THE power flow through a transmission line is a function of line impedance, voltage magnitude and its phase angle. The most effective way to externally manipulate such a power flow is by injecting some form of additional series reactance or acting upon the transmission angle. The former is generally known as series compensation. The first attempts at series compensation were carried out by inserting fixed capacitance in series with the line in order to decrease the effective impedance of the line and therefore increase the power flow through it. The development of power semiconductor devices has allowed the use of thyristors to control the series capacitors and inductors for performing continuous control [1]. In addition modern switching devices with turn off capability have led to the development of voltage source inverters suitable for injecting quadrature voltage in series with the line, allowing power flow control. This voltage source inverter based series compensator is one of the FACTS controllers and is referred as static synchronous series compensator.

In this chapter SSSC is realized using the combined multipulse-multilevel inverter topology proposed in chapter 3. A closed loop control scheme is developed to determine the magnitude and appropriate angle at which the voltage is to be injected and there from control the power flow through the line. The PI regulators suffer from the inadequacies of providing suitable control under parameter variations, non-linearity and load disturbances over a wide range of power system operating conditions. The fuzzy-logic approach [98], on the other hand, provides a
model free approach and is suggested for the closed loop control with the view to enhance the performance of SSSC fed transmission line. The scope includes evaluating its performance in the automatic power flow control mode through MATLAB based simulation.

4.2 STATIC SYNCHRONOUS SERIES COMPENSATOR

The static synchronous series compensator is a synchronous voltage source capable of generating ac voltage of controllable magnitude and phase angle. It emulates an equivalent inductive or capacitive reactance through a series injection of voltage, in quadrature with the transmission line current [1, 17, 18]. It serves to enhance the power flow over the line and accomplish the desired reactive power compensation. The basic schematic diagram of the static synchronous series compensator with its test system [89] is shown in Fig.4.1. The specifications of the test system are given in APPENDIX - C.

![Fig. 4.1 230kV sample power system](image)

The sample power system is a 230 kV network equipped with the SSSC connected in series with the transmission system via series coupling transformer. The feeding network is represented by a Thevenin’s equivalent circuit at bus B₁ where the voltage source is 230 kV with a short circuit power level of 10,000 MVA.
The SSSC is placed between two sections B₁ and B₂ of the transmission line as shown in this figure. SSSC is rated at ±70 Mvar to provide the required dynamic series compensation. The compensator is equipped with a combined multipulse-multilevel inverter, which has the highest performance in providing a nearly sinusoidal waveform with extremely less total harmonic distortion.

4.3 FUZZY BASED CLOSED LOOP CONTROL SCHEME FOR SSSC

The main function of the static synchronous series compensator is to dynamically control the power flow over the transmission line. This is possible by operating the SSSC in the automatic power flow control mode, line impedance compensation mode, direct voltage injection mode or phase angle regulation mode [1, 55, 56]. However, the line impedance and automatic power flow modes are widely employed wherever series compensation is desired. The control scheme proposed by Anil C. Pradhan and P.W. Lehn [55] is based on the line impedance control mode in which the SSSC compensating voltage is derived by multiplying the current amplitude with the desired compensating reactance \( X_{q_{\text{ref}}} \). Since it is difficult to predict \( X_{q_{\text{ref}}} \) under varying network contingencies, in the proposed scheme, this controller is modified to operate the static synchronous series compensator in the automatic power flow control mode.

In this mode the reference input to the controller are \( P_{\text{ref}} \) and \( Q_{\text{ref}} \), which are to be maintained in the transmission line despite of system changes. The instantaneous real and reactive powers over the transmission line, derived from the instantaneous power theory [99] is given by

\[
\begin{bmatrix}
P \\
Q
\end{bmatrix} = \frac{3}{2} \begin{bmatrix}
V_d & V_q \\
-V_q & V_d
\end{bmatrix} \begin{bmatrix}
I_d \\
I_q
\end{bmatrix}
\]

(4.1)

where

- \( P \) is the instantaneous real power flow over the transmission line
- \( Q \) is the instantaneous reactive power flow over the transmission line
- \( V_d \) and \( V_q \) are the direct and quadrature components of the transmission line voltage respectively.
\(I_d\) and \(I_q\) are the direct and quadrature components of the transmission line current respectively.

4.3.1 Fuzzy Logic Controller

The SSSC target is to stabilize the power flow over the transmission line where it is installed, by properly injecting a quadrature voltage of specified magnitude and phase angle. The scheme of the fuzzy logic controller is shown in the Fig.4.2. Two input variables namely the active and reactive power deviations are given as inputs to the FLC. The controller variables i.e., the output of the FLC is the required modulation index \(M_a\) and the angle \(\beta\).

![Fig. 4.2 Scheme of FLC](image)

Two trapezoidal and five triangular membership functions are chosen for both input and output variables. There are seven linguistic variables for each input variable and output variable namely positive large (PL), positive medium (PM), positive small (PS), zero (Z), negative small (NS), negative medium (NM) and negative large (NL). The membership functions are asymmetrical because near the origin, the signals require more precision. The adopted membership functions for the active power deviation and reactive power deviation are depicted in Figs. 4.3 and 4.4 respectively.
Fig. 4.3 Adopted membership functions for active power deviation

Fig. 4.4 Adopted membership functions for reactive power deviation
The control decisions are made on the basis of fuzzified linguistic variables. There are 49 (7×7) rules for a system with two control variables and seven linguistic variables as seen in Table 4.1. The min-max inference is applied to determine the degree of memberships for output variables. Defuzzification of fuzzy decision inferred from the fired rules is done using bisector method.

### Table 4.1 Rule table

<table>
<thead>
<tr>
<th>Change in error</th>
<th>Error</th>
<th>PL</th>
<th>PM</th>
<th>PS</th>
<th>Z</th>
<th>NS</th>
<th>NM</th>
<th>NL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>PL</td>
<td>PL</td>
<td>PL</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td></td>
</tr>
<tr>
<td>NM</td>
<td>PL</td>
<td>PL</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td>PL</td>
<td>PM</td>
<td>PS</td>
<td>PS</td>
<td>Z</td>
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<td>PL</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
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<tr>
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</tr>
</tbody>
</table>

### 4.3.2 Closed Loop Control

In the closed loop control scheme shown in Fig.4.5, the three phase voltages and currents sensed at B2 of transmission line (Fig.4.1) are transformed into two-phase quantities using Park’s transformation, which gives d-q axis currents and voltages for the controller. The actual real and reactive powers are calculated from these d-q components of currents and voltages, using equation (4.1) and compared with the desired P_ref and Q_ref respectively. The error components P_err and Q_err so obtained are stabilized through the fuzzy logic controller. The desired modulation index M_a of the PWM modulator is derived from the active power control part of the circuit. The reference angle $\theta_T$ to the PWM modulator is obtained as described in the phasor diagram [55] of Fig.4.6.
Fig. 4.5 SSSC closed loop control

Fig. 4.6 Phasor diagram of the controller
A phase locked loop is used to determine the instantaneous angle $\theta$ of the three phase voltage $v_{abc}$ sensed at $B_2$ (Fig. 4.1). The current components $I_d$ and $I_q$ are used to determine the amplitude of the current $|I|$ and its angle relative to $v_{abc}$, called $\theta_{ir}$. The required SSSC injected voltage angle is derived as follows:

$$\theta_{ir} = \theta - \theta_{ir} + \frac{\pi}{2} \pm \beta$$

(4.2)

where $\theta$ is the instantaneous angle of the line voltage

$\theta_{ir}$ is the angle between the line voltage and line current

$\beta$ is the small perturbation added to the inverter voltage angle needed to charge or discharge the capacitor voltage

The angle $\pm \pi/2$ is included in (4.2), to enable the quadrature injection of voltage with respect to line current. The angle $\beta$ is derived from the reactive power control part of the circuit. Using the modulation index $M_a$ and the angle $\theta_T$, the three phase reference values of the injected voltage are expressed as

$$V_{T_a}^* = M_a \sin \theta_T$$

$$V_{T_b}^* = M_a \sin (\theta_T + 2\pi/3)$$

$$V_{T_c}^* = M_a \sin (\theta_T - 2\pi/3)$$

(4.3)

where $V_T$ is the quadrature voltage injected in series with the line current.

These reference waveforms are used in the PWM modulator to generate the control pulses for the inverter switches.

4.4 SIMULATION RESULTS AND DISCUSSION

The performance of SSSC is evaluated through MATLAB based simulation, when it is operated in the automatic power flow control mode.

4.4.1 Steady State Response of SSSC

The initial load in the system is Load 1 with the ratings of $P = 300$ MW, $Q = 100$ MVAR connected at load bus $B_3$ through the circuit breaker $CB_1$. In order to
maintain the active and reactive powers over the line to the set reference values, the closed loop controller generates a modulating reference waveform with a modulation index of 0.65 and reference angle 148° as depicted in Figs.4.7 and 4.8. This enables the SSSC to inject a quadrature voltage as shown in Fig.4.9. Since the injected voltage is lagging the line current; emulates capacitive reactance thereby maintaining the power flow over the line to the set reference value as described in Fig.4.10.

![Fig. 4.7 Modulation index for the PWM modulator – single load](image)

![Fig. 4.8 Reference angle for the PWM modulator – single load](image)
Fig. 4.9 SSSC injected voltage and transmission line current – single load

Fig. 4.10 Real and reactive power flow over the line – single load
4.4.2 Transient Response of SSSC under Variable Load

The various transient disturbances due to faults and load variations are created to study the performance of the fuzzy logic controller for SSSC. The initial load in the system is Load 1 with the ratings of \( P = 350 \text{ MW}, \ Q = 75 \text{ MVAR} \) and is disconnected at time \( t = 0.3 \text{ s} \) and Load 2 with ratings of \( P = 400 \text{ MW}, \ Q_L = 100 \text{ MVAR} \) is connected to the system. The transmission line current is lagging the line voltage by an angle \( \theta_{ir} \) as shown in Fig.4.11. The phase angle difference between the line current and voltage is separately highlighted in Fig.4.12. Based on the angle \( \theta_{ir} \) and the amount of desired real and reactive power flow over the transmission line, the closed loop controller generates a modulating reference waveform to the PWM modulator. The variations of the modulation index \( (M_a) \) and the reference angle \( (\theta_T) \) of the PWM modulator are depicted in Figs.4.13 and 4.14 respectively for the load variation given at \( t = 0.3 \text{ s} \).

![Fig. 4.11 Transmission line voltage and current under varying load](image-url)
Fig. 4.12 Phase angle between line current and voltage

Fig. 4.13 Modulation index under varying load
Fig. 4.14 Reference angle for the PWM modulator under varying load

Using the reference angle and modulation index the voltage source inverter generates voltage of desired magnitude and phase angle, and is injected in series with the transmission line as shown in Fig.4.15. This series injected voltage lags the line current by an angle ($\delta$) less than 90° as described in Fig.4.16 and thereby provides capacitive compensation.

The series injected voltage with desired magnitude and angle enables the active and reactive power of the transmission line to track the set reference values namely $P_{ref} = 0.6$ pu and $Q_{ref} = 0.25$ pu irrespective of load variations as depicted in Fig.4.17. However with PI controller for the same load variation given at $t = 0.3$ s, the real and reactive power do not follow the set reference values. The real power reduces to 0.55 pu and reactive power enhances to 0.27 pu as shown in the Fig.4.18. This proves the robustness of the fuzzy logic controller over the conventional PI controller.
Fig. 4.15 SSSC injected voltage and transmission line current under varying load

Fig. 4.16 Phase angle between the line current and injected voltage
Fig. 4.17 Real and reactive power flow over the line with FLC

Fig. 4.18 Real and reactive power flow over the line with PI controller
In addition the system performance is evaluated when a three phase fault is applied at \( t = 0.3 \) s and cleared at \( t = 0.35 \) s as described in Fig. 4.19. P and Q of the transmission line settle to the reference values within a small interval of time after the fault is cleared and this proves the transient stability of the proposed FLC for SSSC.

![Graph showing real and reactive power flow over the line for a three phase fault](image)

**Fig. 4.19 Real and reactive power flow over the line for a three phase fault**

### 4.5 SUMMARY

A combined multipulse-multilevel inverter has been operated suitably to depict the behaviour of SSSC. A closed loop fuzzy logic control scheme has been developed for operating the SSSC in the automatic power flow control mode. The parameters of the fuzzy controller have been varied widely by a suitable choice of membership functions and parameters in the rule base.

It is inferred from the results that the FLC is a viable controller for the SSSC in order to maintain the real and reactive power flow over the transmission line to follow the set reference values under a variety of transient disturbances including high and low load conditions.