_5 + X_C
\]

(4.1)

Where

\[
B_1 = \frac{2(\pi - \alpha) + \text{Sin} 2(\pi - \alpha)}{\pi}, \quad \text{------------------------}(4.2)
\]

\[
B_2 = X_C X_L / (X_C - X_L), \quad \text{------------------------}(4.3)
\]

\[
B_3 = \sqrt{(X_C / X_L)}, \quad \text{------------------------}(4.4)
\]

\[
B_4 = B_3 \tan [B_3 (\pi - \alpha)] - \tan (\pi - \alpha), \quad \text{------------------------}(4.5)
\]

\[
B_5 = 4B_2^2 \cos^2 (\pi - \alpha) \quad \text{------------------------}(4.6)
\]

\[
X_C = \text{Reactance of TCSC capacitor} = 1/(2\pi f C)
\]
\[ X_L = \text{Reactance of TCSC inductor} = 2\pi f L \]
\[ f = \text{Supply frequency} \]

### 4.2.5 Power Flow Controller for TCSC

Commonly used operating modes of TCSC are

i) Constant impedance mode.

ii) Constant power control mode

The structure for power flow controller of TCSC is as shown in Fig.4.4 operates in constant power control mode. \(X_{TCSC}\) is controlled to meet the power demand in the line set by the reference power set point \(P_{\text{ref}}\). The input signals to this controller are reference power \(P_{\text{ref}}\) signal and actual power flowing through line \(P_{\text{m}}\). The output is the appropriate reactance \(X_{TCSC}\) required to the system as per the reference power \(P_{\text{ref}}\).

![Fig.4.4 Power flow controller diagram for TCSC](image)

### 4.2.6 TCSC Controller model for Stability

The Fig.4.5 shows the general block diagram of the TCSC controller for dynamic and steady state stability studies [17] [18] [20]. It consists of Power flow controller and stability controller. Power flow controller is used to control power flow in the transmission line under
steady state condition by comparing power flow in transmission line with reference power set point. If this controller is slow due to the large time constant of PI controller or if it is manually operated, the output (X₀) of power flow controller is to be constant during large disturbances, because of this power oscillations increase. To reduce power oscillations the TCSC must be in a position to provide maximum compensation level immediately after the fault is cleared. This is achieved by adding the stability control loop to power flow control loop as shown in Fig.4.4. The stability controller gives modulation reactance (Xₘ) during transient or dynamic periods. The sum of two outputs (X₀) of power flow controller and (Xₘ) of the stability controller yields the X' which is the final value of reactance required to the system during transient and dynamic periods.

**Fig.4.5** TCSC controller model for stability studies

### 4.2.7 SIMULINK Modeling of TCSC

The SIMULINK TCSC block developed as a phasor model, to perform dynamic and transient stability studies in 3-Ph power systems. In this thesis TCSC assumed as an ideal one and X<sub>TCSC</sub> is
controlled to meet the power demand in the line set by the reference power set point ($P_{ref}$).

### 4.2.7.1 PIPF controller of TCSC

The SIMULINK model block diagram for PIPF controller of TCSC is shown in Fig.4.6.

This controller consists of

- **PI controller:** It gives the appropriate reactance ($X_0$) as per the power error ($P_{ref} - P_m$). Where
  
  $P_{ref} = $ Reference Power setting and $P_m = $ Measured power flow through Transmission line

- **$X$ to alpha converter block:** as per the Characteristics shown in Fig.4.2 It gives equivalent alpha to the Reactance ($X_0$).

- **$X_{TCSC}$ calculation block:** as per Equation 4.1 it gives the reactance to insert into the Transmission line

![PIPF controller of TCSC block diagram](image)

**Fig.4.6** PIPF controller of TCSC block diagram
4.2.7.2 Fuzzy Logic Power Oscillation Damping (FLPOD) controller along with Proportional and Integral Power Flow (PIPF) Controller of TCSC

The SIMULINK model block diagram for FLPOD controller along with PIPF controller of TCSC is shown in Fig.4.8. FLPOD controller is fed by one input that is change in power or difference in power (DP). This gives the appropriate reactance ($X_m$), which is required by the system in dynamic condition. Under steady state condition, it gives zero reactance. The PIPF controller gives appropriate reactance ($X_0$) as per the setting of $P_{ref}$. The block diagram of FLPOD for TCSC is as shown in figure 4.7(a)

![Fig. 4.7(a) Block diagram of FLPOD for TCSC](image-url)
The rules for the proposed FLPOD controller are:

i) If ‘DP’ is ‘DPN’ Then ‘X\textsubscript{m}’ is ‘XN’

ii) If ‘DP’ is ‘DPZ’ Then ‘X\textsubscript{m}’ is ‘XZ’

iii) If ‘DP’ is ‘DPP’ Then ‘X\textsubscript{m}’ is ‘XP’

These rules are in matrix form as given below

<table>
<thead>
<tr>
<th>error (DP)</th>
<th>Out put (X\textsubscript{m})</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPN</td>
<td>XN</td>
</tr>
<tr>
<td>DPZ</td>
<td>XZ</td>
</tr>
<tr>
<td>DPP</td>
<td>XP</td>
</tr>
</tbody>
</table>

The membership functions for input and output of FLPOD controller, Change in power (DP) and reactance (X\textsubscript{e}) are given in Fig.4.7 (b).

**Fig.4.7 (b)** (a) Input membership function (DP) and (b) Output membership function (X\textsubscript{m}) of FLPOD controller
4.3  Static Synchronous Series Compensator (SSSC)

4.3.1 Configuration and operation

The basic scheme of SSSC is shown in Fig.4.9. The SSSC is a series compensation device of the FACTS family using power electronics based on the voltage source converter (VSC) to control power flow in transmission lines and improve transient stability in power system [33]. The SSSC controls the power flow in transmission lines by controlling the magnitude and phase angle of injected voltage ($V_{sc}$) in series with the transmission line where SSSC is connected. The exchange of real and reactive power between SSSC and power system depends on the magnitude and phase displacement with respect to transmission line current.
The Fig. 4.10 shows the four-quadrant operation of SSSC. The line current $I$, is taken as reference phasor while the series injected voltage phasor $V_{se}$ of SSSC is allowed to rotate around the center of the circle defined by the maximum inserted voltage $V_{se\text{-max}}$.

In Capacitive mode of operation, the series injected voltage $V_{se}$ of SSSC is made lag by $90^\circ$ with transmission line current. In this case the SSSC operates like series capacitor with variable capacitance $kX_C$, i.e., $V_{se} = -kX_C*I$, where $k$ is variable. By this action the total reactance of transmission line is reduced while the voltage across the line is increased. This leads to increase in the line current and hence the transmitted power.

In the case of inductive mode of operation, the series injected voltage $V_{se}$ of SSSC is made to lead by $90^\circ$ with transmission line current, i.e., $V_{se} = kX_C*I$. This leads to increase in the transmission line reactance, which results in a decrease in line current and hence the transmitted power. The above equation shows that the magnitude of $V_{se}$ is directly proportional to the line current ($I$) magnitude, this is true for series capacitance, but not for SSSC. Actually the series inserted voltage $V_{se}$ is set by the SSSC control is independent of the line reactance.

The SSSC can control the power flow through the transmission line by controlling the magnitude of $V_{se}$ and injecting in quadrature with transmission line current $I$ as mentioned in the following equation
\[ V_{se} = V_2 - V_1 = V_d + jV_q \]
\[ V_d \approx 0 \]
\[ V_q > 0: \quad \text{SSSC is Capacitive} \]
\[ V_q < 0: \quad \text{SSSC is Inductive} \]

The magnitude of \( V_{se} \) is controlled through the changes in the amplitude modulation ratio \( m_{se} \), as the output voltage magnitude is directly proportional to \( m_{se} \) according to the following equation

\[ m_{se} = \sqrt{8 \times \frac{V_{se}}{V_{dc}}} \]

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**Fig. 4.9.** The basic scheme of SSSC

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**Fig. 4.10** four-quadrant operation of SSSC
4.3.2 V-I Characteristics of SSSC

The fig.4.11 shows the V-I Characteristic of SSSC. The SSSC can provide capacitive voltage and inductive voltage up to its specified maximum current rating. The SSSC can generate a controllable compensating capacitive or inductive voltage, which implies that the amount of transmittable power can be increased as well as decreased from natural power.

4.3.3 General diagram of SSSC for power flow control

Commonly used operating modes of SSSC are

i) Constant voltage injection mode.

ii) Constant impedance emulation mode.
iii) Constant power control mode

The Fig.4.12 shows the general diagram of SSSC for power flow control. This control system is operating based on the power reference values. It consists of

- **PI controller:** Two separate PI controllers are used to control active and reactive power in the transmission line. The outputs of PI controllers are d, q components of the series injected voltage.
- **Power measurement block:** It calculates the active and reactive power flow through the transmission line.
- **SSSC series inject voltage computation block:** This block computes the SSSC output voltage magnitude and the angle depends on the outputs of PI controllers.

### 4.3.4 Power Flow Controller for SSSC

In this thesis, the power flow controller is constant real power flow controller. Structure for the power flow controller of SSSC [21] [23] [25] as shown in Fig.4.13 operates in constant power control mode. Vseq is controlled to meet the power demand in the line set by the reference power set point \((P_{\text{ref}})\). The input signals to this controller are reference power \((P_{\text{ref}})\) signal and actual power flowing through line \((P_m)\). The output is the appropriate series injected
voltage \((V_{seq})\) required by the system as per the reference power \((P_{ref})\).

**4.3.5 SSSC controller model for Stability studies**

The Fig.4.14 shows the general block diagram of the SSSC controller for dynamic and steady state stability studies \([10][21][27]\). It consists of Power flow controller and stability controller. Power flow controller is used to control power flow in the transmission line under steady state condition by comparing power flow in transmission line with reference power set point. If this controller is slow due to the large time constant of PI controller or if it is manually operated, the output \((V_{seq0})\) of power flow controller is to be constant during large disturbances, because of this power oscillations increase. To reduce power oscillations the SSSC must be in a position to provide maximum compensation level immediately after the fault is cleared. This is achieved by adding the stability control loop to power flow control loop as shown in Fig.4.12. The stability controller gives modulation series injected voltage \((V_{seqm})\) during transient or dynamic periods. The sum of two outputs \((V_{seq0})\) of power flow controller and \((V_{seqm})\) of the stability controller yields the \(V_{seq}'\) which is the final value of injected series voltage required by the system during transient and dynamic periods.
Fig. 4.12  General Control diagram of SSSC for power flow control

Fig. 4.13  Power flow controller diagram for SSSC

Fig. 4.14  SSSC controller model for stability studies
4.3.6 SIMULINK Modeling of SSSC

The SIMULINK SSSC block developed as a phasor model, to perform dynamic and transient stability studies in 3-Ph power systems. The SSSC inject series injected voltage (Vq) is controlled to meet the power demand in the line set by the reference power set point (P_{ref}).

4.3.6.1 PI Power Flow controller of SSSC

The SIMULINK model for PIPF controller of SSSC is shown in Fig.4.15. This controller gives the appropriate series injected quadrature voltage required by the system as per the reference Power (P_{ref}).

![Fig.4.15 PIPF Controller block diagram of SSSC](image)

4.3.6.2 FLPOD controller along with PIPF Controller of SSSC

The SIMULINK model block diagram for FLPOD controller along with PIPF controller of SSSC is shown in Fig.4.17. FLPOD controller is fed by one input that is change in power or difference in power (DP). This gives the appropriate injected series voltage (Vqm), which is
required by the system in dynamic condition; under steady state condition it gives zero injected series voltage. The PIPF controller gives injected series voltage \(V_q0\) as per the setting of \(P_{ref}\). The block diagram of FLPOD for SSSC is as shown in figure 4.16(a)

![FIS Editor: FLPOD_SSSC](image)

**Fig. 4.16(a) Block diagram of FLPOD for SSSC**

The rules for the proposed FLPOD controller are:

i) If ‘DP’ is ‘DPN’ (DP Negative) Then ‘Vq’ is ‘VqN’ (Vq Negative)

ii) If ‘DP’ is ‘DPZ’ (DP Zero) Then ‘Vq’ is ‘VqZ’ (Vq Zero)

iii) If ‘DP’ is ‘DPP’ (DP Positive) Then ‘Vq’ is ‘VqP’ (Vq Positive)
These rules are in matrix form as given below

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The membership functions for input and output of FLPOD controller, Change in power (DP) and series injected voltage (Vq) are given in Fig.4.16 (b).

**Fig.4.16 (b)** (a) Input membership function (DP) and (b) Output Membership Function (Vq) of FLPOD controller

**Fig.4.17** FLPOD controller along with PIPF controller block diagram of SSSC
4.4 Summary

In this chapter details of TCSC and SSSC have been discussed. SIMULINK implementation of the TCSC and SSSC has been discussed. The TCSC and SSSC with PI and FLPOD controllers allow the controls line reactance and series injected reactive voltages respectively.