CHAPTER 3

FUZZY LOGIC CONTROLLER FOR LFC AND AVR

3.1 INTRODUCTION

Modern power systems are characterized by extensive system interconnections and increasing dependence on control for optimum utilization of existing resources. The supply of reliable and economic electric energy is a major determinant of the industrial progress and consequent rise in the standard of living. During transmission, both the active power balance and the reactive power balance must be maintained between the generation and utilization of electric power. These two balances correspond to two equilibrium points of frequency and voltage and when the balances are broken and reset at a new level, the equilibrium points will float. A good quality of the electric power system requires both the frequency and voltage to remain at standard values during operation.

The increasing demand for electric power coupled with resource, and environmental constraints pose several challenges to system planners (Padiyar 2002). Stability of power systems has been and continues to be of major concern in system operation and control. The maximum preoccupation and concern of power system engineers are the control of megawatt, the real power and reactive power, because it is the governing element of revenue. Because of increased size and demand, it has forced them to design and control more effective and efficient control schemes to maintain the power system at desired operating levels characterized by nominal system frequency
and voltage (Prabhat kumar and Ibraheem 1998). The main function of a power system is to supply the real and reactive power demand with good quality in terms of constancy in voltage and frequency. Furthermore, for interconnected power system the tie-line power flow between utilities must be maintained within prescribed limits (Chowdhury et al 1999). Automatic control systems are used extensively in the power system for efficient control of voltage and frequency. Controllers are employed at turbine-generator units and also at selected voltage controlled buses.

A well designed and operated power system should cope with changes in the load and with system disturbances, and it should provide an acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits (Taher 2008). The voltage regulator and turbine-governor systems are included as a primary control loop for control of excitation and speed of the generator as shown in Figure 3.1. The voltage regulator adjusts the power output of the generator exciter in order to control the magnitude of generator terminal voltage $V_t$. When a reference voltage $V_{ref}$ is raised or lowered, the output voltage $V_r$ of the regulator increases or decreases the exciter voltage $E_{fd}$ applied to the generator field winding, which in turn changes the terminal voltage. The turbine-governor adjusts the steam valve position to control the mechanical power output $p_m$ of the turbine. When a reference power level $p_{ref}$ is raised (or lowered), the governor moves the steam valve in the open (or close) direction to increase (or decrease) $p_m$ (Kirchmayer 2009). The governor also monitors rotor speed $\omega_m$, which is used as a feedback signal to control the balance between $p_m$ and the electric power output $p_e$ of the generator.
Figure 3.1 Voltage Regulator and Turbine-governor Controls of a Steam Turbine Generator

The ability of the power system to withstand disturbances depends on dynamic performance of the LFC and AVR control loops. The control objectives are dependent on the operating state of the power system. The conventional control strategy for the LFC and AVR problem is to take the integral of control error as the control signal. The proportional integral (PI) control approach is successful in achieving zero steady-state error in the frequency of the system, but it exhibits relatively poor dynamic performance as evidenced by large overshoot and transient oscillations. Furthermore, the controller design is normally based on a fixed parameter model of the system derived by a linearization process and for particular operating point. Hence, the fixed gain controllers designed for particular load, and regulation may no longer be suitable for all operating conditions (Mathur and Manjunath 2007). Many investigations in the area of LFC and AVR of an isolated power system have been reported in the literature and different control strategies like adaptive, optimal, PID controllers have been applied to improve the performance characteristics and to reduce transient oscillations (Zeynelgil
2002, Chaturvedic 1999). The main aim of such control strategies are to extend the margins of the regions of stability and therefore, to satisfy increasingly complex control requirements in the power system (Mohammad et al 2002).

In recent years, modern ‘intelligent’ methods such as Fuzzy Logic (FL), Artificial Neural Network (ANN), and genetic Algorithms (GA), have gained increasing interest for applications in the LFC and AVR of the power generating system (Mukherjee and Ghosal 2008). The first application of fuzzy control comes from the work of Mamdani and Assilian in 1975, with their design of a fuzzy controller for a steam engine. Fuzzy logic is an innovative technology that enhances conventional system design with engineering expertise (Kaimal et al 1997). Karnavas and Papadopoulos (2002) proposed an intelligent load frequency controller to regulate the power output and system frequency and found that the controllers exhibit satisfactory dynamic performance and overcome the drawbacks associated with conventional techniques. It is to be appreciated that, Nanda and Mangla (2004) have studied the conventional integral and fuzzy logic controller in an interconnected hydro-thermal system and proposed a set of fuzzy rules for improving the dynamic performance of the system. Brock LaMeres (1999) developed fuzzy logic rule table on a Digital Signal Processor for improving the transient and steady state performance of AVR in a synchronous generator. Chown and Hartman (1998) designed and implemented fuzzy controller as part of the Automatic Generation Control (AGC) system in Eskom’s National Control Centre and improved operational performance of the plant. Ha and Negnevitsky (1995) provided the application of integral-proportional control with fuzzy tuning to the generation control problem. It focuses on the application of simple fuzzy logic schemes for tuning the controller coefficients to improve robustness with respect to load and generation rate variations. Momoh et al (1995) have mentioned the
applications of fuzzy set theory to power systems and the basic procedures for fuzzy set based methods to solve specific power system problems.

The design of fuzzy controllers is one of the largest application areas of fuzzy set theory, where fuzzy logic is described as computing with words rather than numbers. Fuzzy control is described as control with sentences rather than equations. Instead of describing the control strategy in terms of differential equations, control is expressed as set of linguistic rules (Engelbrecht 2002). In this research, LFC and AVR loops of a single area and two area power system are considered for implementation, and separate fuzzy rules are designed for intelligent control of voltage and frequency. It has better adaptability towards changes in load and regulation than the conventional controllers thereby providing improved performance with respect to peak overshoot, settling time and oscillations.

This chapter is organized as follows: Section 2 describes the model of the plant, including LFC and AVR. Section 3 describes the design of Fuzzy controller. Section 4 demonstrates the simulation results, Section 5 shows the performance comparison, Summary and discussion of the chapter are given in section 6.

3.2 MODEL OF THE PLANT

Electric power is an essential ingredient for industrial and economic development of a country. The control of a power system involves many elements and is one of the major responsibilities of system operators. The parameters to be controlled are system frequency, tie-line flows, line currents, equipment loading and voltage. All these quantities must be kept within limits in order to provide satisfactory service to power system customers (Devaraj 2008). The automatic control system detects these changes and initiates in real time a set of control actions, which will eliminate
as effectively and quickly as possible the state deviations. Synchronous generators are equipped with two major control loops, namely AVR loop and LFC loop. The AVR loop keeps track of output voltage of the generator and initiates the control action under varying loads. The function of LFC is to keep the system frequency and the inter-area tie-line power near to the scheduled values as possible through control action. This section demonstrates the principle of operation of speed governing and excitation systems of a generator.

3.2.1 Basic Generator Control Loops

Both utility and consumer equipments are designed to operate at a certain frequency and voltage rating. Prolonged use of the equipment at outside the range of frequency and voltage could adversely affect their performance. The proper selection and co-ordination of equipment for controlling real and reactive power is an important challenge in power system engineering. The primary controllers installed in the synchronous generator take care of small changes in load demand and maintain the frequency and voltage magnitude within the specified limits.

Changes in rotor angle $\delta$ are caused by a momentary change in generator speed, which affects real power and, thus, the frequency $f$. Voltage magnitude (i.e. on the generator excitation) is mainly dependent on the reactive power. Therefore, load frequency and excitation voltage controls are non-interactive for small changes and can be modeled and analyzed independently. Furthermore, excitation control is fast acting in which the major time constant encountered is that of the generator field and its transient decay much faster; while the power frequency control is slow acting in which the major time constant contributed by the turbine and generator moment of inertia-time constant is much larger than that of the generator field.
(Hadi 1999). Since, the AVR loop is much faster than the LFC loop, cross coupling between the controls can be neglected. Hence, the LFC and AVR are implemented and analyzed separately (Prabha Kundur 2006) (Uma Rao 2007).

### 3.2.2 LFC Loop

Load frequency control (LFC) takes important part in the reliable operation of electric power systems. The aim of LFC is to maintain real power balance in the system through control of system frequency. The control of generation and frequency is commonly referred to as LFC whenever the real power demand changes, a frequency change occurs. This frequency error is amplified, mixed and changed to a command signal which is sent to the turbine governor. The governor operates to restore the balance between the input and output by changing the turbine output. This method is also referred as Megawatt frequency or Power-frequency (P-f) control. The regulation of the frequency in the power system requires the speed control of the prime mover using the governor. This would require sensing of the speed and translating it to suitable control action. The prime mover control must have been drooping characteristics to ensure proper division of load, when generators are operating in parallel. It is also necessary for the prime mover control to adjust the generation according to economic dispatch schedule. The functional block diagram in Figure 3.2 indicates the speed-governing system, which includes AGC, speed governor, speed controller, turbine and load. The speed sensing and conditioning is done by electronic circuits in electro-hydraulic systems and by mechanical components in mechanical-hydraulic systems.
3.2.3 AVR Loop

The aim of this control is to maintain the system voltage between limits by adjusting the excitation of the machines. The automatic voltage regulator senses the difference between a rectified voltage derived from the stator voltage and a reference voltage. This error signal is amplified and fed to the excitation circuit. The change of excitation maintains the VAR balance in the network. This method is also referred as Megawatt Volt Amp Reactive (MVAR) control or Reactive-Voltage (QV) control (Wood 2006). The field winding of the AC generators needs a DC excitation. The excitation system consists of the device supplying the DC, called the exciter and a voltage regulator which controls the output of the exciter so that the required voltage is generated. The voltage regulator is normally a continuously acting system, which takes corrective action for any deviation in the AC terminal voltage.

The general arrangement of excitation system components is shown in Figure 3.3. The voltage regulator controls the exciter output, such that the terminal voltage of the AC generator equals the desired voltage, often called the reference voltage. According to the error signal and the value of load current, the field current is increased or decreased in order to make the actual
voltage closer to the desired voltage (Awadallah 2001). The auxiliary controls for feedback of speed, frequency and accelerations are required to improve the stability, damping and overshoot, etc., of the excitation system (Uma Rao 2007).

Figure 3.3 Excitation System

3.3 DESIGN OF INTELLIGENT CONTROLLER

With increasing demands for high precision autonomous and intelligent controllers with wide operating regions, conventional PID control approaches are unable to adequately deal with system complexity, nonlinearities, spatial and temporal parameter variations, and with uncertainty. Intelligent Control or self-organising / learning control is a new emerging discipline that is designed to deal with real-time problems. Rather than being a model based intelligent controller is experiential based, and it is the amalgam of the disciplines of Artificial Intelligence, Systems Theory and Operations Research. For practical implementation, intelligent controllers
must demonstrate rapid learning convergence, be temporally stable, be robust
to parameter changes and internal and external disturbances.

Conventional PID controllers generally do not work well for non-linear systems, higher order and time-delayed linear systems, complex and vague systems that have no precise mathematical models. In a conventional controller, what is modeled is the system or process being controlled whereas in a fuzzy logic controller, the focus is on the human operator's behavior. Conventionally, the system is modeled analytically by a set of differential equations from which the control parameters are adjusted to satisfying the controller specification. Hence, to overcome this drawback, alternate methods using improved dynamic models or adaptive and intelligent controllers are required (Barjeev 2003) (Mathur 2006) (Moon et al 2002). A fuzzy logic-based design can resolve the weaknesses of conventional approaches cited above. In the fuzzy logic controller (FLC), the adjustments on the control parameters are handled by a fuzzy rule-based expert system. The use of fuzzy logic control is motivated by the need to deal with high complex and performance robustness problems. It is well known that fuzzy logic is much closer to human decision making than traditional logical systems. Fuzzy control provides a new design paradigm such that a controller can be designed for complex, ill-defined processes without knowledge of quantitative data regarding the input-output relations. In this thesis, the conventional controllers in the secondary control loop are replaced with FLC, and their performance is analyzed for various operating conditions by detailed digital computer simulations. The efficacy of the proposed method was validated and compared against the conventional controller for different load and regulation parameters (Khodabakshian and Goldbon 2005) (Mathur and Manjunath 2007) (Yukita 2000).
3.3.1 Fuzzy Logic

In recent years, fuzzy system applications have received increasing attentions in various areas of power systems such as operation, planning, control, and management. The concept of Fuzzy Logic was conceived by Lotfi Zadeh, a professor at the University of California at Berkley, and presented as a way of processing data by allowing partial set membership rather than crisp set membership or non-membership. The backbone of FLC is embodied in a set of fuzzy rules, not on the elaborated set of equations. The success of fuzzy logic controllers is mainly due to their ability to cope with knowledge represented in a linguistic form instead of representation in the conventional mathematical framework. The main advantage is their ability to incorporate experience, intuition, and heuristics into the system instead of relying on mathematical models. The mathematical models provide only for specific situations of the power systems under respective assumptions. With these assumptions, the solutions of power systems problems are not trivial. Therefore, there exist limitations for the mathematical model based schemes.

In order to overcome these limitations, new intelligent techniques such as fuzzy systems, neural networks, and genetic algorithms have been investigated in different areas of power systems (Hiyama and Tomsovic 1999). Hence, fuzzy set theory based approach, has emerged as a complement tool to mathematical approaches for solving power system problems. The design of the fuzzy logic controller for isolated and interconnected power system is demonstrated in this section.

3.3.2 Fuzzy Logic Controller Design

Fuzzy control system is a real time expert system that enhances conventional system design with engineering expertise. It implements a part
of human operator’s or process engineer’s expertise, which does not lend itself to be easily expressed in PID-parameters or differential equations but rather in situations/action rules. (Driankov et al 2001). Furthermore, it provides a mathematical morphology to emulate certain perceptual and linguistic attributes associated with human cognition. The basic structure of the fuzzy control systems is shown in Figure 3.4, where controlled plant represents the LFC and AVR model developed using transfer function approach. The purpose of designed fuzzy controller ‘D’ is to guarantee the desired response of the plant output ‘Y’.

**Figure 3.4 Basic Structure of the Fuzzy Control Systems**

The main objective in the controller design is to develop an intelligent FLC ‘D’ that takes care of the response characteristics of the plant output ‘Y’. The model shown in Figure 3.4 is implemented using SIMULINK, an interactive environment in MATLAB for modeling, analyzing and simulating a wide variety of dynamic systems. The fuzzy file (.FIS) created in the fuzzy toolbox is linked to the model through the FLC block included in the control loop.
The FLC with a rule viewer is selected from the library of the fuzzy toolbox in MATLAB and placed in the feedback loop as shown in Figure 3.5. It is regarded as a nonlinear static function that maps controller inputs into controller outputs. The inputs to the system can change the state of the system, which causes variations in the response characteristics. The task of the controller is then to take corrective action by providing a set of inputs that ensures the desired response. The steps in designing a fuzzy control system are as follows,

1) Identify the input and output variables of the plant.
2) Divide the universe of discourse into a number of fuzzy subsets and assign a linguistic label to each subset.
3) Membership Function is assigned each fuzzy subset.
4) Rule base is formed to relate the input and output variables.
5) Choose appropriate scaling factors for input and output variables in order to normalize the variables to (0,1) or (-1,1) interval.
6) Fuzzify the inputs to the controller.

7) Verify the output contributed from each rule.

8) Aggregate the fuzzy outputs recommended by each rule.

9) De-fuzzify the output for converting into crisp values.

The design steps are followed in sequence by creating Fuzzy Inference System (FIS) editor as shown in Figure 3.6. The Inputs and outputs are selected from the edit window in a popup menu. The diagram indicates the names of each input variable on the left and output variable in the right.

![FIS Editor](image)

**Figure 3.6** FIS Editor
The FIS Editor displays the detailed information about input/output, input/output, filename, FIS type, name, fuzzification and de-fuzzification method, etc. The input and output of the system are labeled and the membership function is edited by double clicking the input variable icon. The rules are edited by selecting ‘Edit Rules’ in the ‘Edit’ command in the drop down menu. Below the FIS name in the left is the pop-up menu that allows to modify the inference process variables. To its right, the name of the current variable, its associated membership function type and its range are displayed. The basic structure of FLC consists of four main sections namely, Fuzzification, Knowledge base and Defuzzification.

3.3.2.1 Fuzzification

The fuzzy based control system is designed to control the voltage and frequency of the synchronous generator. The controller uses two input state variables and one output control variable. The difference between the set value and the actual value (error) is termed as the first input variable. The change in error, the difference between the errors in consecutive steps of simulation is assigned as another input variable.

\[ \text{Input 1: error} \quad \Delta f = f_{\text{nom}} - f_1 = e_t \]

\[ \text{Input 2: Change in error} \quad \Delta e_t = e_t - e_{t-1} = ce_t \]

The fuzzy output control variable is the change in the control signal. This control signal acts as the input signal to the speed governor and excitation system of LFC and AVR of the generator. The input and output variables in the proposed controller are represented as a set of nine linguistic variables namely,

- NVL - Negative Very Large
- NH - Negative High
NM - Negative Medium
NL - Negative Low
ZE - Zero Error
PL - Positive Low
PM - Positive Medium
PL - Positive Large
PVL - Positive Very Large

In fuzzification, the precise numerical values obtained by measurements are converted to membership values of the various linguistic variables. The degree to which a fuzzy number belongs to a set or not is known as Membership Function (MF). In LFC, the universe of discourse of the input state variable MF is -0.8 to +0.8 as shown in Figure 3.7.

![Membership Function for Error in LFC](image)

**Figure 3.7 Membership Function for Error in LFC**

Degree of membership plays an important role in designing a fuzzy controller. In LFC design, the linguistic variables are represented by triangular MF except for NVL and PVL by trapezoidal membership. The shape of the fuzzy set is not a concern. However, in practice symmetric triangles (or) trapezoids centered about representative values are used to represent fuzzy sets.
In AVR, the universe of discourse of the input state variable MF is -1.5 to +1.5 as shown in Figure 3.8. In this design, triangular membership function is selected because of its simplicity and more efficient for this application. The MF is symmetrical in shape and overlaps the adjacent MF by 50%. Overlapping in MF is important because it allows for a good interpolation of input values, i.e., the entire input space is accommodated. The fuzzification module converts these crisp values of the control inputs into fuzzy values, so that they are compatible with the fuzzy set representation in the rule base.

**Figure 3.8  Membership Function for Voltage in AVR**

### 3.3.2.2 Knowledge Base

The knowledge base consists of a database of the LFC and AVR model. It provides all the necessary definitions for the fuzzification process such as membership functions, fuzzy set representation of the input-output variables and the mapping functions between the physical and fuzzy domain. The rule base should cover all the possible combinations of input value, but such coverage is typically neither practical nor necessary. Rule conditions are joined by using minimum intersection operator so that the resulting membership function for a rule is given by Equation (3.1),
\[ \mu(e,ce) = \min (\mu_{Ai}(e), \mu_{Bi}(ce)) \] 

(3.1)

The rules of a FLC give the controller its intelligence, since the rules are developed based on the expert knowledge obtained from the experienced operator. In FLC design, the desired effect is to keep the output voltage and frequency of the generator at its rated value under varying loads. From this desired objective, the rules are derived for every combination of input state variables in order to obtain desired output variable. As the number of rule increases, the computational efficiency and robustness of the system will also be improved. Fuzzy rule bases are developed using a conjunctive relationship of the antecedents in the rules. This is termed as an Intersection Rule Configuration (IRC) by Combs and Andrews (1998) because the inference process maps the intersection of antecedent fuzzy sets to output consequent fuzzy sets. IRC is a general exhaustive search of solutions that utilizes every possible combination of rules in determining an outcome.

The combinatorial explosion in rules is given by

\[ R = l^n \]

where, \( R \) = Number of rules, \( l \) = Number of linguistic labels for each input variable and \( n \) = Number of input variables. In the present work, the value of ‘\( l \)’ is 9 and ‘\( n \)’ is 2, hence the number of rules \( R \) for LFC is 81 as mentioned in Table 3.1. Similarly, for AVR the value of ‘\( l \)’ is 7 and ‘\( n \)’ is 2, hence \( R \) is 49. The set of rules which relates the input and output of AVR is tabulated in Table 3.2.
### Table 3.1 Rule Base for LFC

<table>
<thead>
<tr>
<th>Change in Error</th>
<th>Error</th>
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<tbody>
<tr>
<td></td>
<td>NVL</td>
</tr>
<tr>
<td>NVL</td>
<td>PVL</td>
</tr>
<tr>
<td>NL</td>
<td>PVL</td>
</tr>
<tr>
<td>NM</td>
<td>PL</td>
</tr>
<tr>
<td>NS</td>
<td>PL</td>
</tr>
<tr>
<td>ZR</td>
<td>PM</td>
</tr>
<tr>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td>PM</td>
<td>PS</td>
</tr>
<tr>
<td>PL</td>
<td>PS</td>
</tr>
<tr>
<td>PVL</td>
<td>ZR</td>
</tr>
</tbody>
</table>

### Table 3.2 Rule Base for AVR

<table>
<thead>
<tr>
<th>Change in Error</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NL</td>
</tr>
<tr>
<td>NL</td>
<td>PL</td>
</tr>
<tr>
<td>NM</td>
<td>PL</td>
</tr>
<tr>
<td>NS</td>
<td>PL</td>
</tr>
<tr>
<td>ZR</td>
<td>PL</td>
</tr>
<tr>
<td>PS</td>
<td>PL</td>
</tr>
<tr>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>PL</td>
<td>ZE</td>
</tr>
</tbody>
</table>
In IRC approach, the intersection of the input values that is related to the output is achieved with an ‘AND’ operation and are of IF-THEN type. The basic function of the rule base is to represent in a structured way the control policy of an experienced human operator in the form of a set of production rules such as

**IF (process state) THEN (control output)**

For example

If the change in error is **NM** and error is **NS** then the output is **PM**

If error voltage is **NS** and change in error voltage is **PL**, then the field current is **NM**.

The above IF-THEN rule is a fuzzy description of the control logic representing the human expert’s qualitative knowledge. Since the controller selected from the fuzzy toolbox is with a rule viewer, the effect of control signal for change in rules can be viewed through the graphical user interface (GUI) as shown in Figure 3.9. The first two columns of plots (the six yellow plots) show the membership functions referenced by the antecedent, or the if-part of each rule. The third column of plots (the three blue plots) shows the membership functions referenced by the consequent, or the then-part of each rule. Seven linguistic variables are used to represent each input variable; hence 49 rules are developed in the rule base. The rule viewer is a MATLAB technical computing environment based display of the FIS. It is used as diagnostic test to find which rules are active and how individual membership function shapes is influencing the results. The rule viewer is road map for the whole fuzzy inference process. The three plots across the top of the figure represent the antecedent and consequent of the first rule. Each rule is a row of plots, and each column is a variable. The rule numbers are displayed on the left of each row.
From the fuzzy ruleviewer screen shot in Figure 3.9, it is inferred that,

If DELF is -0.0529 and DEL P_{tie} is -0.196, then control signal is -0.0546.

At this particular instance, if the change in frequency is 0.0529 and the tie-line power change is -0.0196. The control signal generated to initiate the turbine-governor action is -0.0546. The Rule Viewer also shows how the shape of certain membership functions influences the overall result. After rules are evaluated, crisp values are produced by defuzzification of the corresponding membership function.
3.3.2.3 Defuzzification

The mathematical procedure of converting fuzzy values into crisp values is known as defuzzification. Defuzzification plays a great role in a fuzzy logic based control system design, since it converts fuzzy set into a numeric value without losing any information. Different defuzzification methods exist to accomplish the task and naturally there exist trade-offs to each method. The selection of right strategy depends on the application and the type of MF used. The performance of FLC depends on the defuzzification process, since the system under control is determined by the defuzzified output. Centre of gravity method is used, because of its computational speed and accuracy in realtime control (Cirstea 2002). Figure 3.10 shows the graphical representation of centre of gravity method and an output condition with two significant linguistic values. The output fuzzy variable is converted into a crisp value by centroid method as given in Equation (3.2),

\[
\Delta u = \frac{\sum_{j=1}^{nr} \mu_j u_j}{\sum_{j=1}^{nr} \mu_j}
\]  

(3.2)

where \( \mu_j \) is the membership value of linguistic variable recommending the fuzzy controller action, and \( u_j \) is the precise numerical value corresponding to that fuzzy controller action. Since the final output is a combination of recommended actions of many rules, the controller is more robust to accommodate the changes in power system parameters.
Synchronous generators are responsible for the bulk source of the electric power generated in the world today. They are mainly used in power stations and usually connected to an infinite bus or used as isolated power generating systems. The control system should incorporate a certain amount of artificial intelligence such that it is flexible and not specific to a particular type of generator set (Hiyama and Tomsovic 1999). Fuzzy Logic Controllers has attracted considerable attention as candidates for the novel computational systems because of the rapidity and robustness and interesting properties in comparison to the classical control schemes. To obtain a satisfactory response and characteristics for the closed loop control system, it is necessary to connect an additional controller into the loop. In this research, fuzzy logic controller is designed and implemented for maintaining voltage and frequency within the specified limits of an autonomous power generating system. To validate the effectiveness of the proposed controller, two areas interconnected LFC system is modeled and tested. Since the components of the power system are non-linear, a linearized model around an operating point is used in the
design process of LFC and AVR. In this section, simulations of the proposed fuzzy controllers are analyzed and compared for different loads and regulation parameters. Table 3.3 indicates the nominal parameter values in per unit (pu) used for the simulation of LFC and AVR.

Table 3.3  LFC and AVR Simulation Parameters

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
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<tbody>
<tr>
<td>LFC</td>
</tr>
<tr>
<td>AVR</td>
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</tbody>
</table>

For analyzing the performance improvement, the models are simulated initially with conventional PID controller, using the simulink package version 6.3 available in MATLAB 7.1. MATLAB is a software package for high performance numerical computation and visualization. It provides an interactive environment with hundreds of reliable and accurate built in mathematical functions. The tool boxes in MATLAB are specialized collections of M-files (MATLAB language programs) built specifically for solving particular classes of problems. The fuzzy logic toolbox contains comprehensive identification tools for, automatic control, signal processing, system pattern recognition, time series prediction, data mining and financial applications.

3.4.1  PID Controller

The Simulink model for single area power system with conventional PID controller was simulated for a change in load of 0.10 p.u, 0.30 p.u and 0.8 p.u. The simulations are repeated for speed regulations 75, 100 and 125, and the response is plotted for a time period of 100 seconds. The frequency deviation and terminal voltage responses obtained for a change in
load of 0.10 p.u and speed regulation of 75 are shown in Figures 3.11 and 3.12 respectively..

![Figure 3.11 LFC with PID Controller for R=75 and ΔP_L=0.10 p.u](image1)

**Figure 3.11** LFC with PID Controller for R=75 and ΔP_L=0.10 p.u

![Figure 3.12 AVR with PID Controller for ΔP_L=0.10 p.u](image2)

**Figure 3.12** AVR with PID Controller for ΔP_L=0.10 p.u

From Figure 3.12, it is observed that the terminal voltage takes 38 seconds to settle in its optimum value. The speed of the AVR is of great interest in fixing the quality and stability of the power system. The AVR has to sense the generator output voltage and then initiate corrective action by changing the exciter control in the desired direction. The performance of PID controller for various load changes and speed regulations are tabulated in Table 3.4, from which it is inferred that frequency deviation does not have
any positive peak overshoots. The terminal voltage response of the single area power system with PID controller does not have any transient overshoots. Simulation results of classical PID controllers are kept as benchmark functions to design the rule base for fuzzy based controller.

**Table 3.4 Performance Analysis of PID Controller for Single Area Network**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( R=100 )</th>
<th></th>
<th>( R=125 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta P_L = 0.30 )</td>
<td>( \Delta P_L = 0.80 )</td>
<td>( \Delta P_L = 0.30 )</td>
<td>( \Delta P_L = 0.80 )</td>
</tr>
<tr>
<td>LFC</td>
<td>AVR</td>
<td>LFC</td>
<td>AVR</td>
</tr>
<tr>
<td>Settling Time (sec)</td>
<td>45.5</td>
<td>36.65</td>
<td>44.2</td>
</tr>
<tr>
<td>Overshoot</td>
<td>-0.0155</td>
<td>0</td>
<td>-0.045</td>
</tr>
<tr>
<td>Oscillation</td>
<td>0 to -0.0155</td>
<td>0 to 1</td>
<td>0 to -0.045</td>
</tr>
</tbody>
</table>

The procedure for simulation of fuzzy logic based LFC and AVR controllers are as follows,

1. Initialize the graphics window on the VDU screen.
2. Set the parameters start time, stop time, Minimum and maximum time step sizes.
3. Draw Power System, turbine, Speed Governor, transfer function blocks and set the default values of the co-efficient of the numerator and denominator polynomials.
4. Connect the output of the ‘speed governor’ block to the input of the ‘Turbine’ block to realize the combined transfer function \( G_{GT1}(s) \).
(5) Draw ‘Fuzzy Logic controller’ block for area #1 and create the Fuzzy Inference System (.FIS) file for the fuzzy block.

(6) Fuzzy controller block is selected from the fuzzy tool box by dragging and pasting.

(7) The fuzzy file (.FIS) created by Fuzzy tool box is called by the fuzzy controller by double clicking it.

(8) Draw the gain block B1 for representing frequency bias constant parameter for Area #1 and set its default value. The value of frequency bias constant should be within 0 and 1.0.

(9) Draw the gain block ‘1/R1’ for representing the reciprocal of area governing regulation for Area #1 and set its default value.

(10) Draw the step function block ’$\Delta PD1$’ for representing step load input to Area #1. The value of $\Delta PD1$ should preferably be within 0 and 1.0pu.

(11) Provide an option for pointing any block by moving the cursor with the help of the mouse in order to change the default system and control parameters through the keyboard and/or mouse.

(12) Repeat steps (3) to (11) for Area #2.

(13) Draw the gain blocks for representing the ‘2p Tij’ parameter for the transmission lines connecting the i-th area with j-th area.

(14) Draw the required summer and integrator blocks.

(15) Connect all the blocks with straight line connectors as per the block interconnections.
(16) Set the names of the output data files for storing all the time responses for the deviations of area frequencies, area tie powers and tie-line power flows,

(17) Apply the step load (s) for one or more area (s),

(18) Simulate the model, by setting the simulation parameters like start and stop time, type of solver, step sizes and tolerances.

(19) Store the output parameters in the corresponding output data files (or) view the results using scopes.

(20) Start the simulation and store the results in a file or view it in scope.

### 3.4.2 Fuzzy Controller for Single Area Power System

In order to demonstrate the effectiveness of the fuzzy controller, the Simulink model for single area power system is simulated and the frequency response is plotted for a time period of 100 seconds. The change in frequency for different loads and regulation parameter ‘R’ is obtained, and transient responses are found to be stable. It is clear from the simulation results that, FLC can bring down the frequency to its rated value immediately after the disturbance and without any oscillations. Figure 3.13 shows the response of frequency obtained for a sudden increase in load of 0.1p.u and for regulation value of 75. The FLC makes an intelligent decision on the amount of steam input to the turbine and hence the speed of the generator is altered to maintain the desired frequency response. From Figure 3.13, it is clear that the frequency deviation ranges from 0 to -0.0066 and the settling time is 14 seconds, which is less by a factor of 61% when compared to PID controller. in short the proposed Fuzzy controller reduces the settling time
and thereby making the system to respond immediately for the sudden increase in load.

Figure 3.13 LFC with Fuzzy Controller for \( R=75 \) and \( \Delta P_L=0.10 \) p.u

The voltage characteristics of fuzzy based AVR are obtained with change in load of 0.1 p.u as shown in Figure 3.14. The simulation is conducted and the response of the proposed controller is plotted for a duration of 100 seconds. The AVR reduces the settling time by 73% and the desired volatge is reached in 10.5 seconds without any transient oscillations.

Figure 3.14 AVR with Fuzzy Controller for \( \Delta P_L=0.10 \) p.u
The success of the proposed excitation control lies in increasing the dynamic performance of the system under varied operating conditions. The performance of the controller cannot be judged by the single result; hence the models are simulated for various load changes and regulations to validate the efficiency of the proposed algorithms. Load disturbance of 0.3 and 0.8 p.u is applied along with change in regulation values of 100 and 125 each at a time and the results are tabulated in Table 3.5. The value of R determines the slope of the governor characteristics, and it determines the change in the output for a given change in frequency. In practice ‘R’ is set on each generating unit so that change in load on a system will be compensated by generated output. The mesh and contour plots of the peaks surface for the change in frequency is plotted in Figure 3.15. The plot clearly indicates how the control parameters evolve with change in load with respect to time.

![Contour and Mesh Plots of Change in Frequency](image)

**Figure 3.15** Contour and Mesh Plots of Change in Frequency
Table 3.5  Performance Analysis of Fuzzy Controller for Single Area Network

<table>
<thead>
<tr>
<th>Parameters</th>
<th>R=100</th>
<th>R=125</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ΔP_L =0.30</td>
<td>ΔP_L =0.80</td>
</tr>
<tr>
<td>LFC</td>
<td>AVR</td>
<td>LFC</td>
</tr>
<tr>
<td>Settling Time(sec)</td>
<td>21.5</td>
<td>13.1</td>
</tr>
<tr>
<td>Overshoot</td>
<td>0.015</td>
<td>0</td>
</tr>
<tr>
<td>Oscillation</td>
<td>0 to -0.015</td>
<td>0 to 1</td>
</tr>
</tbody>
</table>

Controllers based on the fuzzy logic give the linguistic strategies control conversion from expert knowledge in automatic control strategies. In addition, the application of fuzzy logic provides desirable small and large control signal to provide dynamic performance, which is not possible with linear control technique. Therefore, fuzzy logic controller has the ability to improve the robustness of the synchronous generator by bringing its output frequency and voltage to pre-established values. Further the scope of the research is extended for evaluating the performance of proposed controller in multi-area power system.

3.4.3  Fuzzy Controller for Two Area Power System

A multi-area interconnection is comprised of regions or areas, which are interconnected by tie-lines. Tie-lines have the benefit of providing inter-area support for abnormal conditions as well as transmission paths for contractual energy exchange between the areas. A two area system consists of two single areas connected through a tie-line. Each area feeds its user pool and the tie-line allows electric power to flow between areas. In each control
area, all generators are assumed to form a coherent group. Since both areas are interconnected, a load disturbance in one area affects the output frequencies of both areas as well as the power flow on the tie-lines (Sabahi et al 2008).

The most important aspect of electrical system reliability is to keep the synchronous generators working in parallel and with adequate capacity to satisfy the load demand. The trend of frequency measured in any area is an indicator of the trend of mismatch power in the interconnection and for that particular area alone. Information about the other areas found in the output frequency fluctuation of that area and in the tie-line power fluctuations. Hence, the tie-line power is sensed and the resulting tie-line power signal is feedback into both areas (Ertugrul and Kocaarslan 2005). The dynamic model in state-space variable form obtained from the associated transfer function is as shown in Equation (3.3),

\[ x = Ax(t) + Bu(t) + Ld(t) \]  

(3.3)

where A is system matrix, B and L are the input and disturbance distribution matrices. A two-area power system is considered for simulation where, state vector \( x(t) \), control vector \( u(t) \), and disturbance vector \( d(t) \) are defined as in Equation (3.4),

\[
  x(t) = (\Delta f_1, \Delta P_{g1}, \Delta P_{v1}, \Delta P_{tie12}, \Delta f_2, \Delta P_{g2}, \Delta P_{v2}) \\
  u(t) = (u_1, u_2) \\
  d(t) = (\Delta P_{d1}, \Delta P_{d2})
\]  

(3.4)

where \( \Delta f_1, \Delta f_2, \Delta P_{g1}, \Delta P_{g2}, \Delta P_{v1}, \) and \( \Delta P_{v2} \) denote deviation from nominal values of frequency, governor power, valve power of area1 and area2 respectively. The tie-line power between area1 and area2 is given by \( \Delta P_{tie12} \) (Mathur and Manjunath 2007).
In the design of fuzzy controller, the area control error of area-1 (ACE-1) and area-2 (ACE-2) and change in errors of ACE-1 and ACE-2 are taken as the inputs and the control outputs are $\Delta P_{c1}$ and $\Delta P_{c2}$. The comparative study of system dynamic performance is carried out by investigating the frequency response for a change in load of 0.20 p.u and speed regulation of 75 in both areas. The response of LFC in Figure 3.14 shows that the controller is successful in stabilizing the frequency of the generating system for interconnected areas. Any load change in one of the control areas affects the tie-line power flow causing other control area to generate the required power to damp the frequency oscillations. The response time of LFC is very important to have the power system to gain control with increased stability margins.

![Figure 3.16 LFC with Fuzzy Controller for R=75, $\Delta P_{L1} =$0.20 p.u and $\Delta P_{L2} =$0.20 p.u](image)

The performance characteristics of change in frequency in Figure 3.16 reveal that, the oscillations for area1 and area2 varies between 0 to -0.0063 and the settling time is 10 seconds which is reduced by 80% when compared to PID controller. Table 3.6 indicates the simulation results
obtained for two area network with fuzzy controller for speed regulations of 100 and 125 for sudden load perturbations of 0.2 and 0.3 p.u.

Table 3.6 Performance Analysis of Fuzzy Controller for Two Area Network

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Settling Time (sec)</th>
<th>Overshoot</th>
<th>Oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>R=100 LFC</td>
<td>( \Delta P_{L_1} = 0.10 )</td>
<td>Area 1 11.32</td>
<td>-0.0042</td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{L_2} = 0.20 )</td>
<td>Area 2 13.18</td>
<td>-0.0056</td>
</tr>
<tr>
<td>R=100 LFC</td>
<td>( \Delta P_{L_1} = 0.20 )</td>
<td>Area 1 14.5</td>
<td>-0.0057</td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{L_2} = 0.30 )</td>
<td>Area 2 13.2</td>
<td>-0.0086</td>
</tr>
<tr>
<td>R=125 LFC</td>
<td>( \Delta P_{L_1} = 0.20 )</td>
<td>Area 1 17.4</td>
<td>-0.0052</td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{L_2} = 0.30 )</td>
<td>Area 2 17.5</td>
<td>-0.0079</td>
</tr>
<tr>
<td>R=125 LFC</td>
<td>( \Delta P_{L_1} = 0.30 )</td>
<td>Area 1 18.3</td>
<td>-0.0084</td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{L_2} = 0.40 )</td>
<td>Area 2 20.2</td>
<td>-0.0096</td>
</tr>
</tbody>
</table>

From the investigations of results in Table 3.6, the influence of FLC for interconnected power system outperforms the behavior of conventional PID controller. Irrespective of the load in either areas or both areas, the controller exhibits efficient control to guarantee zero steady state error. It is observed that the proposed controller provides better dynamic response with reduced settling time, oscillations and overshoot in both areas.

3.5 PERFORMANCE COMPARISION

An investigation on the dynamic responses of change in frequency and voltage has been carried out using fuzzy logic controller for LFC and AVR of a synchronous power generating system and compared with conventional PID controller for different loads and regulation. When an electrical load change occurs, the turbine-generator rotor accelerates or
decelerates, and frequency undergoes a transient disturbance. The controller should not allow transient oscillations or overshoot, which in-turn trips the under-frequency relay connected in the system. The response time of the controllers is very important to have the power system gain control with increased stability margin. Figure 3.17 represents the comparison between the conventional PID and fuzzy controller at a speed regulation of 75 and for a change in load 0.10 p.u.

The graph demonstrates the effectiveness of proposed controller over the conventional controllers in terms of settling time, overshoot and oscillations (Barjeev and Srtivastava 2003), (Juang and Flu 2005), (Mitra et al 2008), (Sambariya et al 2009). It is observed that, for LFC, the settling time is reduced by 78.19%, peak overshoot and oscillations is reduced by 44.6% when compared to PID controller. For AVR, the terminal voltage settling time is reduced by 78.28% as compared to conventional PID controller. Hence, by using FLC, the results are achieved very close to the practical decision-making by human experts. Therefore, an efficient and well-established method of regulating the terminal voltage and frequency of a generator set is implemented and tested.

![Figure 3.17 PID and Fuzzy Controllers Performance Comparison](image_url)
3.6 SUMMARY

In this chapter, Fuzzy based LFC and AVR is proposed for isolated and interconnected power generating systems. The LFC and AVR models are developed in simulink package version 6.3 available in MATLAB 7.1. The models are simulated for different load and regulation parameters and the results are compared with conventional PID controller.

From the simulation results of LFC, it is clear that the proposed fuzzy controller exhibits dynamic performance characteristics and the settling time is also reduced comparatively when compared to conventional controllers. The FLC based AVR is successful in controlling the output voltage of the generator with no transient oscillations and reduced settling time.

Investigation is also extended for two area interconnected power system and the frequency deviations of both areas achieve better settling time and reduced magnitude of oscillatory modes. It is observed that the output frequency is maintained constant, while there are variations in the generator speed, depending on the load and the actions taken by the controller.

Since the expert knowledge is embodied in designing the rule base, higher degree of control and robustness is achieved to solve LFC and AVR of power generating system. For many electrical equipments and applications that are very sensitive to voltage and frequency variations, fuzzy based controllers are recommended. Fuzzy control offers simple but robust solutions that cover a wide range of system parameters and can adjust itself for major disturbances.
The work can be extended in future by including non-linear parameters in the LFC and AVR model of the power system. The three area interconnected systems can be modeled in future to test the performance the proposed controller. The Evolutionary Algorithms like GA, PSO, ACO, and hybrid algorithms like GA-PSO, Fuzzy PSO, Bacterial Foraging-PSO etc., can be implemented to improve the performance characteristics of the generating system.