CHAPTER 6

INTELLIGENT CONTROLLER DESIGN FOR UPFC SYSTEM

6.1 INTRODUCTION

The digital simulation of the following closed loop schemes has been described in this chapter.

i) Fuzzy logic converter based UPFC fed power system.

ii) PI controller based UPFC fed power system.

iii) AWPI controller based UPFC fed power system.

The performance of these closed loop schemes has been compared with its counterpart the open loop system. The performance of UPFC mainly depends on how quickly and accurately it does the work of compensation and mitigates the voltage sag and swell. The simulated results demonstrate the effectiveness of fuzzy logic, PI and AWPI controllers in terms of peak overshoot and steady state errors.

6.2 FUZZY LOGIC BASED CONROL SYSTEM

6.2.1 Fuzzy Logic Algorithm

The term fuzzy logic inspires certain skepticism, sounding equivalent to "half-baked logic" or "bogus logic". The logic involved can deal with concepts that cannot be expressed as "true" or "false" but rather as
"partially true". It is a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false, respectively). Fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans.

6.2.2 Fuzzy Logic Controller

The structure of complete fuzzy control system composed of four blocks viz., fuzzification, knowledge base, inference engine and defuzzification. The fuzzification module converts the crisp values of the control inputs into fuzzy values. A fuzzy variable are defined by linguistic variables (fuzzy set or sub sets) such as low (L), Medium (M) and high (H), big (b), zero (Z), slow where each refers to a gradually varying membership functions. In fuzzy set terminology, all the possible values that a variable can assume are named universe of discourse and the fuzzy sets (characterized by membership function) cover whole universe of discourse. The shape of fuzzy sets can be triangular, trapezoidal etc.

6.2.3 Fuzzification

Assuming membership function values to the linguistic variables is known as fuzzification. For example, L for low, H for high, M for medium and Z for zero etc.
6.2.4 Fuzzy Set

Fuzzy sets were introduced by Lotfi A. Zadeh (1965) and are sets whose elements have degrees of membership. The fuzzy sets are extension of classical sets. The membership of classical set theory is assessed in binary terms as 1 or 0. But the fuzzy set membership functions are valued in the interval [0, 1]. In fuzzy set theory, the classical sets are termed as crisp sets. The fuzzy sets are inexact defined classes, as they do not have sharply defined boundaries.

6.2.5 Degree of Membership

The degree of membership is the degree to which a crisp value belongs to a fuzzy set. It is expressed over a range as 0.0 to 1.0 or as percentage ranging from 0% to 100%.

6.2.6 Membership Functions

The membership function of fuzzy set is the representation of the degree of truth. It describes the degree of membership of an entity to a class with inexact defined boundaries. It illustrates how completely a crisp value belongs to a fuzzy set. For any set X, a membership function on X is any function X from to the real unit interval [0, 1]. The membership functions on X represent fuzzy subsets of X. For a fuzzy set $\tilde{A}$, the membership function is denoted by $\mu_{\tilde{A}}$. For an element $x$ of $X$, the value $\mu_{\tilde{A}}(x)$ is called the membership degree of $x$ in the fuzzy set $\tilde{A}$. The membership degree $\mu_{\tilde{A}}(x)$ measures the rank of the membership element $x$ to the fuzzy set $\tilde{A}$. The value 0 means that $x$ is not a member of the fuzzy set; the value 1 means $x$ is fully a member of the fuzzy set. The values in the interval [0, 1] illustrate fuzzy members, which belong to the fuzzy set only partially.
The fuzzy membership functions are classified into four types based on the shapes. They are:

1. Trapezoidal Membership Functions
2. Triangular Membership Functions
3. Gaussian Membership Functions
4. Generalized Bell Membership Functions

The most popular shapes are triangular and trapezoidal membership functions as these shaped are easy to represent designer’s idea and also require low computation time.

(a) Membership Function of Fuzzy Set

(b) Triangular Membership Function

Figure 6.1 (Continued)
(c) Trapezoidal Membership Function

(d) Gaussian Membership Function

(e) Generalized Bell Membership Function

Figure 6.1 Fuzzy Membership Functions
6.2.7  **Rule or Knowledge Base**

The rule base is a collection of expert control rules which are needed to obtain the controlled output. The rule base is of IF-Then type. The If-Then statement is the one in which the words are characterized by continuous membership functions. After defining the fuzzy sets and assigning their membership functions, rules must be written to describe the action to be taken for each combination of control variables. These rules will relate the input variables to the output variable using If-Then statements which allow decisions to be made. Each rule is represented as follows:

IF (antecedent) Then (consequence)

For instance:

If the tank is full, then stop the pump.

If the speed of the car is less, then apply more acceleration.

6.2.8  **Inference Engine**

Inference engine is a software code that processes the rules based on the facts of a given situation. It is an information processing system, which employs inference steps similar to that of a human brain.

6.2.9  **Defuzzification**

The output membership functions obtained from the inference engine are converted into the crisp values in the defuzzifier. This process is termed as defuzzification. There are different methods of defuzzification. The common methods of defuzzification are:

1. Centre of Gravity (COG)
2. Bisector of Area (BOA)
3. Mean of Maximum (MOM)
6.2.9.1 Centre of Gravity (COG)

COG is called centre of gravity for singletons (COGS), where the crisp control value is the abscissa of the centre of gravity of the fuzzy set is calculated using Equation (6.1):

\[ U_{cog} = \frac{\sum \mu_A(x_i) x_i}{\sum \mu_A(x_i)} \]  \hspace{1cm} (6.1)

Where, \( x_i \) is a point in the universe of the conclusion \((i=1, 2, 3, \ldots)\) and \( \mu_A(x_i) \) is the membership value of the resulting conclusion set.

6.2.9.2 Bisector of Area (BOA)

The Bisector of Area (BOA) defuzzification method is a computationally complex method, in which the abscissa of the vertical line is calculated that divides the area of the resulting membership function into two equal areas. For discrete sets, \( u_{BOA} \) is the abscissa \( x_j \) that minimizes

\[ | \sum_{i=1}^{j} \mu_A(x_i) - \sum_{i=j+1}^{i_{\text{max}}} \mu_A(x_i) |, i < j < i_{\text{max}} \]  \hspace{1cm} (6.2)

Here \( i_{\text{max}} \) is the index of the largest abscissa \( x_i \).

6.2.9.3 Mean of Maximum (MOM)

In Mean of Maximum (MOM) method the crisp value is to choose the point with the highest membership. When there are several points which have maximum membership value, then, the mean of all the maximum membership values is calculated using Equation (6.3):

\[ u_{MOM} = \frac{\sum_{i \in I} x_i}{|I|}, \quad I = \{ i | \mu_A(x_i) = \mu_{\text{max}} \} \]  \hspace{1cm} (6.3)
Here $I$ is the (crisp) set of indices $i$ where $\mu_A(x_i)$ reaches its maximum $\mu_{max}$, and $|I|$ is its cardinality (the number of members).

Based on the defuzzification process the fuzzy logic controllers are classified into two types namely, Mamdani Fuzzy controller and Takagi – Sugeno Fuzzy Controller.

6.2.10 Mamdani Fuzzy Controller

The Mamdani Fuzzy Controller is a crisp based controller which produces crisp outputs from crisp inputs. The inference engine utilizes Mamdani fuzzy inference method proposed by Ebrahim Mamdani (1975). In this model the output membership functions are of fuzzy sets. These fuzzy sets are defuzzified to crisp values. In Mamdani method, commonly the centre of gravity (COG) method of defuzzification is used to obtain the crisp outputs. The structure of Mamdani fuzzy controller consists of four main parts: Fuzzification of the inputs, Rule Evaluation, Aggregation of the rules and Defuzzification. The block diagram of the Mamdani Model is depicted in Figure 6.2.

![Figure 6.2 Block Diagram of Mamdani Fuzzy Controller](image-url)
Fuzzification converts the input data to degree of membership functions. The data is matched with the rule condition and for any particular instance it’s determined how well the data is matched with the rule. In this way, the degree of membership is determined. Based on the system requirement, the If – Then rules are written. Generally the fuzzy controller works on both MIMO and SISO logics. The inference engine aggregates the degree of fulfillment of the fuzzy sets according to the conditions specified in the rule base. In activation min of two aggregated value is selected and only thickened part of singleton are activated. Its multiplication result in slighter smooth control. Then all activated conclusions are accumulated using max operations. The resulting fuzzy set is converted into its crisp value by using centre of gravity method of defuzzification.

6.2.11 Sugeno Fuzzy Controller

The Sugeno fuzzy controller is another type of fuzzy controller, in which, the membership functions are not used by the defuzzification process to obtain the crisp outputs. This model was proposed by Takagi, Sugeno and Kang (1985). They made an effort to develop a systematic approach to generate fuzzy rules from a given input-output dataset. The typical fuzzy rule of Takagi-Sugeno model is as follows:

If \( x \) is \( A \) and \( y \) is \( B \), then \( z = f(x,y) \)

where, \( A \) and \( B \) are fuzzy sets in the antecedent, while \( z = f(x,y) \) is a crisp function in the consequent. The block diagram of Takagi-Sugeno fuzzy controller is shown in Figure 6.3. The block diagram shows that the crisp outputs are obtained directly from the inference engine without using defuzzification block.
6.3 FUZZY LOGIC CONTROLLER BASED UPFC FED POWER SYSTEM

A UPFC is used with Fuzzy Logic controller to improve the power quality i.e., to reduce the duration of sag, swell and the peak overshoot. The block diagram of FLC is shown in Figure 6.4. The error between the reference values and the measured system parameters and the rate of change of error (CE) are calculated. These values form the crisp inputs for the Sugeno fuzzy system. The triangular membership functions are used to obtain the fuzzified values from the crisp values, as this membership function is the simplest compared to the other membership functions. The fuzzy inference system, then generates the required switching pulses for the UPFC. Table 6.1 shows the fuzzy rule base with 4 rules which were designed on the dynamic behavior of signal error and its rate of change. Load 2 is switched on and the time taken for switching the UPFC is approximately 0.01 sec.
The error between the reference voltage value and the measured voltage and the rate of change of voltage error are fed as input to the fuzzy logic controller. These values are fed as crisp inputs to the fuzzy logic controller and are converted into fuzzy sets by using min-max method. The input functions are framed from the following expressions.

\[
\text{Error, } E = e(t) = V_r(t) - V_a(t) \tag{6.4}
\]

\[
\text{Change in error, } CE = e(t) - e(t-1) \tag{6.5}
\]

Where,

\( V_r \) = reference voltage in volts
\( V_a \) = measured voltage in volts
\( e(t-1) \) = error at the previous instant

**Table 6.1 Linguistic Rule Table**

<table>
<thead>
<tr>
<th>Change in Error (CE)</th>
<th>Error (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>L</td>
<td>Z</td>
</tr>
<tr>
<td>M</td>
<td>Z</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>
Membership function values are assigned to the linguistic variable using two fuzzy subsets viz., L (low) and H (High). The partition of fuzzy subsets and the shape of the membership function adapt the shape of the appropriate system. Table 6.1 depicts the linguistic rule for fuzzifying the input error and change in error values. The IF-THEN rules are framed as follows:

IF E = L AND CE = L THEN OUTPUT FUZZY SET = Z
IF E = L AND CE = H THEN OUTPUT FUZZY SET = Z
IF E = H AND CE = L THEN OUTPUT FUZZY SET = M
IF E = H AND CE = H THEN OUTPUT FUZZY SET = H

The proposed fuzzy based UPFC system is simulated using Matlab/Simulink. The fuzzy editor, the corresponding fuzzy rule viewer and surface viewer are shown in Figure 6.5. The two inputs viz., error and change in error are framed using triangular membership functions. The advantage of sugeno fuzzy model is that the output of this model will be a crisp value instead of a fuzzy set. It is obvious from the output membership function shown in Figure 6.5 (d).

(a) Fuzzy Editor

Figure 6.5 (Continued)
(b) Error Membership Function

(c) Change in Error Membership Function

Figure 6.5 (Continued)
(d) Output Membership Function

(e) Rule Viewer

Figure 6.5 (Continued)
6.4 PI CONTROLLER BASED UPFC FED POWER SYSTEM

In a PI Controller, with the proportional band \((K_p)\) the controller produces the output proportional to the error and the integral action produces the output proportional to the amount of time the error is present. Due to the proportional controller offset will be present and increasing the \(K_p\) value will make the loop go unstable. The integral action eliminates the offset in the output. It may be noted that the presence of integral term in PI controller facilitates the system to reach its target value. The PI controller almost eliminates steady state error in the closed loop system. Hence the use of PI controllers is quiet common in the field of control systems. The PI controller is governed by the Equation 6.4. The basic block diagram of a PI controller is shown in Figure 6.6.
\[ P_{out} = K_p \, e(t) + K_i \int e(t) \] (6.4)

\[ e(t) = SV - MV \] (6.5)

Where,

- \( K_p \) = Proportional gain
- \( K_i \) = Integral gain
- \( e(t) \) = Error between actual measured value of system voltage (MV) and the set value of system voltage (SV)

![Figure 6.6 Basic block of PI controller](image)

The MATLAB/Simulink model of the PI controller based closed loop UPFC system is depicted in Figure 6.7. Ziegler-Nicholas method of tuning is employed to determine the values of \( K_p \) and \( K_i \) in the PI controller system.
The effect caused by real actuators having an input – output characteristic involving saturation or limiting the actuation output is termed as integral wind-up. Figure 6.8 shows the effect of the saturation characteristic.

**Figure 6.8 Effect of Saturation Characteristic**
6.5.1 Anti-Wind-Up Circuit

The integral wind-up phenomenon can be overcome by using anti-wind-up circuits. The anti-wind-up circuits detects when actuator saturation is reached and then switches off the integral action. When the control signal returns to the linear region, then the integral action should be resumed once more. A simple anti-wind-up circuit for PI controller is shown in Figure 6.9.

![Figure 6.9 A Simple Anti-Wind-Up Circuit](image)

In the above circuit, when switch Sw = 0, then the input to the integrator is zero and so the integral action will be stopped. For normal operation Sw = 1. If the output of PI control remains in linear unsaturated region, then the switch signal Sw = 1. When it enters the saturation region, then the switch signal Sw = 0. This disintegrates the integrator action and the integrator output is held at a constant value. The actuator output takes the saturation level at this time. This situation is maintained until the output falls back in the linear region. When this happens then the switch signal Sw = 1 and the integral action is resumed.
6.5.2 Back Calculation Anti-Wind-Up Scheme

As the back calculation anti-windup scheme is the simplest form among all other anti-windup schemes such as dead zone anti-windup, conditional integration, anti-windup with tracking etc., it has been taken up for the study. The model of back calculation anti-windup scheme is shown in Figure 6.10. In this scheme the integral limit is set from the feedback of the output signal. In back-calculation technique the integral term is calculated based on the saturation of the output.

![Back Calculation Anti-Wind-Up Scheme](image)

Figure 6.10 Back Calculation Anti-Wind-Up Scheme

The back calculation scheme has an additional feedback loop, which is formed by calculating the difference between the controller output and the actuator output. This error is fed back to the integrator through anti-wind-up gain $K_a$. When there is no saturation, the error is zero and will not have any effect on the normal operation. When saturation occurs in the actuator, the normal feedback path breaks as the process input remains constant. The additional feedback path remains unchanged and causes the integrator output to be driven to a value such that the integrator input becomes zero. Thus the back calculation scheme prevents the integrator from winding up.
6.5.3 Anti-Windup PI Controller based UPFC System

Figure 6.11 Simulation Model of AWPI controller based UPFC System

The Matlab/Simulink model of the anti-windup PI (AWPI) controller based UPFC system is depicted in Figure 6.11.

6. 6 SIMULATION RESULTS

(a) Real Power

Figure 6.12 (Continued)
(b) Reactive power

(c) Voltage across Load 2 and Load 1

Figure 6.12 Simulated Wave forms of Fuzzy based UPFC system
In order to test the performance of the UPFC using the proposed FLC PI and AWPI controller based schemes, these schemes have been simulated using MATLAB/Simulink. The ratings of existing load and additional load are taken as $(200+j31.4)\Omega$, and $(25+j15.7)\Omega$ respectively. The
transmission line impedance is considered as \(j9.24\ \Omega\). The ratings of the DC link capacitor have been fixed as \(9000\mu F\) and 12kV.

The simulated results of the UPFC fed power system with various control schemes have been depicted in Figures 6.12 to 6.14. To ascertain the performance of the UPFC with the aforesaid control schemes, the comparisons have been made among the simulated values of peak overshoot, duration of sag and swell and instantaneous voltage across load 1 and load 2 during the period of sag and swell. It has been observed that in the event of addition or deletion of load in the UPFC based power system with fuzzy logic controller, the sag and swell persist for 0.01 sec and 0.02 sec respectively and the peak overshoot has been found to be 3.11% during sag and 3.9% during swell. The voltage across load 1 and load 2 and the real and reactive powers of the fuzzy based UPFC scheme have been depicted in Figure 6.12 for sag and Figure 6.14 depicts the voltage profile of the PI, AWPI and fuzzy based UPFC fed systems during swell condition.

![Graph showing voltage across load 1 and load 2](image)

(a) PI Controller based UPFC System

Figure 6.14 (Continued)
In the case of PI controller based UPFC fed power system the addition and deletion of load causes the sag and swell to sustain for duration of 0.02 sec and 0.023 sec respectively. The peak overshoots during the transition of switching have been perceived as 13.1% and 15.2% in the event
of addition and deletion of load respectively. With the AWPI controller, the UPFC fed power system exhibits duration of sag for 0.0178 sec and swell for 0.022 sec against addition and deletion of load respectively. A peak overshoot of 11.8% and 12.4% have been obtained during the switching ON and OFF the loads respectively.

Figure 6.15 compares the voltage across load1 during sag period of open loop, PI, AWPI and fuzzy logic controller based UPFC system. It is clear that the sag period of FLC based UPFC is very short than the other schemes. Tables 6.2 and 6.3 indicate the sag and swell condition parameters viz., duration of sag and swell and the peak overshoot of the voltage during the transient period.

Figure 6.15 Comparison of Output voltage across the load during open loop, PI, AWPI controller and fuzzy controller based systems
### Table 6.2 Comparison of sag condition parameters

<table>
<thead>
<tr>
<th>Controller</th>
<th>Sag period (sec)</th>
<th>Peak Overshoot (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Loop</td>
<td>0.1</td>
<td>15.33</td>
</tr>
<tr>
<td>PI</td>
<td>0.02</td>
<td>13.1</td>
</tr>
<tr>
<td>AWPI Controller</td>
<td>0.0178</td>
<td>11.8</td>
</tr>
<tr>
<td>Fuzzy</td>
<td>0.01</td>
<td>3.11</td>
</tr>
</tbody>
</table>

### Table 6.3 Comparison of swell condition parameters

<table>
<thead>
<tr>
<th>Controller</th>
<th>Swell period (sec)</th>
<th>Peak Overshoot (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Loop</td>
<td>0.1</td>
<td>17.2</td>
</tr>
<tr>
<td>PI</td>
<td>0.023</td>
<td>15.2</td>
</tr>
<tr>
<td>AWPI Controller</td>
<td>0.022</td>
<td>12.4</td>
</tr>
<tr>
<td>Fuzzy</td>
<td>0.02</td>
<td>3.9</td>
</tr>
</tbody>
</table>

### 6.7 CONCLUSION

From the comparative analysis shown in Figure 6.15 it is clear that there is a drastic change in the peak overshoot occurred during the switching ON of the UPFC. The UPFC System with fuzzy logic controller scheme has less peak overshoot compared to its counterparts AWPI, PI and Open loop controller based UPFC systems. Also the response time for the clearance of
the fault is less in fuzzy logic controller scheme compared to the other schemes.

Figures 6.11 to 6.15 reveal that the fuzzy logic controller based UPFC fed power system has an edge over the other schemes of interest on the aspects of peak overshoot, duration of sag and swell and real and reactive power flow.

The control strategies suggested so far were developed to mitigate the power quality issues viz. voltage sag and swell using unified power flow controller. The voltage mitigation is achieved by determining the voltage and current injected by the UPFC at each step. The simulation results evaluate the aforesaid intentions.