CHAPTER 3

Load Frequency Control using PI, Fuzzy and Polar Fuzzy Controller

3.1 Introduction

Power system frequency regulation entitled load frequency control (LFC), as a major function of automatic generation control (AGC), has been one of the important control problems in electrical power system design and operation. The normal frequency deviation beyond certain limits can directly impact on power system operation and system reliability. A large frequency deviation can damage equipments, degrade load performance, cause the transmission lines to be overloaded and can interfere with system protection schemes and ultimately lead to an unstable condition for the power system. Maintaining frequency and power interchanges with neighbouring control areas at the scheduled values are the two primary objectives of a power system LFC. These objectives are met by measuring control error signal, called the area control error (ACE), which represents the real power imbalance between generation and load, and is a linear combination of net power interchange and frequency deviations.

ACE is used to perform an input control signal for a usually proportional integral (PI) controller. Depending on the control area characteristics, the resulting output control signal is conditioned by limiters, delays and gain constants. This control signal is then distributed among the LFC participant generator units in accordance with their participation factors to provide appropriate control commands for set points of specified plants. The net errors in frequency and net power interchange have to be corrected by tuning the integral controller settings. Tuning of the dynamic controller is an important factor to obtain optimal LFC performance. Proper tuning of controller parameters is needed to obtain good control action.

The frequency control is becoming more significant today due to the increasing size, the changing structure of complex interconnected power systems. In-creasing
economic pressures for power system efficiency and reliability have led to a requirement for maintaining system frequency and tie-line power flows closer to scheduled values as much as possible. Therefore, in a modern power system, LFC plays a fundamental role, as an ancillary service, in supporting power exchanges and providing better conditions for the electricity trading.

Polar fuzzy is a new fuzzy control methodology. As the name suggest, in this new control methodology fuzzy sets are defined in polar coordinate. The (x, y) co-ordinates of a point in the plane are called its Cartesian co-ordinates. But there is another way to specify position of a point, and that is to use polar co-ordinates in terms of magnitude and angle (r, θ) as shown in Figure 3-1. For polar co-ordinates we take an origin O, and a fixed initial line OA. A point P is then described by specifying a distance r, from the origin and the angle θ from the initial line. The point then has polar co-ordinates (r, θ). In polar fuzzy controller these polar coordinates are used. The control decision is mainly dependent on the angle. The magnitude of control is increased or decreased by radius ‘r’.

![Polar co-ordinate representation](image)

**Figure 3-1 Polar co-ordinate representation**
3.2 Different generating plants and their selection

Electricity is generated by different types of power generating plants. These plants can be classified as conventional such as thermal, hydro, nuclear, gas, diesel, and non-conventional such as solar, wind, geo-thermal, biogas etc. The capacity of non-conventional power generating plants is very low as compared to conventional generating plants. Another important difference is non-conventional power generating is normally distributed in a wide area unlike to conventional generation which are centralized. Single, two and three area systems, which are made by Thermal-Hydro-Nuclear plants, are chosen for simulation. These generating plants are considered due to the following reasons:

- Thermal plants are main contributor in electricity generation our country. Coal fired plants accounting for 40% of India's total energy consumption.
- The signing of the Indo-U.S. nuclear deal in October 2008 has opened up opportunities for the growth of nuclear power in the country. The Nuclear Power Corporation of India Ltd. (NPCIL), the only nuclear power generating company in the country, aims to increase its installed capacity from 4,120 MW to 21,000 MW in the next five years, but policy of Government of India prohibits foreign direct investment in nuclear power plants.
- The Indian nuclear market is estimated to be worth $100 billion, and planners hope to build 40,000 MW of nuclear capacity by 2020. The Government of India wants the share of nuclear in the overall fuel mix to increase from around 3% to 25% by 2050.
- India also envisages increasing the contribution of nuclear power to overall electricity generation capacity from 4.2% to 9% within 25 years.
- The country has five nuclear reactors under construction (third highest in the world) and plans to construct 18 additional nuclear reactors (second highest in the world) by 2025.
- India boosts a quickly advancing and active nuclear power program. It is expected to have 20 GW of nuclear capacity by 2020, though they currently stand as the 9th in the world in terms of nuclear capacity.
There of hydropower in the country’s generation is expected to remain around 25% in the long run. Even if the potential of 150,000 MW is fully exploited by 2030-31, the share of hydro power would in fact be less than 25%. However, the XI Plan has seen slippages of 5,200 MW of hydro projects, including 1,100 MW by NTPC and 2,000 MW by NHPC.

The gross energy generation target of 855 BU for the year 2011-12, fixed in consultation with the various generating companies and approved by Ministry of Power is detailed as under:

<table>
<thead>
<tr>
<th>Type</th>
<th>Generation Target (MU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>7,12,234</td>
</tr>
<tr>
<td>Nuclear</td>
<td>25,130</td>
</tr>
<tr>
<td>Hydro</td>
<td>1,12,050</td>
</tr>
</tbody>
</table>

That’s why thermal-hydro-nuclear plants are chosen for simulation work. In the same area there may be one or more than one power plant as their load requirements and the type of plants may be same or different depending upon the type of fuel. Primarily single area thermal power plants are discussed. A single area thermal power system has three main parts that are speed governor, turbine, and generator. In starting it is assumed that this system is linear for simplicity.

### 3.3 Modeling of Single area system

An isolated electric area, where one generating unit or bunch of generating units, is placed in close vicinity to distribute the electricity in the same area is called single area system. There is no other generating unit which is distant apart is placed. Only the generating unit(s) present in that area is responsible to maintain the desired frequency in normal and abnormal conditions.

For LFC scheme of single generating unit has basically three parts:
• Turbine speed governing system
• Turbine
• Generator and load

In the next section, mathematical transfer function model of single area thermal system is developed.

3.3.1 Turbine speed governing system

When the generator electrical load is suddenly increased, the generated power also increases to satisfy the load demand, which in turns exceeds the mechanical power input. This mechanical power deficiency is supplied by the kinetic energy stored in the rotating system. The reduction in kinetic energy causes the reduction in turbine speed and consequently, the generator frequency falls. The change in speed is sensed by the turbine governor which acts to adjust the turbine input by adjusting valve position to change the mechanical power output to bring the speed to a new steady-state. The earliest governors were the Watt governors which sense the speed by means of rotating fly-balls and provide mechanical motion in response to speed changes. There are some inherent drawbacks and limitations of Watt type governor such as problem of backlash, dead band and other nonlinearities etc. These governors are mechanical type and hence slow in their operation. However, most modern governors use electronic means to sense speed changes and its control. Figure 3-2 shows schematically the essential elements of a conventional Watt governor which consists of the following major parts:

- **Speed governor**: this is heart of the system which senses the change in speed (frequency). As the speed increases the fly balls move outwards and the point B on linkage mechanism moves downwards. The reverse happens when the speed decreases.
- **Linkage Mechanism**: These are links for transforming the fly-balls movement to the turbine valve through a hydraulic amplifier and providing a feedback from the turbine valve movement.
- **Hydraulic Amplifier:** It comprises a pilot valve and main piston arrangement. Low power level pilot valve movement is converted into high power level piston valve movement. This is necessary in order to open or close the steam valve against high pressure steam.

- **Speed changer:** It provides steady state power output setting for the turbine. Its downward movement opens the upper pilot valve so that more steam is admitted to the turbine under steady conditions. The reverse happens for upward movement of speed changer.

Figure 3- 2 Block Diagram of Speed governing model
3.3.1.1 Model of speed governing system

Assume the system is initially operating under steady conditions. It means that the linkage mechanism stationary and pilot valve closed and steam valve opened by a definite magnitude, turbine running at constant speed with turbine output balancing the generator load. Let the operating conditions be characterized by

\[ f_0 = \text{system frequency} \]
\[ P_g = \text{generator output} = \text{turbine output (neglecting generator losses)} \]
\[ Y_E = \text{steam valve setting}. \]

A linear incremental model is considered around these operating conditions. Let a point A on the linkage mechanism be moved downwards by a small amount \( \Delta y_A \). It is a command which causes the turbine power output to change and can therefore can be written as

\[ \Delta y_E = K_c \Delta P_c \]  \hspace{1cm} (3.1)

where \( \Delta P_c \) is the commanded change in power.

The command signal \( \Delta P_c \) (i.e. \( \Delta Y_E \)) sets into a sequence of events – the pilot valve moves upwards, high pressure oil flows on to the top of the main piston moving it downwards; the steam valve opening consequently increases, the turbine generator speed increases, i.e. the frequency goes up. Let us model these events mathematically.

The two factors contribute to the movement of C:

1. \( \Delta y_A \) contributes \( -(l_2/l_1) \Delta y_A \) or \(-k_1 \Delta y_A \) (i.e. upwards) or \(-k_1 k_c \Delta P_c \).

2. Increase in frequency \( \Delta f \) causes the fly balls to move outwards so that B moves downwards by a proportional amount \( k_2' \Delta f \). The consequent movement of C with A
remaining fixed at $\Delta y_A$ is $+(\frac{l_1+l_2}{l_1})K_2\Delta f = K_2\Delta f$ (i.e. downwards). The net movement of $C$ is therefore

$$\Delta y_C = -k_1k_c\Delta P_c + k_2\Delta f \quad (3.2)$$

The movement of $D$, $\Delta y_d$ is the amount by which the pilot valve opens. It is contributed by $\Delta y_c$ and $\Delta y_E$ and can be written as

$$\Delta Y_D = \left[\frac{l_1}{l_3 + l_4}\right] \Delta Y_C + \left[\frac{l_3}{l_3 + l_4}\right] \Delta Y_E$$

$$= K_3\Delta y_C + K_4\Delta y_E \quad (3.3)$$

The movement $\Delta y_D$ depending upon its sign opens one of the ports of the pilot valve admitting high-pressure oil into the cylinder thereby moving the main piston and opening the steam valve by $\Delta y_D$ certain justifiable simplifying assumptions, which can be made at this, are:

1. Inertial reaction forces of main piston and steam valve are negligible compared to the forces exerted on the piston by high-pressure oil.

2. Because of above observation (1) the rate of oil admitted to the cylinder is proportional to port opening $\Delta y_D$.

The volume of oil admitted to the cylinder is thus proportional to the time integral of $\Delta y_D$. The movement $\Delta y_E$ is obtained by dividing the oil volume by the area of cross-section of the piston. Thus

$$\Delta Y_E = K_5 \int_0^t - (\Delta y_D) dt \quad (3.4)$$

It can be verified from the schematic diagram that a positive movement $y_D$, causes negative (upward) movement $\Delta y_e$ accounting for the negative sign used in (3.3).

Taking the Laplace transform of equations (3.2), (3.3) and (3.4), we get
Eliminating $\Delta Y_C(s)$ & $\Delta Y_D(s)$, we can write:

$$\Delta Y_E(s) = -K_5 \frac{1}{s} \Delta Y_D(s)$$  \hspace{1cm} (3.7)

Eliminating $\Delta Y_C(s)$ & $\Delta Y_D(s)$, we can write:

$$\Delta Y_E(s) = \frac{K_1 K_3 \Delta P_C(s) - K_2 K_3 \Delta F(s)}{K_4 + \frac{s}{K_5}}$$

$$= \left[ \Delta P_C(s) - \frac{1}{R} \Delta F(s) \right] \left\{ \frac{K_{sg}}{1 + T_{sg}} \right\}$$  \hspace{1cm} (3.8)

where

$K_{sg} = $ gain of speed governor

$R = $ speed regulation of the governor

$T_{sg} = $ time constant of speed governor

The speed governing system of a hydro turbine is more involved. An additional feedback loop provides temporary droop compensation to prevent instability. This is necessitated by the large inertia of the penstock gate, which regulates the rate of water input to the turbine as given in Figure 3-3 (here subscript ‘T’ stands for thermal power plant).
3.3.2 Turbine model

Let us now relate the dynamic response of a steam turbine in terms of changes in power output to change in steam valve opening $Y_E$. Figure 3-4 shows a two stage steam turbine with a reheat unit. The dynamic response is largely influenced by two factors:

1. Entrained steam between the inlet steam valve and first stage of turbine
2. The storage action in the reheater, which causes the output of low pressure stage to lag behind that of the high pressure stage.
Thus, the turbine transfer function is characterized by two time constants. For ease of analysis, it will be assumed here that turbine can be modeled to have a single equivalent time constant. Figure 3-5 and 3-6 shows the transfer function model of a steam turbine without reheat and with reheat unit respectively. Typically the time constant $T_1$ lies in the range 0.2–2.5 s. Steam valve writing the power balance equation, we have

$$
\Delta P_G - \Delta P_D = \frac{2H}{f^0} \frac{d}{dt} (\Delta f) + B \Delta f
$$

Dividing throughout by $P_r$ and rearranging, we get

$$
\Delta P_G(\nu) - \Delta P_D(\nu) = \frac{2H}{f^0} \frac{d}{dt} (\Delta f) + B(\nu)\Delta f
$$

Taking the Laplace transform, we can write $\Delta f(s)$

$$
\Delta f(s) = \frac{\Delta P_g(s) - \Delta P_d(s)}{B + \frac{2H}{f^0}(s)}
$$

$$
= [\Delta P_g(s) - \Delta P_d(s)] * \left( \frac{K_p(s)}{1 + T_p(s)} \right) 
$$

(3.9)
where

\[ T_{ps} = \frac{2H}{Bf^0} \] = power system time constant;

\[ K_{ps} = \frac{1}{B} \] = power system gain.

Equation (3.9) can be represented in block diagram as shown in Figure 3-7.

### 3.3.3 Generator load model

The increment in power input to the generator load system is \( \Delta P_g - \Delta P_d \). where \( \Delta P_g \) - incremental turbine power output and \( \Delta P_d \) is the load increment. This increment in power input to the system is accounted in two ways:

\[ \Delta P_{dT}(s) \]

\[ \Delta P_{TR}(s) = \Delta P_{gT}(s) \]

\[ \frac{K_{psT}}{1 + T_{psT}(s)} \]

\[ \Delta f_T(s) \]

**Figure 3-7 Block Diagram of Generator- load model**

1. Rate of stored kinetic energy in the generator rotor. At scheduled frequency (f), the stored energy is

\[ W_{ke} = H \cdot P_r \text{ kW} - \text{s (kj)} \]

Where \( P_r \) is the kW rating of the turbo-generator and H is defined as its inertia is constant. The kinetic energy being proportional to square of speed (frequency), the kinetic energy at a frequency of (f + \( \Delta f \)) is given by
\[ W_{ke} = W_{ke}^0 \frac{(f^0 + \Delta f)^2}{f^0} \]

\[ = HP_r (1 + \left( \frac{2\Delta f}{f^0} \right)) \quad (3.10) \]

Rate of change of kinetic energy is therefore

\[ \frac{d}{dt} (W_{ke}) = \frac{2HP_r}{f^0} \frac{d}{dt} (\Delta f) \quad (3.11) \]

2. As the frequency changes, the motor load changes being sensitive to speed, the rate of change of load with respect to frequency, i.e. can be regarded as nearly constant for small changes in frequency \( \Delta f \) can be expressed as

\[ \left( \frac{\partial P_d}{\partial f} \right) \Delta f = B \Delta f \quad (3.12) \]

where the constant \( B \) can be determined empirically. \( B \) is positive for a predominantly motor load.

### 3.3.4 Load frequency control in a single area system

In this section, the analysis of load frequency control of a single area power system is presented. The complete system to be considered for the design of controller is shown in Figure 3-8. The system response has been obtained for uncontrolled and controlled system.
3.3.4.1 Steady state response

In uncontrolled case, speed changer has fixed settings, i.e. $\Delta P_{\text{ref}} = 0$

For step load change $= \Delta P_D$

Laplace transform of it is $\Delta P_{\text{ref}} = 0$

Now from block diagram shown in Figure 3-8, system equation can be written as

$$\left[ \left( \Delta P_{\text{ref}} - \frac{1}{R} \Delta f \right) * K_{sg} K_T - \Delta P_D \right] = \Delta f$$

(3.13)

Laplace transform

$$\Delta f(s) = \frac{K_P}{1 + \left( \frac{1}{R} \right) K_p K_{sg} K_T} \Delta P_D(s)$$

(3.14)

Using the final value theorem

$$\Delta f_{ss} = \lim_{s \to 0} [s \Delta f(s)] = \frac{s K_P}{1 + \left( \frac{1}{R} \right) K_p K_{sg} K_T} \frac{\Delta P_D}{s}$$
If $\beta = [B + 1/R]$ p.u. MWhz

Then

$$\Delta f_s = -\frac{\Delta P_D}{\beta}$$ (3.16)

where $\beta$ is called area freq. response characteristic (AFRC). Thus, in uncontrolled case the steady state response has constant error.

### 3.3.4.2 Dynamic response

The dynamic response of a single area thermal system for a step load is calculated in this section. By taking inverse Laplace transform of equation (3.17), the frequency can be calculated in time domain $\Delta f(t)$. However, as $K_H, K_T, K_{ps}$ contain at least one time constant each, the denominator will be of third order, resulting in unwieldy algebra.

$$(T_{sg} << T_i << T_{ps})$$ where $T_p$ is generally 20 s. $T_{sg} \approx T_i \leq 1$ s, thus assume $T_{sg} = T_i = 0$ and the dynamic frequency response can be calculated as

$$\Delta f(s) = \frac{K_p}{1 + \frac{1}{sT_{ps}}} \cdot \frac{\Delta P_D}{s}$$ (3.17)

Above equation can also be written as

$$\Delta f(s) = -\Delta P_D \frac{RK_{ps}}{R + K_{ps}} \left(\frac{1}{s} - \frac{1}{R + K_{ps} \frac{s}{RT_{ps}}}\right)$$ (3.18)

Taking inverse Laplace transform of above equation we get

$$\Delta f(s) = -\Delta P_D \frac{RK_p}{R + K_{ps}} \left[1 - e^{-t\left(R \frac{K_{ps} + R}{RT_{ps}}\right)}\right]$$ (3.19)
Thus the error = \( e^{-t \left( \frac{K_{ps} + R}{RT_{ps}} \right)} \). This persists in uncontrolled case.

Model and simulated response of uncontrolled single area without reheat system is shown in Figure 3.9 and 3.10 respectively.

![Block diagram model of single area Thermal System without controller and reheat unit](image)

Figure 3- 9 Block diagram model of single area Thermal System without controller and reheat unit

Where \( T_g = 0.08 \) t; \( T_t = 0.3 \) t; \( T_{ps} = 20 \) t; \( K_g = 1 \); \( K_t = 1 \); \( K_{ps} = 120 \); \( R = 2.4 \); \( P_D = 1\% \).

![Simulated Result of single area Thermal System without controller and reheat unit](image)

Figure 3- 10 Simulated Result of single area Thermal System without controller and reheat unit
3.3.4.3 Response with controller

Control area

The power pools in which all the generators are assumed to be tightly coupled with change in load. Such as area, where all the generators are running coherently is termed as control area.

With PI controller

Using the conventional control strategy, we can control the dynamic frequency response and also make the steady state error to zero with changes in load. An integral controller is added to the un-controlled system which actuates the speed changer by real power command signal $\Delta P_c$.

$$\Delta P_c = -K_t \int \Delta f dt \quad (3.20)$$

The negative polarity must be chosen so as the frequency error will give a negative control to reduce the value of command signal. Here $K_g$ and $K_t$ are such that $K_g K_t \approx 1$.

Area control error (ACE), is

$$ACE = \Delta f \quad (3.21)$$

Taking Laplace transform of equation (3.20), we get $\Delta P_c$

$$\Delta P_c(s) = \frac{K_I}{s} \Delta f(s)$$

and for step input load:

$$\Delta P_D(s) = \frac{\Delta P_D}{s}$$
Using final value theorem, we readily obtain from the above equation the static frequency droops:

\[
\Delta f_{\text{steady}} = \lim_{s \to 0} [s \Delta f(s)] = 0, \text{ i.e. no error.}
\]

Model and simulated response of PI controlled single area without reheat thermal system is shown in Figure 3.11. Its simulation result is shown in Figure 3-12 in which frequency error becomes zero.

Figure 3-11 Block diagram model of PI controlled single area without reheat unit Thermal System
3.4 Modeling of Two area systems

In real time power system many loads are connected to many generators located in different regions (areas). This may be assumed as extended power system which can be divided into number of load frequency control areas interconnected by means of tie lines (Figure 3-14).

![Two interconnected control Areas](image)

**Figure 3-13 Two interconnected control Areas**

In these areas load changes and abnormal conditions lead to mismatches in frequency and scheduled power interchanges through tie line between areas. These mismatches have to be corrected by Governor Control, which is defined as the regulation of the power output of generators within a prescribed area. The key assumptions in the classical Governor Control problem are:
- The steady state frequency error following a step load change should vanish. The transient frequency and time errors should be reduced.
- The static change in the tie line power following a step load in any area should be zero, provided each area can accommodate its own load change.
- Any area in need of power during an emergency should be assisted from other areas.

The two area system is a form of multi-area system of AGC, where a group of generator is closely coupled internally and swing in unison. Furthermore, the generator turbine tends to have the same response characteristics. Such a group of generators are said to be “coherent”, then it is possible to represent the whole system, which is referred as a “control area”.

The objective is to regulate the frequency of each area and simultaneously regulate the tie line power as per inter-area power contracts. Since a tie line transport power in or out of area, this fact must be accounted for in the incremental power balance equation of each area.

In two area system, generation and load demand of two domains are dealt. Any load change within the area has to be met by generators in both the area. Thus, we can maintain the constant frequency operation irrespective of load change. Tie line control system must use two pieces of information: the system frequency and the net power flowing in or out over the tie lines.

- If frequency decreases and net interchange power leaving the system also increases then the load increased outside the system.
- If frequency decreases and net interchange power leaving the system also decreases, then the load increased inside the system. Area control error is the change in area frequency which is used in an integral control loop, forces the steady state error zero. The steady state tie line power error in the two area control be made zero and this is done by another control loop introduced to integrate the tie line power signal and feed it back to speed changer.
The steady state tie line power error in the two area control be made zero another control loop must be introduced to integrate the tie line power signal and feed it back to speed changer. Simulink models of uncontrolled and controlled two area thermal systems are shown in Figure 3-14 and Figure 3-15. This is defined by a single block by redefining ACE as combination of incremental frequency and tie line power.

Thus for control areas: \[ ACE_1 = \Delta P_{tie1} + b_1\Delta f_1 \] (3.23)

Where, \( b_1 \) is the biasing factor. ACE for area one can be expressed as:

\[ ACE_1(s) = \Delta P_{tie1}(s) + b_1\Delta F_1(s) \] (3.24)

Similarly, the ACE for area two can be expressed as:

\[ ACE_2(s) = \Delta P_{tie2}(s) + b_2\Delta F_2(s) \] (3.25)
Figure 3-15 Simulink Model of Two Area Thermal System with PI Controller
3.4.1 Model development of hydro-electric power system

As for the requirement of hydro-electric power system modeling for load frequency control, speed governor, turbine and generator should be modeled. The model development of different components of single area hydro system is explained in following sections.

3.4.1.1 Model of hydro-Electric speed Governor

Transfer function for the mechanical hydraulic governor and turbine is given by equation 3.26.

\[
T_{gh} = \left( \frac{K_{gh}}{1 + sT_{gh2}} \right) \left( \frac{1 + sT_{Hz}}{1 + sT_{H4}} \right)
\]

(3.26)

and the block diagram model is shown in Figure 3-16.

![Block Diagram Model](image)

**Figure 3- 16 Transfer function block diagram model of Hydro-Electric speed Governor**

Where, K and T are the gain and time constant of the hydraulic system (H, 2 and 4 are suffix for Hydro area and g for governor).

\[
K_{gh} = 1; \quad R_H = 2.4 \text{Hz/pu MW}
\]

\[
T_{gh2} = \text{governor time constant of hydro electric system} = 48.7 \text{ s};
\]
$T_{H2}, T_{H4} =$ hydro area time constant $= 5\text{ s and 0.513 s.}$

$\Delta Y_{EH} =$ change in the water valve position of hydro electric system

### 3.4.1.2 Model of hydro turbine

Transfer function model of hydro turbine is

$$\frac{\Delta P_{tH}}{\Delta Y_{EH}} = \left(\frac{1-sT_w}{1+0.5sT_w}\right)$$ (3.27)

Where

$\Delta Y_{EH}(s) =$ change in the water valve position of hydro electric system

$\Delta P_{tH}(s) =$ change in the turbine power of hydro electric system

$T_w = \text{water time constant } = 1\text{ s.}$

and the block diagram model is shown in Figure 3-17.

![Figure 3-17 Model of Hydro Turbine](image-url)

### 3.4.1.3 Transfer function model of hydro Generator

The generator dynamics is modeled by swing equation and given in equation (3.28)

$$\frac{2H}{\omega_s} \frac{d^2 \Delta \delta}{dt^2} = \Delta P_m - \Delta P_e$$ (3.28)

Where

$H =$ Inertia constant of generator
Δδ - change in angle

ΔP_m - change in mechanical power

ΔP_e - change in electrical power

For small perturbation the above relation can be represented by a block diagram as shown in Figure 3-18.

\[ \Delta P_e(s) \rightarrow \frac{1}{H_s} \rightarrow \Delta \omega(s) \]

\[ \Delta P_m(s) \]

**Figure 3- 18 Block diagram representation of swing equation**

Similarly the composite load is considered and the corresponding transfer function for the load model is given as

\[ \Delta P_e = \Delta P_L + D \Delta \omega \]  \hspace{1cm} (3.29)

Where

\[ \Delta P_L - \text{non frequency sensitive load change} \]

\[ D \Delta \omega - \text{frequency sensitive load change} \]

\[ \Delta P_e(s) \rightarrow \frac{1}{H_s + D} \rightarrow \Delta \omega(s) \]

**Figure 3- 19 Model of Hydro Generator**
Where $\Delta P_L$ is the non frequency sensitive load change and $D\Delta \omega$ is the frequency sensitive load change. $D$ is expressed as percentage change in load divided by the percentage change in frequency. Therefore, the combined transfer function for the generator load model is shown in Figure 3-19.

### 3.4.2 Model development of nuclear power system

As for the requirement of nuclear power system modeling for load frequency control, speed governor, turbine and generator should be modeled. These are modeled as follows:

#### 3.4.2.1 Speed governor model of nuclear power plant

The transfer function block diagram model of governor is shown as in Figure 3-20:

![Figure 3-20 Model of Speed Governor of Nuclear Power Plant](image)

Where

\[
\Delta P_{CN} = \text{change in speed changer setting of nuclear system}
\]

\[R_N = \text{speed regulation of nuclear governor}= 2.4 \text{Hz/pu MW}\]

\[T_{RN} = \text{governor time constant of nuclear system}= 0.08 \text{ s}\]
3.4.2.2 Model development of turbine of nuclear power plant

The Mathematical model considered for nuclear unit tandem-compound turbines, one HP section and two LP section with HP reheater as shown in Figure 3-21. The HP exhausts Moisture-Separator-Reheater (MSR) before entering the LP turbine. The MSR reduces the moisture content of the steam entering the LP section, thereby reducing the moisture and erosion rates. High pressure steam is used to reheat the HP exhaust [HAS 12].

\[
\begin{align*}
\Delta Y_{EN}(s) & \rightarrow \frac{k_{H1}}{1 + sT_1} \quad \text{HP Turbine} \\
\frac{k_{R1}}{(1 + sT_1)(1 + sT_{RH_3})} & \rightarrow \quad + \\
\frac{1 + sT_{RH_2}}{1 + sT_{RH_3}} & \rightarrow \frac{1}{1 + sT_2} \quad \text{LP Turbine}
\end{align*}
\]

Figure 3- 21 Transfer Function Block Diagram model of Turbine of Nuclear Power Plant

Where

\[k_{H1} = 0.2-2.0; \quad k_{R1} = 0.3; \quad T_1 = 0.5 \text{ s}; \quad T_{RH_1} = 7 \text{ s}; \quad T_{RH_2}; T_{RH_3} = 6 \text{ s}; \quad 10 \text{ s}; \quad T_2 = 9 \text{ s}.\]

The dynamic performance of LFC has been made based upon a linearized analysis. The simple LFC model does not consider the effects of the physical constraints. Although considering all dynamics in frequency control synthesis and analysis may be difficult and
not useful, it should be noted that to get an accurate perception of the LFC subject it is necessary to consider the important inherent requirement and the basic constraints imposed by the physical system dynamics, and model them for the sake of performance evaluation.

### 3.5 Modeling of Three area system

To illustrate LFC system behavior in a multi-area power system, consider three different interconnected control areas as shown in Figure 3.22. The system dynamics response following a simulations 0.01 pu load step disturbance in control areas. If disturbance is given to any one of the three areas, the power to compensate the tie-line power change initially comes from all the three areas and frequency drops in all the areas and this drop of frequency is sensed by the speed governors of the three areas. However, after a few seconds (steady state), additional power against the local load changes come only from that disturbed area.

![Representation of a Three System](image)

**Figure 3-22 Representation of a Three System**

Change in the tie line power between area 1 and 2

\[
\Delta P_{\text{tie,1-2}} = \frac{2\pi}{s} T_{12} (\Delta f_1(s) - \Delta f_2(s))
\]  

(3.30)

Change in the tie line power between area 1 and 3

\[
\Delta P_{\text{tie,1-3}} = \frac{2\pi}{s} T_{13} (\Delta f_1(s) - \Delta f_3(s))
\]  

(3.31)
Change in the tie line power between area 2 and 3

\[
\Delta P_{\text{tie,2-3}} = \frac{2\pi}{s} T_{23} (\Delta f_2(s) - \Delta f_3(s)) \quad (3.32)
\]

Where

- \( T_{ij} \) - Tie line power between \( i^{th} \) and \( j^{th} \) areas.
- \( f_i \) - Frequency of \( i^{th} \) area.

So the total tie line power change between area 1 and the other two areas can be calculated as

\[
\Delta P_{\text{tie,1}} = \Delta P_{\text{tie,1-2}} + \Delta P_{\text{tie,1-3}} = \frac{2\pi}{s} \left( \sum_{j=2,3} T_{1j} \Delta f_1 - \sum_{j=2,3} T_{1j} \Delta f_j \right) \quad (3.33)
\]

Similarly for \( N \) control areas, the total tie line power change between area 1 and other area is (as shown in Figure 3.23)
Therefore three area system can be modeled as shown in Figure 3.24.

\[
\Delta P_{\text{tie},i} = \sum_{j=1}^{N} \Delta P_{\text{tie},i,-j} - \frac{2\pi}{s} \left( \sum_{j=1}^{N} T_{ij} \Delta f_i - \sum_{j=1}^{N} T_{ij} \Delta f_j \right) \quad (3.34)
\]

Therefore three area system can be modeled as shown in Figure 3.24.
Figure 3-24 Simulink Model of Three Area System
Conventional controllers

Most common controllers available commercially are the proportional integral (PI) and proportional integral derivative (PID) controller [28]. The PI controllers are used to improve the dynamic response as well as to reduce or eliminate the steady state error [9]. The derivative controller adds a finite zero to the open loop plant transfer function and improves the transient response. PID is made up of three main components i.e. proportional, integral and derivative.

3.5.1 Proportional term

The proportional term (sometimes called gain) makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant $K_p$, called the proportional gain.

The proportional term is given by

$$P_{out} = K_p e(t) \quad (3.35)$$

where

$P_{out}$: Proportional term of output

$K_p$: Proportional gain, a tuning parameter

$e$: Error = Set value - Actual value

$t$: Instantaneous time in sec.

3.5.2 Integral term

The contribution from the integral term (sometimes called reset) is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been
corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output. The magnitude of the contribution of the integral term to the overall control action is determined by the integral gain, $K_i$.

The integral term is given by:

$$I_{out} = K_i \int_{0}^{t} e(\tau) d\tau$$

(3.36)

where

$I_{out}$: Integral term of output

$K_i$: Integral gain, a tuning parameter

$e$: Error = Set Value - Actual Value

$t$: instantaneous time

$\tau$: a dummy integration variable

3.5.3 Derivative term

The rate of change of the process error is calculated by determining the slope of the error over time (i.e., its first derivative with respect to time) and multiplying this rate of change by the derivative gain $K_d$. The magnitude of the contribution of the derivative term (sometimes called rate) to the overall control action is termed the derivative gain, $K_d$.

The derivative term is given by:

$$D_{out} = K_d \frac{d}{dt} e(t)$$

(3.37)

where
\( D_{\text{out}} \): Output of Derivative term

\( K_d \): Derivative gain (a tuning parameter)

\[ e = \text{Error} = \text{Set Value - Actual Value} \]

\[ t : \text{instantaneous time in sec.} \]

### 3.5.4 Conventional PI Controller

This controller is one of the most popular in industry. The proportional gain provides stability and high frequency response. The integral term insures that the average error is driven to zero. Advantages of PI include that only two gains must be tuned, that there is no long-term error, and that the method normally provides highly responsive systems. The predominant weakness is that PI controllers often produce excessive overshoot to a step command. The PI controller is characterized by the transfer function

\[
G_c(s) = K_p \left( 1 + \frac{1}{sT_i} \right)
\]  

(3.38)

The PI controller is a lag compensator. It possesses a zero at \( s = -1/T_i \) and a pole at \( s = 0 \). Thus, the characteristic of the PI controller is infinite gain at zero frequency. This improves the steady-state characteristics. However, inclusion of the PI control action in the system increases the type number of the compensated system by 1, and this causes the compensated system to be less stable or even makes the system unstable. Therefore, the values of \( K_p \) and \( T_i \) must be chosen carefully to ensure a proper transient response. By properly designing the PI controller, it is possible to make the transient response to a step input exhibit relatively small or no overshoot. The speed of response, however, becomes much slower.
3.5.5 Conventional PID controllers

A Conventional PID controller is most widely used in industry due to ease in design and inexpensive cost. The PID formulas are simple and can be easily adopted to corresponding to different controlled plants but it can’t yield a good control performance if controlled system is highly order and nonlinear. The PID controller is a combination of the PI and PD controllers. The PD control, as in the case of the lead compensator, improves the transient-response characteristics, improves system stability, and increases the system bandwidth, which implies fast rise time [41].

![Figure 3-25 PID Control of Plant](image)

PID is a lag-lead compensator. PI control action and PD control action occur in different frequency regions. The PI control action occurs at the low-frequency region and PD control action occurs at the high- frequency region. The PID control may be used when the system requires improvements in both transient and steady-state performances.

Figure 3-25 shows a PID controller of a plant. If a mathematical model of the plant can be derived, then it is possible to apply various design techniques for determining parameters of the controller that will meet the transient and steady-state specifications of the closed-loop system. However, if the plant is so complicated that its mathematical model cannot be easily obtained, then an analytical approach to the design of a PID controller is not possible. Then we must resort to experimental approaches to the tuning of PID controllers. The process of selecting the controller parameters to meet given performance specifications is known as controller tuning. Ziegler and Nichols suggested rules for tuning PID controllers (meaning to set values $K_p$, $T_d$, and $T_i$) based on
experimental step responses or based on the value of \( K_p \), that results in marginal stability when only proportional control action is used. Such rules suggest a set of values of \( K_p \), \( T_d \) and \( T_i \) that will give a stable operation of the system. However, the resulting system may exhibit a large maximum overshoot in the step response, which is unacceptable. In such a case we need series of fine tunings until an acceptable result is obtained. In fact, the Ziegler-Nichols tuning rules give an educated guess for the parameter values and provide a starting point for fine tuning, rather than giving the final settings for \( K_p \), \( T_i \) and \( T_d \) in a single shot. Because of the complex tuning in PID controller, in this work the tuning is done by hit and trial approach.

Usually the PID controller is a fixed parametric controller and the power system is dynamic and its configuration changes as its expansion takes place. Hence, fixed parametric PI or PID controllers are unable to give their best responses. To cope up with this complex, dynamic and fuzzy situations, fuzzy logic was proposed in literature by many researchers.

### 3.6 Development of Fuzzy logic Controller

Fuzzy logic was initiated in 1965 by Lotfi A. Zadeh, professor in Department of Computer Science at the University of California in Berkeley. Fuzzy set theory and fuzzy logic establish the rules of a nonlinear mapping. The use of fuzzy sets provides a basis for a systematic ways for the application of uncertain and indefinite models. Fuzzy control is based on a logical system called fuzzy logic which is much closer in spirit to human thinking and natural language than classical logical systems. Now a days fuzzy logic is used in almost all sectors of industry and science.

The idea behind the Fuzzy Logic Controller (FLC) is to fuzzify the controller inputs, and then infer the proper fuzzy control decision based on defined rules. Fuzzy knowledge based system is shown in Figure 3-26. The FLC output is then produced by defuzzifying this inferred fuzzy control decision. Thus, the FLC processes contain following main components:

- Fuzzification
3.6.1 FLC Structure

**Fuzzification**

Fuzzification is the process of transferring the crisp input variables of controller to corresponding fuzzy variables. Selection of control variables relies on the nature of the system and its desired output. It is more common in literature to use the output error and derivative of the output as controller inputs. The membership function maps the crisp values into fuzzy variables.

**Classification of Fuzzy Sets**

The fuzzy sets can be classified based on the membership functions. They are:

- **Normal fuzzy set**- if the membership function has at least one element in the universe whose value is equal to 1, then that set is called as normal fuzzy set.

- **Non-normal fuzzy set**- If the membership function has the membership values less than 1, then that set is called as non-normal fuzzy set.
Convex fuzzy set- If the membership function has membership values those are monotonically increasing, or, monotonically decreasing, or they are monotonically increasing and decreasing with the increasing values for elements in the universe, those fuzzy set A is called convex fuzzy set.

Non-convex fuzzy set- If the membership function has membership values which are not strictly monotonically increasing or monotonically decreasing or both monotonically increasing and decreasing with increasing values for elements in the universe, then this is called as non-convex fuzzy set.

3.6.2 Features of Membership Function

The feature of the membership function is defined by three properties. They are:

- Core
• Support
• Boundary

These features of membership function are shown in Figure 3.29.

![Figure 3-29 Features of membership function](image)

**3.6.3 Type of memberships functions**

Triangular membership function is used because it is a simple function and often allowing for the prediction and calculation of an output of the fuzzy system. Another reason is that the extra smoothness introduced by higher order fuzzy sets and demanding higher computational consumption is not strongly reflected in the output quality of a fuzzy model. However, the problem of the membership function choice has not yet been solved theoretically. Different researchers used different shapes of their application problems such as trapezoidal, Gaussian, sigmoidal etc.
Figure 3-30 Membership Functions

For load frequency problem triangular and sigmoidal membership functions are used.
3.6.4 Rule base for fuzzy logic system

Working of fuzzy logic controller is based on 49 rules. These fuzzy logic rules are in ‘if and then’ format. These rules can be placed in form of table (as in table 3-2). Here error and cumulative error are two inputs of fuzzy logic controller.

Table 3- 2 FAM Table

<table>
<thead>
<tr>
<th>Error</th>
<th>nb</th>
<th>nm</th>
<th>ns</th>
<th>z</th>
<th>ps</th>
<th>pm</th>
<th>pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>nb</td>
<td>pb</td>
<td>pb</td>
<td>pm</td>
<td>pm</td>
<td>ps</td>
<td>ps</td>
<td>z</td>
</tr>
<tr>
<td>nm</td>
<td>pb</td>
<td>pb</td>
<td>pm</td>
<td>pm</td>
<td>ps</td>
<td>z</td>
<td>z</td>
</tr>
<tr>
<td>ns</td>
<td>pb</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>z</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>z</td>
<td>pb</td>
<td>pm</td>
<td>pm</td>
<td>z</td>
<td>ns</td>
<td>nm</td>
<td>nb</td>
</tr>
<tr>
<td>ps</td>
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<td>pm</td>
<td>ns</td>
<td>ns</td>
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<td>pm</td>
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<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nb</td>
</tr>
</tbody>
</table>

Figure 3-31 Error input membership function
3.6.5 Defuzzification

The resulting fuzzy set must be converted to a number that can be sent to the process as a control signal. This operation is called defuzzification. The resulting fuzzy set is thus defuzzified into a crisp control signal. There are several defuzzification methods.
3.6.5.1 Defuzzification Methods

There are seven methods used for defuzzifying the fuzzy output functions. They are

1. Max-membership principle,
2. Centroid method,
3. Weighted average method,
4. Mean–max membership,
5. Centre of sums,
6. Bisector of area, and
7. First of maxima or last of maxima

![Type of Defuzzification](image1)

![Type of Defuzzification](image2)

The fuzzy logic based controller has been developed using the above steps and this controller will be tested for LFC system. Developed fuzzy logic controller will be applied in single and multi-area systems. This controller will be tested and compared to other conventional controllers.
Limitations of Fuzzy Logic Controller

1. The tuning of FLC is quite difficult due to large number of parameters such as number of linguistic terms, number of membership functions, shape of membership functions, their range etc.
2. The appropriate number of rules of FLC is not an easy task.
3. The selection of conjunctive, disjunctive and implication operators used are problem dependent.
4. The appropriate size of rule base of FLC is not known.

### 3.7 Development of Polar fuzzy controller

To overcome some of the drawbacks of FLC, polar fuzzy logic controller is proposed in this section. The polar fuzzy sets were first introduced in 1990 [HAD 90]. The linguistic values are formed to vary with $\theta$, the angle defined on the unit circle and their membership values are on $\mu(\theta)$. Polar fuzzy is useful in situations that have a natural basis in polar coordinates or in situations where the value of a variable is cyclic. Polar fuzzy sets are applied in quantitative description of linguistic variables known truth-values. Polar fuzzy sets differ from standard fuzzy sets only in their universe of angle and hence repeat shapes every $2\pi$ radian.

Therefore, in the work reported, a polar fuzzy approach is used to control the load frequency problem. Polar fuzzy controller (PFC) handles all these problems of fuzzy controller easily and efficiently. The fuzzy logic controller (FLC) in PFC works on the basis of an angle, which is considered one input and controller response as an output. Hence, FLC of PFC is a single input–single output system (SISO), and the final output is calculated by multiplying magnitude of polar quantity and output FLC of PFC. In PI controller, two gains (Kp and Ki) are to be tuned, however the PFC needs only one gain to be tuned, because the angle of PFC is calculated from the ratio of frequency deviation and the integral of frequency deviation, Hence, only one gain is sufficient to tune it. The FLC of PFC is a SISO system and therefore, only two rules are sufficient in the rule base. The
PFC is quite simple in construction and has great power to control complex non linear power systems.

In this section, the working of PFC is described. The block diagram of polar fuzzy logic controller is shown in Figure 3-35. Primarily frequency deviation and cumulative error define in complex plane and this complex quantity (consisting of real and imaginary part) is then converted into equivalent polar co-ordinates (i.e. angle and magnitude). The input to polar fuzzy controller is angle and its output is intermediate control action. Two fuzzy sigmoid membership functions are used which are large positive (LP) and large negative (LN) as shown in Figure 3-36 for angle as input. These two membership functions are complimentary to each other. The variation of angle ($\theta$) as input of FLC with respect to time is shown in Figure 3-37. The range of variation of $\theta$ is from 0 to 11. Most of the time, PFC operates in first quadrant. This can be easily seen in rule viewer (Figure 3-38). Control action should be such that system attains desired frequency as early as possible with minimum deviation and oscillations. Output of the fuzzy logic controller ($U_{FLC}$) is defined into two linguistic variables namely, positive (P) and negative (N), which are triangular membership functions as shown in Figure 3-39. There are only two simple rules are considered.

Rule 1 - If $\theta$ is LP then $U_{FLC}$ is P.

Rule 2 - If $\theta$ is LN then $U_{FLC}$ is N.

Hence, the output of FLC unit of PFC is a function of angle ($\theta$) i.e.

$$U_{FLC} = f_1(\theta),$$

and final PFC output $U = U_{FLC} \cdot R$

Where

$$\theta - \text{angle in degree} = \tan^{-1}(ce/e);$$

$$R - \text{Magnitude} = \sqrt{e^2 + ce^2};$$
\( e = K_o \Delta f \) and \( ce \) – cumulative frequency error.

**Figure 3- 35 Working of Polar Fuzzy Controller**
For FLC two triangular output membership functions P (positive) and N (negative) are taken in the range -0.15 to +0.15. The variation of magnitude of polar coordinates during LFC with respect to time is also shown in Figure 3-40. The output of FLC and magnitude multiplied together to get the final output ‘U’. The performance of the Polar fuzzy logic controller is shown in Figure 3-41.
Figure 3- 38 Rule Viewer

Figure 3- 39 Fuzzy sets of output variable for PFC
Figure 3- 40 Variation of Magnitude with respect to Time for PFC

Figure 3- 41 Variation of PFC Output with respect to Time
3.8 Load frequency control of single area and two area systems

The above developed controllers have been used for load frequency control of single area thermal system. In starting, the performance of PFC has been tested for a disturbance of 1% step change in load in single area thermal system. From the simulation results, it is found that the frequency deviation from its nominal value is lesser in PFC as compared to Fuzzy and PI controller. Also, it is shown in simulation results that the settling and steady state time is lesser in case of proposed PFC controller. This developed polar fuzzy controller is tested and simulated for two area and three area thermal-hydro-nuclear systems. In these systems, the performance of developed polar fuzzy controller is also compared with fuzzy and conventional PI controllers.

3.8.1 Single area thermal system simulations with different controllers

The above described single area thermal system has been implemented in Simulink of Matlab with different controller and different system complexities like with and without reheat as in Figure 3-42. The results are compared for different controllers. It is found that polar fuzzy controller gave better results in terms of less deviation in frequency in first undershoot, less settling time, and less oscillations as compared to fuzzy controller and conventional PI controllers.

![Figure 3-42 Simulink model of PI controlled single area Thermal System without reheat unit](image-url)
The frequency deviation of single area thermal system for 1% disturbance is shown in Figure 3-43 for without reheat unit using PI controller and without controller.

Figure 3- 43 Comparison of with and without controller for single area Thermal System without reheat unit

Figure 3- 44 Simulink model of PI controlled single area Thermal System with reheat unit
Figure 3-45 Simulated result of PI controlled single area Thermal System with reheat unit

Figure 3-46 Simulation model of Fuzzy controlled single area Thermal System with reheat unit

Also the system is simulated with reheat and PI controller as shown in Figure 3-44 and the result is shown in Figure 3-45. The same system is also simulated using fuzzy controller (ref. Figure 3-46) and polar fuzzy controller (ref. Figure 3-47). The results are shown in Figure 3-46 and 3-47 with out and with reheat and also tabulated in tables 3-3 and 3-4.
Figure 3-47 Simulation model of Polar Fuzzy controlled single area Thermal System with reheat unit

Figure 3-48 Comparison of different controller for single area Thermal System without reheat unit

Figure 3-49 Comparison of different controller for single area Thermal System with reheat unit
Table 3-3 Time analysis parameters of simulations of single area Thermal system without reheat

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.03</td>
<td>0.026</td>
<td>0.024</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;100</td>
<td>55</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 3-4 Time analysis parameters of simulations of single area Thermal system with reheat

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.046</td>
<td>0.039</td>
<td>0.035</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;100</td>
<td>55</td>
<td>8</td>
</tr>
</tbody>
</table>

The table 3-3 and 3-4 show that polar fuzzy controller performs better than the other PI and Fuzzy controller in terms of overshoot, undershoot, and settling time.

3.8.2 Single area hydro system simulation

The above described single area hydro system has been implemented in Simulink of Matlab with different controller and different system complexities. The results are compared for different controllers. It is found that polar fuzzy controller give better results in terms of less deviation in frequency in first undershoot, less settling time, and less oscillation as compared to fuzzy controller and conventional PI controllers.

Simulations models for single area hydro system w/o controller, with PI controller are shown in Figures 3-50 to 3-51 respectively and results are shown in Figure 3-52. Results of different controller are shown in Figure 3-53 and table 3-5. The PFC is consistently giving good results.
Figure 3- 50 Simulation model of single area Hydro System without controller

Figure 3- 51 Simulation model of single area Hydro System with PI controller

Figure 3- 52 Simulated Results of single area Hydro System without and with PI controllers
Table 3-5 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.

### 3.8.3 Single area nuclear system simulation

The above described single area nuclear system has been implemented in Simulink of Matlab with different controller and different system complexities like with and without reheat. The results are compared for different controllers. It is found that polar fuzzy controller gave better results in terms of less deviation in frequency in first undershoot, less settling time, and less oscillations as compared to fuzzy controller and conventional PI controllers. The Simulink model for single area nuclear system without and with PI controller is shown in Figures 3-54 and 3-55 respectively. The frequency of deviation after simulation of single area nuclear system is given in Figure 3-56.
Figure 3- 54 Simulation model of single area Nuclear System without controller

Figure 3- 55 Simulation model of single area Nuclear System with PI controller

Figure 3- 56 Simulated Result of single area Nuclear System without and with PI controllers
The fuzzy logic and polar fuzzy logic controller are developed for single area nuclear system and implemented in Matlab Simulink environment. The results obtained from simulation are compared with conventional PI controller as shown in Figure 3-57 and table 3-6. From results it is clear that PFC is better than fuzzy and PI controllers in terms of undershoot, settling time and oscillations.

Figure 3- 57 Simulated result of compared response of different controller for a single area Nuclear System

Table 3- 6 Time analysis parameters of simulations of single area nuclear system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Hz)</td>
<td>.012</td>
<td>.01</td>
<td>0</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.072</td>
<td>0.068</td>
<td>0.046</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>12</td>
<td>10</td>
<td>4</td>
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</tbody>
</table>

Table 3-6 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Table 3-7 Time taken in simulation for different single area systems

<table>
<thead>
<tr>
<th>Name of the system</th>
<th>Simulation time of the system with Fuzzy Controller (sec.)</th>
<th>Simulation time of the system with Polar Fuzzy Controller (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal system without reheat unit (for 100 s simulation run)</td>
<td>1.38</td>
<td>.08</td>
</tr>
<tr>
<td>Thermal system with reheat unit (for 100 s simulation run)</td>
<td>1.40</td>
<td>0.08</td>
</tr>
<tr>
<td>Hydro system (for 100 s simulation run)</td>
<td>0.58</td>
<td>0.050</td>
</tr>
<tr>
<td>Nuclear system (for 50 s simulation run)</td>
<td>1.36</td>
<td>0.104</td>
</tr>
</tbody>
</table>

Table 3-7 shows that simulation time taken by Fuzzy logic and Polar Fuzzy logic controllers are used. In table 3-7 it is seen that polar fuzzy controller takes less simulation time as compared to fuzzy controller. From table 3-3 to 3-7 it is shown that overall performance polar fuzzy controller better than the other PI and Fuzzy controller and conventional PI controller.

### 3.8.4 Two area thermal-thermal system

In this section, thermal system is considered in both areas and the model is developed and implemented in Matlab ver. 2007a as shown in Figure 3-58. The performance of different controllers has been tested in two area thermal-thermal system and compared for 1% disturbance in first area or second area or both and the result have been compared for polar fuzzy logic controller with fuzzy logic controller and conventional PI controller as shown in Figure 3-59. The controller performance also compared for settling time, undershoot, overshoot etc. and given in table 3-8, when
disturbance in area-1. It is very important to note that the performance of PFC is consistently good as compared to Fuzzy and PI controllers.

Table 3-8 Time analysis parameters of simulations of area 1 for Thermal-Thermal system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>-0.032</td>
<td>-0.029</td>
<td>-0.027</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;60</td>
<td>&lt;60</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 3-8 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.

Table 3-9 Time analysis parameters of simulations of area 2 for Thermal-Thermal system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
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<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.029</td>
<td>0.023</td>
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</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;60</td>
<td>&lt;60</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3-9 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller. The performance of controllers is also compared for the disturbance in both areas as shown in Figure 3-61 and table 3-10.
Figure 3-58 Simulation model of two area thermal-thermal System with PI controller
Figure 3-59 Deviation in frequency of area-1 of a two area Thermal System with reheat unit when disturbance in area-1.

Figure 3-60 Deviation in frequency of area-2 of a two area Thermal System with reheat unit when disturbance in area-1.
Deviation in frequency of area-1 of a two area Thermal System with reheat unit when disturbance in both areas.

Table 3-10 Time analysis parameters of simulations of area 1 for Thermal-Thermal system when disturbance in both areas

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.046</td>
<td>0.040</td>
<td>0.034</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>60</td>
<td>45</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3-10 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.

3.8.5 Two area thermal-hydro system simulation

In this system thermal plant is in area-1 and hydro plant is in area-2 as shown in Figure 3-62 with PI controller. The performance of different controllers has been tested and compared for 1% disturbance in first area or second area or both.
Figure 3- 62 Simulation model of two area thermal-hydro System with PI controller
Figure 3- 63 Deviation in frequency of area-1 of a two area Thermal-Hydro System with when disturbance in area-1.

Table 3- 11 Time analysis parameters of simulations of area 1 for Thermal-hydro system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.048</td>
<td>0.04</td>
<td>0.034</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>40</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3-11 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 64 Deviation in frequency of area-2 of a two area Thermal-Hydro System with when disturbance in area-1.

Table 3- 12 Time analysis parameters of simulations of area 2 for Thermal-hydro system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.055</td>
<td>0.047</td>
<td>0.042</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>40</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3-12 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3-65 Deviation in frequency of area-1 of a two area Thermal-Hydro System with when disturbance in area-2.

Table 3-13 Time analysis parameters of simulations of area 1 for Thermal-hydro system when disturbance in area 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.055</td>
<td>0.051</td>
<td>0.047</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>40</td>
<td>22</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 3-13 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 66 Deviation in frequency of area-2 of a two area Thermal-Hydro System with when disturbance in area-2.

Table 3- 14 Time analysis parameters of simulations of area 2 for Thermal-hydro system when disturbance in area 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>42</td>
<td>22</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 3-14 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3-67 Deviation in frequency of area-1 of a two area Thermal-Hydro System with when disturbance in both areas.

Table 3-15 Time analysis parameters of simulations of area 1 for Thermal-hydro system when disturbance in both areas

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.085</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>22</td>
<td>20</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 3-15 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 68 Deviation in frequency of area-2 of a two area Thermal-Hydro System with when disturbance in both areas.

Table 3- 16 Time analysis parameters of simulations of area 2 for Thermal-hydro system when disturbance in both areas

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.097</td>
<td>0.093</td>
<td>0.09</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>24</td>
<td>20</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3-16 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.

3.8.6 Two area thermal-nuclear system simulation

In this section, two area system is considered consisting of thermal plant is in area-1 and nuclear plant is in area-2 as shown in Figure 3-69. The performance of different controllers has been tested and compared for 1% disturbance in first area or second area or both as shown in Figure 3-70 to 3-75.
Figure 3- 69 Simulation model of two area thermal-nuclear system with PI controller
Figure 3- 70 Deviation in frequency of area-1 of a two area Thermal-Nuclear System with when disturbance in area-1.

Table 3- 17 Time analysis parameters of simulations of area 1 for Thermal-nuclear system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.018</td>
<td>0.015</td>
<td>0.012</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>110</td>
<td>90</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 3- 71 Deviation in frequency of area-2 of a two area Thermal-Nuclear System with when disturbance in area-1.

Table 3- 18 Time analysis parameters of simulations of area 2 for Thermal-nuclear system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Hz)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.010</td>
<td>0.0065</td>
<td>0.006</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>110</td>
<td>90</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3-18 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 72 Deviation in frequency of area-1 of a two area Thermal-Nuclear System with when disturbance in area-2.

Table 3- 19 Time analysis parameters of simulations of area 1 for Thermal-nuclear system when disturbance in area 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>.01</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>50</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3-19 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 73 Deviation in frequency of area-2 of a two area Thermal-Nuclear System with when disturbance in area-2.

Table 3- 20 Time analysis parameters of simulations of area 2 for Thermal-nuclear system when disturbance in area 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Hz)</td>
<td>.003</td>
<td>.007</td>
<td>.006</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.021</td>
<td>0.018</td>
<td>0.018</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>40</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 3-20 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.

![Graph showing deviation in frequency of area-1 of a two area Thermal-Nuclear System with disturbance in both areas.](image)

Figure 3- 74 Deviation in frequency of area-1 of a two area Thermal-Nuclear System with disturbance in both areas.

Table 3- 21 Time analysis parameters of simulations of area 2 for Thermal-nuclear system when disturbance in both areas

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.024</td>
<td>0.018</td>
<td>0.015</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>90</td>
<td>80</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3-21 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 75 Deviation in frequency of area-2 of a two area Thermal-Nuclear System with when disturbance in both areas.

Table 3- 22 Time analysis parameters of simulations of area 2 for Thermal-nuclear system when disturbance in both areas

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.024</td>
<td>0.021</td>
<td>0.021</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>110</td>
<td>90</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3-22 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.

3.8.7 Two area hydro-nuclear system simulation

This section deals with a two area system simulation in Simulink of Matlab consisting of hydro electric plant in area-1 and nuclear plant is in area -2 as shown in Figure 3-76. The different controllers have been tested and compared for 1% disturbance in first area or second area or both as shown in Figure 3-77 to 3-82.
Figure 3- 76 Simulation model of two area hydro-nuclear system with PI controller
Figure 3-77 Deviation in frequency of area-1 of a two area Hydro-Nuclear System with when disturbance in area-1.

Table 3-23 Time analysis parameters of simulations of area 1 for Hydro-nuclear system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Hz)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;90</td>
<td>&lt;80</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3-23 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 78 Deviation in frequency of area-2 of a two area Hydro-Nuclear System with when disturbance in area-1.

Table 3- 24 Time analysis parameters of simulations of area 2 for Hydro-nuclear system when disturbance in area 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>.024</td>
<td>.024</td>
<td>.024</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;90</td>
<td>&lt;80</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3-24 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3-79 Deviation in frequency of area-1 of a two area Hydro-Nuclear System with when disturbance in area-2.

Table 3-25 Time analysis parameters of simulations of area 1 for Hydro-nuclear system when disturbance in area 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Sec)</td>
<td>0</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.023</td>
<td>0.018</td>
<td>0.022</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>75</td>
<td>28</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3-25 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 80 Deviation in frequency of area-2 of a two area Hydro-Nuclear System with when disturbance in area-2.

Table 3- 26 Time analysis parameters of simulations of area 2 for Hydro-nuclear system when disturbance in area 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Sec)</td>
<td>0</td>
<td>.004</td>
<td>0</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.022</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>75</td>
<td>27</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3-26 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 81 Deviation in frequency of area-1 of a two area Hydro-Nuclear System with when disturbance in both areas.

Table 3- 27 Time analysis parameters of simulations of area 1 for Thermal-nuclear system when disturbance in both areas

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Sec)</td>
<td>0.008</td>
<td>0.017</td>
<td>0.014</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;90</td>
<td>&lt;80</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 3-27 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.
Figure 3- 82 Deviation in frequency of area-2 of a two area Hydro-Nuclear System with when disturbance in both areas.

Table 3- 28 Time analysis parameters of simulations of area 2 for Thermal-nuclear system when disturbance in both areas

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undershoot (Hz)</td>
<td>0.036</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>&lt;90</td>
<td>&lt;70</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3-28 shows that polar fuzzy controller performs better than the other PI and Fuzzy controller.

Table 3-29 shows that simulation time taken by the different systems when different controllers are used. In table 3-29 it is shown that polar fuzzy controller takes lesser time than fuzzy controller (as shown in table 7-27). From table 2 to 28 it is shown that overall performance polar fuzzy controller better than the other PI and Fuzzy controller. So it is conclude that polar fuzzy controller performs best not only in single area but also in multi area systems.
Table 3-29 Time taken in simulation for different two area systems

<table>
<thead>
<tr>
<th>Name of the system</th>
<th>Simulation time of the system with Fuzzy Controller (sec.)</th>
<th>Simulation time of the system with Polar Fuzzy Controller (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal-Thermal system (for 100 s simulation run)</td>
<td>3.28</td>
<td>0.14</td>
</tr>
<tr>
<td>Thermal-Hydro system (for 200 s simulation run)</td>
<td>5.75</td>
<td>0.24</td>
</tr>
<tr>
<td>Thermal-Nuclear system (for 150 s simulation run)</td>
<td>9.15</td>
<td>0.35</td>
</tr>
<tr>
<td>Hydro-Nuclear system (for 100 s simulation run)</td>
<td>2.70</td>
<td>0.13</td>
</tr>
</tbody>
</table>

3.9 Load Frequency Control of Three Area System

A three area system model is developed for multi-area concept. In three area system hydro system is taken as area 1 and nuclear system is taken as area 2 and thermal system is taken as area 3. This three area system is simulated for 1% disturbance in thermal system. This three area system is modeled without nonlinearities. The performance of different controllers are tested and compared for three area system. A three area Hydro-Nuclear-Thermal system is shown in Figure 3-83. Simulated and compared responses of different controllers of different areas are shown in Figure 3-84 to 3-86. Table 3-30 to 3-32 shows that polar fuzzy controller performs better than the other PI and Fuzzy controllers.
Figure 3-83 Simulation model of a three area Hydro-Nuclear-Thermal system without nonlinearities and with PI controller
Figure 3- 84 Frequency deviation of hydro system (area 1) of a three area Hydro-Nuclear-Thermal system without nonlinearities when disturbance in thermal area (area 3).

Table 3- 30 simulation performance of different controllers of hydro system (area 1) of a three area Hydro-Nuclear-Thermal system without nonlinearities when disturbance in thermal area (area 3)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Sec)</td>
<td>0.01</td>
<td>0.0075</td>
<td>0.005</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.027</td>
<td>0.022</td>
<td>0.016</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>30</td>
<td>22</td>
<td>9</td>
</tr>
</tbody>
</table>
Figure 3- 85 Frequency deviation of nuclear system (area 2) of a three area Hydro-Nuclear-Thermal system without nonlinearities when disturbance in thermal area (area 3).

Table 3- 31 simulation performance of different controllers of nuclear system (area 2) of a three area Hydro-Nuclear-Thermal system without nonlinearities when disturbance in thermal area (area 3)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>.011</td>
<td>.009</td>
<td>.008</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>65</td>
<td>45</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure 3- 86 Frequency deviation of thermal system (area 3) of a three area Hydro-Nuclear-Thermal system without nonlinearities when disturbance in thermal area (area 3).

Table 3- 32 simulation performance of different controllers of thermal system (area 3) of a three area Hydro-Nuclear-Thermal system without nonlinearities when disturbance in thermal area (area 3)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System with PI Controller</th>
<th>System with Fuzzy Controller</th>
<th>System with Polar Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (Sec)</td>
<td>0.007</td>
<td>0.005</td>
<td>0</td>
</tr>
<tr>
<td>Undershoot (Hz)</td>
<td>0.027</td>
<td>0.024</td>
<td>0.02</td>
</tr>
<tr>
<td>Settling time (Sec)</td>
<td>30</td>
<td>20</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 3-33 Time taken in simulation for a three area Hydro-Nuclear-Thermal system

<table>
<thead>
<tr>
<th>Name of the system</th>
<th>Simulation time of the system with PI Controller (sec.)</th>
<th>Simulation time of the system with Fuzzy Controller (sec.)</th>
<th>Simulation time of the system with Polar Fuzzy Controller (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three area Hydro-Nuclear-Thermal system without nonlinearities (for 100 s simulation run)</td>
<td>0.075</td>
<td>4.82</td>
<td>0.201</td>
</tr>
</tbody>
</table>

Table 3-33 shows that simulation time taken by the different systems when different controllers are used. In this table it is shown that polar fuzzy controller takes little bit more time than PI controller but the performance of polar fuzzy controller is better than other conventional PI and fuzzy controllers (as shown in table 3-30 to 3-32).

3.10 Conclusions

In this chapter single area thermal, hydro and nuclear systems have been modeled and these areas are simulated in Simulink environment. Also multi area system model (two area and three area systems) have been developed and simulated. All these aforesaid systems are controlled with conventional PI controller, Fuzzy controller and proposed polar fuzzy controller. The performance of all these controllers has been compared with different systems. It is found that polar fuzzy controller shows the best performance among all, in terms of settling time, less frequency dip, and minimum oscillations.