CHAPTER 3

MODELING OF UPFC FOR ENHANCEMENT OF POWER SYSTEMS STABILITY

3.1 INTRODUCTION

The control of AC power flow is a function of the transmission line impedance, the magnitude of the sending and receiving end voltages and the phase angle between these voltages. The idea behind Flexible AC Transmissions (FACTS) concept is to control these parameters in real time and there by vary (increase or decrease) almost instantaneously the transmitted power according to prevailing system conditions. The ability to control power rapidly within appropriately, defined boundaries can increase the transient (first swing) stability, as well as damping of the system. Increased transient stability and damping allow a corresponding increase in the transmittable steady-state power and thus a higher utilization of the system (Prabha Kundur 1994, Johns and Song 1999).

Again due to steady increase in power demand, maintaining power system stability becomes a difficult and very challenging problem. The aim of this section of dissertation is to examine the ability of FACTS devices, such as Unified Power Flow Controller in damping of electromechanical oscillations in a power system. The UPFC is one of the most versatile flexible AC transmission system devices, which is a pair of back-to-back power electronic converters, can be used to control the active and reactive power flows in a transmission line by injecting a variable voltage in series and
reactive current in shunt. A dynamic model of Unified Power Flow Controller has been developed. This model can also be used to represent the system with a Static Synchronous Compensator or a Static Synchronous Series Compensator. The control strategy is based on d-q axis theory. In the present work two different types of controllers are proposed for UPFC, namely Genetic Algorithm (GA) tuned Proportional Integral (PI) and Single–Input Fuzzy Logic Controller (SFLC). The above information is used in the Single Machine Infinite Bus (SMIB) for carrying out transient stability studies.

### 3.1.1 Basic Circuit Configuration of UPFC

The advent of advanced power electronics technology has enabled the use of voltage source inverters (VSI) at both the transmission and distribution levels. A stream of VSI based systems such as UPFC, STATCOM and SSSC has made the design of FACTS (Hingorani and Gyugyi 2000) possible. Successful applications of FACTS equipment for power flow control, voltage control and transient stability improvement have been reported in the literature (Nabavi and Iravani 1996, Renz et al 1999, Kannan et al 2004, Eskandar and Shahrokh 2005).

In recent years increasing interest has been seen in applying fuzzy theory (Lee 1990) to controller design in many engineering fields. This chapter focuses on the use of UPFC with SFLC (Byung-Jae Choi et al 2000) for the Shunt and Series Inverter of the UPFC for transient stability improvement and voltage control of power system. The principal function of the UPFC is to control the flow of real and reactive power by injecting a voltage in series with the transmission line. The UPFC consists of two solid-state voltage source inverters connected by a common dc link that includes a storage capacitor (shown in Figure 3.1).
Figure 3.1 Basic circuit configuration of the UPFC

The first inverter (shunt inverter) known as a STATCOM (Static Synchronous Compensator) injects an almost sinusoidal current of variable magnitude at the point of connection. The second inverter (series inverter), known as SSSC (Static Synchronous Series Compensator) provides the main functionality of the UPFC by injecting an AC voltage $V_c$, with a controllable magnitude ($0 \leq V_c \leq V_c^{\text{max}}$) and phase angle ($\geq 0^\circ$, $\leq 360^\circ$). Thus, the complete configuration operates as an ideal AC to AC power converter in which real power can flow freely in either direction between the AC terminals of the two inverters. The phasor diagram in Figure 3.1 illustrates that the UPFC is able to inject a controlled series voltage $V_c$ into the transmission line. Thus, the magnitude and angle between the sending and receiving end of the transmission line are modulated resulting in power flow control in the transmission line. Therefore, the active power controller can significantly affect the level of reactive power flow and vice versa. In order to improve the dynamic performance and reduce the interaction between the active and reactive power control, the watt-var decoupled control algorithm has been
proposed. In addition, each inverter can independently modulate reactive power at its own AC output terminal.

The remainder of the chapter is organized as follows. At first, the modeling of synchronous generator along with AVR and PSS, modeling of UPFC and the conventional control scheme of a UPFC have been described along with a study of the simulation results under transient disturbance. Subsequently, the design of the proposed SFLC for the Shunt and Series inverter of UPFC has been derived followed by a comparative evaluation of this new controller’s performance via computer simulation results. Finally, the conclusions of this study are reported.

3.2 MATHEMATICAL MODEL OF UPFC

Single machine infinite bus power system is considered in this work. The load and the UPFC are connected at the load bus located between the generator bus and the infinite-bus. The mathematical models for the system components along with their control systems are described as follows:

3.2.1 Synchronous Generator Modeling

The synchronous generator is described by a third-order nonlinear mathematical model given by equation (3.1 to 3.3).

\[
\frac{d\Delta \delta}{dt} = \Delta \omega
\]  

(3.1)

\[
\frac{d\Delta \omega}{dt} = \frac{1}{M} \left[ P_m - E'_q i_q - (x_q - x'_q) i_d i_q \right]
\]  

(3.2)

\[
\frac{dE'_{q}}{dt} = \frac{1}{T_{do}} \left[ E_{id} - E_{q}' - (x_d - x'_d) i_d \right]
\]  

(3.3)

where \( \Delta \delta = \delta - \delta_0 \) and \( \Delta \omega = \omega - \omega_0 \).
The excitation system of the generator consists of a simple automatic voltage regulator (AVR) along with a supplementary power system stabilizer (PSS). The complete AVR + PSS control system is shown in Figure 3.2.

Figure 3.2 AVR Exciter and PSS control system

3.2.2 Dynamical Modeling of UPFC

Figure 3.3 shows the equivalent circuit model of a power system equipped with a UPFC. The series and shunt VSIs are represented by controllable voltage sources $V_c$ and $V_p$ respectively. $R_p$ and $L_p$ represent the resistance and leakage reactance of the shunt transformer.

Figure 3.3 One-line circuit diagram model of UPFC installed in a power system
The dynamic model of UPFC is derived by performing standard d-q transformation of the current through the shunt transformer and series transformer and is presented in equations (3.4 to 3.7).

**Shunt Inverter**

\[
\frac{di_{pd}}{dt} = \frac{R_p}{L_p} i_{pd} + \omega i_{pq} + \frac{1}{L_p} (V_{sd} - V_{pd}) 
\]

(3.4)

\[
\frac{di_{pq}}{dt} = \frac{R_p}{L_p} i_{pq} - \omega i_{pd} + \frac{1}{L_p} (V_{sq} - V_{pq}) 
\]

(3.5)

**Series Inverter**

\[
\frac{di_{bd}}{dt} = -\frac{w_br_e}{x_e} i_{bd} + \omega i_{bq} + \frac{w_b}{x_e} (V_{ud} - V_b \sin \delta) 
\]

(3.6)

\[
\frac{di_{bq}}{dt} = -\frac{w_br_e}{x_e} i_{bq} - \omega i_{bd} + \frac{w_b}{x_e} (V_{uq} - V_b \cos \delta) 
\]

(3.7)

where \( \omega \) is the angular frequency of the voltages and currents.

For fast voltage control, the net input power should instantaneously meet the charging rate of the capacitor energy. Thus, by applying power balance conditions, we get equation (3.8).

\[
P_s - P_u = V_{sd} (i_{pd} + i_{bd}) + V_{sq} (i_{pq} + i_{bq}) - (V_{ud} i_{bd} + V_{uq} i_{bq}) \\
= V_{dc} i_{dc} \\
= V_{dc} \left[ C \frac{dV_{dc}}{dt} + g_{cp} V_{dc} \right] 
\]

(3.8)

Thus, equation 3.8 can be rearranged and written as given in equation (3.9).

\[
\frac{dV_{dc}}{dt} = \frac{g_{cp} \omega}{b_{cp}} V_{dc} + \frac{1}{CV_{dc}} \left[ V_{ud} i_{pd} + V_{uq} i_{pq} + (V_{sd} - V_{ud}) i_{bd} + (V_{sq} - V_{uq}) i_{bq} \right] 
\]

(3.9)
3.3 CONVENTIONAL CONTROL STRATEGY FOR UPFC

Different controllers have been designed for the UPFC for reliable and fast operation. As discussed earlier the UPFC has two VSIs connected back to back. One can take the advantages to utilize any one of the VSI by switching off the second one. The Shunt inverter injects an almost sinusoidal current of magnitude, at the point of connection. There are two control objectives in UPFC control, i.e., Shunt inverter control and Series inverter control. For the Shunt inverter there are two voltage regulators designed for this purpose: AC bus voltage regulators and DC voltage regulator. The real and reactive power flow in the line can be controlled independently using the series injected voltage which meets almost instantaneously to a command and this voltage is generated by series inverter. The shunt inverter injects a controlled shunt current (indirectly) by varying the shunt inverter voltage. This inverter is responsible for AC-bus and DC-link voltage control (indirectly). Therefore, in the PI control scheme, the control strategies for both the inverters are addressed separately. The modeling and control design are carried in the standard synchronous d-q frame.

3.3.1 Series Inverter Control

An appropriate series voltage (both magnitude and phase) should be injected for obtaining the commanded active and reactive power flow in the transmission line, i.e., \((P_u, Q_u)\). The current references are computed from the desired power references and are given by equations (3.10 and 3.11),

\[
\begin{align*}
    i_{cd}^{\text{ref}} &= \frac{P_{\text{ref}} V_{ud} - Q_{\text{ref}} V_{uq}}{V_u^2} \quad \text{(3.10)}
    \\
    i_{cq}^{\text{ref}} &= \frac{P_{\text{ref}} V_{uq} - Q_{\text{ref}} V_{ud}}{V_u^2} \quad \text{(3.11)}
\end{align*}
\]
The power flow control is then realized by using appropriately designed controllers to force the line currents to track their respective reference values. Conventionally, two separate PI controllers are used for this purpose. These controllers output the amount of series injected voltages \( V_{cd}, V_{cq} \). The block diagram of series inverter control system is shown in Figure 3.4.

\[
\begin{align*}
P_{\text{ref}} & \rightarrow \text{Equations (3.10) and (3.11)} \\
Q_{\text{ref}} & \rightarrow \Sigma \quad K_{pd} = \frac{K_{id}}{s} \quad V_{cd} \\
& \quad + \quad i_{ed} \\
& \quad + \quad i_{ref} \\
& \quad i_{cq} \\
& \quad K_{pq} = \frac{K_{iq}}{s} \quad V_{cq} \\
& \quad - \quad i_{cq}
\end{align*}
\]

Figure 3.4 Series inverter control structure for UPFC

### 3.3.2 Shunt Inverter Control

As mentioned earlier, the conventional control strategy for this inverter concerns with the control of ac-bus and dc-link voltage. The dual control objectives are met by generating appropriate current reference (for \( d \)– and \( q \)–axis) and then, by regulating those currents. PI controllers are conventionally employed for both the tasks while attempting to decouple the \( d \)– and \( q \)–axis current regulators.

\[
\begin{align*}
q' & \rightarrow q \\
d' & \rightarrow d \\
V_s & \rightarrow \delta_s
\end{align*}
\]

Figure 3.5 Phasor diagram showing \( d \)-\( q \) and \( d' \)-\( q' \) frame
In this study the strategy adopted in Padiyar and Kulkarni (1998) for shunt current control has been taken. The inverter current \(i_p\) is split into real \(i_{pd}\) (in phase with ac-bus voltage) and reactive components. The reference value for the real current is decided so that the capacitor voltage is regulated by power balance. The reference for reactive component is determined by ac-bus voltage regulator. As per the strategy, the original currents in d-q frame \((i_{pd}, i_{pq})\) are now transformed into another frame, \(d'-q'\) frame, where \(d'\)-axis coincides with the ac-bus voltage \(V_s\), as shown in Figure 3.5. Thus, in \(d'-q'\) frame, the currents \(i_{pd'}\) and \(i_{pq'}\) represent the real and reactive currents and are given by equations (3.12 and 3.13).

\[
i_{pd'} = i_{pd} \cos \delta_s + i_{pq} \sin \delta_s \tag{3.12}
\]
\[
i_{pq'} = i_{pq} \cos \delta_s - i_{pq} \sin \delta_s \tag{3.13}
\]

Now, for current control, the same procedure has been adopted by re-expressing the differential equations as given in equations (3.14 to 3.18).

\[
\frac{di_{pd'}}{dt} = -\frac{R_p}{L_p} i_{pd'} + \omega_i i_{pq'} + \frac{1}{L_p} (V_s - V_{pd'}) \tag{3.14}
\]
\[
\frac{di_{pq'}}{dt} = -\omega_i i_{pd'} - \frac{R_p}{L_p} i_{pq'} + \frac{1}{L_p} (-V_{pq}) \tag{3.15}
\]

where

\[
V_{pd} = V_{pd} \cos \delta_s + V_{pq} \sin \delta_s \tag{3.16}
\]
\[
V_{pq} = V_{pq} \cos \delta_s - V_{pd} \sin \delta_s \tag{3.17}
\]

and

\[
\omega = \omega_0 + \frac{d \delta}{dt} \tag{3.18}
\]
The VSI voltages are controlled as given in equations (3.19) and (3.20).

\[ V_{pq} = -\omega L_p i_{pd'} + L_p u_{qd'} \]  \hspace{1cm} (3.19)

\[ V_{pd} = \omega L_p i_{pq'} + V_s - L_p u_{dq} \]  \hspace{1cm} (3.20)

By substituting the above expressions for \( v_{pd'} \) and \( v_{pq} \) in equations (3.14) and (3.15), the following sets of decoupled equations are obtained.

\[ \frac{di_{pd'}}{dt} = -\frac{R_p}{L_p} i_{pd'} + u_{dq} \]  \hspace{1cm} (3.21)

\[ \frac{di_{pq'}}{dt} = -\frac{R_p}{L_p} i_{pq'} + u_{dq} \]  \hspace{1cm} (3.22)

Conventionally, the control signals \( u_{dq} \) and \( u_{dq} \) are determined by linear PI controllers. The complete cascade control architecture is shown below in Figure 3.6, where \( K_{pd}, K_{iq}, K_{pc}, K_{ic}, K_{p}, K_{iq}, K_{pd}, \) and \( K_{id} \) are the respective gains of the PI controllers.

**Figure 3.6 Shunt inverter control structure for UPFC**

In this study, the above design was used for demonstration of UPFC control scheme. This approach leads to good control as illustrated by the simulation results shown in later section (3.5). However, it must be
emphasized here that the decoupling approach taken in the above is not able to decouple the d-q currents completely because of the coupled equations (3.19) and (3.20) and finally, in the frame transformation from $d' - q'$ to $d - q$. Moreover, there are several PI controller gains to be determined for an effective control of the complete system. Further, the above decoupling technique does not take into account the coupling resulting through the dc-capacitor voltage. The tuning of conventional Proportional Integral control is time consuming, as the tuning is based on trial and error method. This is overcome by using Genetic Algorithm (GA) based PI controller.

The important stage of the design of UPFC involves tuning of parameters of UPFC, which is posed as an optimization problem. In this problem the optimal output gain $K_0$ are determined by maximizing the damping of transient voltage oscillations of the bus voltage being controlled. This is in effect carried out by minimizing Sum Squared Deviation (SSD) of the bus voltage being controlled from the desired value through non-linear simulation of power system under typical operating condition and disturbance. The nonlinear simulation is carried using a Transient Stability algorithm employing Runge-Kutta method and the optimal search is carried out through Genetic Algorithm.

### 3.3.3 Tuning of UPFC Parameters Using Genetic Algorithm

Genetic Algorithms (GA) are computerised search and optimisation algorithms based on the mechanics of natural genetics and natural selection. The operation of GA begins with a population of random strings representing design or decision variables. Thereafter, each string is evaluated to find the fitness value. The population is then operated by three main operators – reproduction, crossover, and mutation – to create a new population of points. The new population is further evaluated and tested for termination. If the
termination criterion is not met, the population is iteratively operated by the
above three operators and evaluated. This procedure is continued until the
termination criterion is met. One cycle of these operations and the subsequent
evaluation procedure is known as a generation in GA’s terminology (Goldberg 1989). The optimization problem for a power system with UPFC is stated as follows:

Determine the optimal value of $K_0$ to minimize the Sum Squared Deviation index (SSDI) defined as follows:

$$\text{SSDI} = \sum_{k=1}^{n_t} [V(k) - V_{ss}]^2$$  \hspace{1cm} (3.23)

Subject to the following constraint:

$$K_{0\text{min}} < K_0 < K_{0\text{max}}$$

where $n_t$ - total number of samples up to the final time of simulation
$V(k)$ - the bus voltage at sampling time $t = k \Delta T$
$V_{ss}$ - bus voltage at the $n_t$th sampling interval

Comparing the fitness function of both the parents and off springs, the best strings will go for the next generation. Uniform crossover technique proposed is used in this work, by which the convergence speed is faster than the one-point and two-point crossovers. In this work the genetic iterations are stopped where the difference between the minimum fitness and maximum fitness is 0.001 or where the genetic iterations reached the maximum. Advantage of genetic-algorithm technique is that the parameter limits can be varied during the optimization, making the technique computationally efficient but the limitation is the computational time associated with this technique. GA parameters used for obtaining optimal PI parameter setting is mentioned in Table 3.1.
Table 3.1 GA control parameters used for obtaining optimal PI setting

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Generation</td>
<td>100</td>
</tr>
<tr>
<td>Size of population</td>
<td>30</td>
</tr>
<tr>
<td>String length</td>
<td>5</td>
</tr>
<tr>
<td>Crossover probability</td>
<td>0.85</td>
</tr>
<tr>
<td>Mutation probability</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Although, the PI control structure yields good performance, it is not very much effective for all operating conditions because of the unsuitability of one set of PI gains for all four regulators of the cascade controllers and the inherent coupling between the d and q axis. In essence, since the complete model is highly nonlinear, the linear approach obviously does not offer better dynamic decoupling. All these difficulties always demand better and deeper modern control engineering approach.

3.4 SINGLE - INPUT FLC

The Fuzzy Logic Controller (FLC) scheme has been robust over PI controller (Lo and Laiq 2000, Dash et al 2004). But the number of rules of FLC scheme can be reduced by using the proposed scheme namely Single input Fuzzy Logic Controller (SFLC). The SFLC uses only one input variable which is called as signed distance. Also in SFLC the total numbers of rules are greatly reduced compared to existing fuzzy logic controllers and hence, generation and tuning of control rules are much easier. The SFLC (Byung-Jae Choi et al 2000) design has been tested by computer simulations under various types of large disturbances occurring in a single-machine infinite-bus power system equipped with AVR and PSS. The comparison of the results
with conventional GA tuned PI cascaded control structure of UPFC reveals the supremacy of the SFLC.

### 3.4.1 Design of SFLC

In existing fuzzy logic controllers (FLC), input variables are mostly the error \( e \) and the change-of-error \( \dot{e} \) regardless of complexity of controlled plants. Either control input \( u \) or the change of control input \( \Delta u \) is commonly used as its output variable. A rule table is then constructed on a two-dimensional (2-D) space. This scheme naturally inherits from conventional proportional-derivative (PD) or proportional-integral (PI) controller. Observing that 1) rule tables of most FLC’s have skew-symmetric property and 2) the absolute magnitude of the control input \( |u| \) or \( |\Delta u| \) is proportional to the distance from its main diagonal line in the normalized input space, a new variable called the *signed distance* is derived, which is used as a sole fuzzy input variable in our simple FLC called *single-input FLC* (SFLC). The SFLC has many advantages: The total number of rules is greatly reduced compared to existing FLC, and hence, generation and tuning of control rules are much easier.

The rule form for the conventional (PI-type) FLC using two fuzzy input variables of the error and the change-of-error is as follows:

If \( e \) is \( LE_i \) and \( \dot{e} \) is \( LDE_i \) is then \( u \) is \( LU_{ij} \) where \( i = 1, 2, \ldots M \) and \( j = 1, 2, \ldots N \), are the linguistic values taken by the process state variables \( e \), \( \dot{e} \) and \( u \) respectively. Here the number of control rules is \( M \times N \). In case of complex higher order plants, fuzzy input variables generally require all process states. Then the number of rules is numerous and generation and tuning of rules is very difficult. Hence, PD or PI-type FLC is used in many applications regardless of the complexity of the controlled plants.
We first consider a control rule table of conventional FLC with the control rule form, when every five linguistic values for error, change-of-error and control input are used, a typical rule table is as shown in Table 3.2 with 25 rules.

Table 3.2 Rule base matrix for conventional FLC

<table>
<thead>
<tr>
<th>e</th>
<th>LE₂</th>
<th>LE₁</th>
<th>LE₀</th>
<th>LE₁</th>
<th>LE₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDE₂</td>
<td>LU₀</td>
<td>LU₁</td>
<td>LU₂</td>
<td>LU₂</td>
<td></td>
</tr>
<tr>
<td>LDE₁</td>
<td>LU₂</td>
<td>LU₀</td>
<td>LU₁</td>
<td>LU₂</td>
<td></td>
</tr>
<tr>
<td>LDE₀</td>
<td>LU₂</td>
<td>LU₂</td>
<td>LU₀</td>
<td>LU₁</td>
<td></td>
</tr>
<tr>
<td>LDE₂</td>
<td>LU₂</td>
<td>LU₂</td>
<td>LU₀</td>
<td>LU₁</td>
<td></td>
</tr>
<tr>
<td>LDE₁</td>
<td>LU₂</td>
<td>LU₂</td>
<td>LU₀</td>
<td>LU₁</td>
<td></td>
</tr>
</tbody>
</table>

In Table 3.2, subscripts –2, –1, 0, 1, and 2 denote fuzzy linguistic values of negative big (NB), negative small (NS), zero (ZR), positive small (PS) and positive big (PB), respectively. Similar to Table 3.2, most rule tables have skew-symmetric property, namely, \( U_{ij} = -U_{ji} \).

Figure 3.7 Rule table with infinitesimal quantization
The absolute magnitude of the control input is proportional to the distance from the following straight line called the switching line as shown in Figure 3.7. Different switching lines can be obtained by varying the parameter $\lambda$ in equation (3.24).

$$s_l : e + \lambda e = 0$$ (3.24)

The magnitude of the control input $|u|$ is approximately proportional to the distance from the main diagonal line as shown in Figure 3.8.

![Figure 3.8 Derivation of the signed distance](image)

In this work two SFLC have been designed in the same manner for two control signals $u_d$ and $u_q$ for shunt inverters and two SFLC for series inverters. The control inputs above and below the switching line have opposite signs. Now we introduce a new variable called signed distance $d_s$. In this section all the PI controllers (series as well as shunt controllers) are replaced by SFLC controllers. So $e$ and $e$ are either derivative of voltage error and voltage error, or derivative of capacitor voltage error or change in capacitor voltage error, it depends upon the SFLC type. So the output $u$ is equal to either $u_d / u_q$ for shunt controllers or $V_{cd} / V_{cq}$ for series controllers.
Let $Q(e, e)$ be the intersection point of the switching line and line perpendicular to the switching line from an point $P$ (present operating point) as illustrated in Figure 3.8. The distance $d_i$ between $Q$ and $P$ can be expressed as:

$$d_i = \left( e - e_i \right)^2 + \left( e - e_i \right)^2$$

(3.25)

Equation (3.25) can be written in general for any $(e, e)$:

$$d_s = \frac{e + ie}{\sqrt{1 + \lambda^2}}$$

Then, the signed distance $d_s$ is defined for a general point $P (e, e)$ as follows:

$$d_s = sgn(s_i) \cdot \frac{e + ie}{\sqrt{1 + \lambda^2}} = \frac{e + ie}{\sqrt{1 + \lambda^2}}$$

$$sgn(s_i) = \begin{cases} 1, & \text{for } s_i > 0 \\ -1, & \text{for } s_i < 0 \end{cases}$$

(3.26)

Since, the sign of the control input is negative for $S_i > 0$ and positive for $S_i < 0$ and its absolute magnitude is proportional to the distance from the line $S_i = 0$, we conclude that,

$$u \propto -d_s$$

(3.27)

Then, a fuzzy rule table can be established on a one – dimensional (1 – D) space on $d_s$ instead of the 2 – D space of the phase plane for FLC’s with skew – symmetric rule table. That is, the control action can be determined by $d_s$. 


only. So, we call it as SFLC. Figure 3.9 represents the fuzzy membership functions sets for error, change-of-error, control input and signed distance. The rule form for the SFLC is given as follows in Table 3.3. If \( d_s \) is NB then \( u \) is PB.

\[
\begin{array}{ccccc}
\text{NB} & \text{NS} & \text{ZR} & \text{PS} & \text{PB} \\
\mu(x) & -1 & 0 & 1 & x \\
\end{array}
\]

Figure 3.9 The fuzzy membership functions

Table 3.3 Rule base matrix for SFLC

<table>
<thead>
<tr>
<th>( d_s )</th>
<th>NB</th>
<th>NS</th>
<th>ZR</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u )</td>
<td>PB</td>
<td>PS</td>
<td>ZR</td>
<td>NS</td>
<td>NB</td>
</tr>
</tbody>
</table>

where NB-big negative, NS-small negative, NR-Zero, PS-Small positive, PB-positive big. Hence, the number of rules is greatly reduced compared to the case of the conventional FLC. Furthermore, we can easily add or modify rules for fine control. The defuzzification stage produces the final crisp output of SFLC on the base of fuzzy input. The Root Sum Square (RSS) method is employed for defuzzification.

3.5 RESULTS AND DISCUSSION

The performance of the UPFC with GA tuned PI controller for stabilization of synchronous generator is evaluated by computer simulation studies. In the simulation studies UPFC has been connected to load bus of
SMIB. Then the result is compared with SFLC based UPFC for different operating conditions.

The System Parameters used, are given below:

\( x_d = 1.9 \text{ p.u., } x_q = 1.6 \text{ p.u., } x'_d = 0.17 \text{ p.u., } T'_d = 4.314 \text{ sec., } \omega_0 = 100\pi \text{ rad / sec, } x_{i1} = 0.2 \text{ p.u., } x_{i} = 0.2 \text{ p.u., } r_e = 0.0, M = 0.03 \text{ p.u., } \kappa_e = 200, \)
\( T_e = 0.1 \text{ sec, } K_{pw} = 5, K_{iw} = 12, E_{fd}^{\text{max}} = 6 \text{ p.u., } E_{fd}^{\text{min}} = -6 \text{ p.u., } u_{\text{pss}}^{\text{max}} = 0.01 \text{ p.u., } \)
\( u_{\text{pss}}^{\text{max}} = -0.01 \text{ p.u., } \kappa_f = 0.01, T_f = 0.5 \text{ sec.} \)

\( b) \quad \text{Converter parameters} \)
\( R_p = 0.04 \text{ p.u., } \omega_0 L_p (-x_p) = 0.1 \text{ p.u., } R_{dc} = 150, C = 5000 \ \mu F. \)

\( c) \quad \text{PI Controllers of Shunt inverter} \)
\( K_{ps} = 2, K_{is} = 20, K_{pc} = 0.5, K_{ic} = 2, K_{pd} = 50, K_{id} = 50/0.003, K_{pq} = 5, \)
\( K_{iq} = 5/0.003 \)

\( d) \quad \text{PI Controllers of Series inverter} \)
\( K_{pa} = 0.1, K_{ip} = 1, K_{qa} = 0.1, K_{iq} = 1 \)

Case 1

The transient performances of the rotor angle, rotor speed deviation are compared in Figure 3.10 for three phase fault when the generator is operating at \( P = 1.2 \text{ p.u. and } Q = 0.85 \text{ p.u.} \). This study clearly indicates better stabilizing properties of UPFC, particularly the restoration of bus voltages to the pre-disturbance value.
Case 2

A comparison of the system responses for a 3-phase fault at infinite bus (P=1.2 p.u., Q=0.85 p.u.) which is cleared after 0.1sec is shown in Figure 3.11. The transient oscillations in rotor angle and speed exhibit good damping behavior for SFLC compared to GA tuned PI controllers. This is possible because of nonlinear control of bus voltage, resulting in better power modulation, by SFLC controller for stabilizing the synchronous generator.
Figure 3.11  Comparison of transient performances for three phase fault applied at infinite bus at 0.2 s and cleared at 0.3s 
(P = 1.2 p.u., Q = 0.85 p.u.) UPFC with GA tuned PI (---), SFLC based UPFC (—)

Case 3

Similar damped oscillations are also seen in the case of 50% line switching, for (P = 1.2 p.u., Q = 0.85 p.u.) in Figure 3.12.
All the above simulation results demonstrate the superior performance of the proposed SFLC over the GA tuned PI controllers for large disturbances like 3-phase fault and line switching, and validate its performance in respect of transient stability enhancement in a single machine infinite bus power system (Dash et al 2004).

3.6 SUMMARY

Unified Power Flow Controller for damping the electromechanical oscillations in a power system is attempted. A dynamic model of UPFC has been developed. The control strategy is based on d-q axis theory. Two types of controllers are proposed for UPFC, namely GA tuned Proportional Integral and Single–Input Fuzzy Logic Controller. The above schemes are implemented on Single Machine Infinite Bus system to carry out transient stability studies. Advantage of GA technique is that the parameter limits can be varied during the optimization, making the technique computationally efficient but the limitation is the computational time associated with this technique. All these difficulties always demand better and deeper modern
control engineering approach. The proposed SFLC for UPFC is proved to be very effective in damping power system oscillations and thereby enhancing system transient stability. The superiority in damping the electromechanical oscillations of the synchronous generator by this proposed control strategy over the conventional control approach was illustrated through computer simulation studies for a variety of severe transient disturbances.

The next chapter addresses the power quality issues in the power distribution section, its impact on the modern industry. An electromagnetic transient model and control strategy of Distribution Static Var Compensator are also discussed.