Control of Thermal Power System Using Adaptive Fuzzy Logic Control

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Control of Thermal Power System Using
Adaptive Fuzzy Logic Control

by

Nastaran Naghshineh

A Thesis Submitted in Partial Fulfilment of the
Requirements for the Degree of Master of Science in Electrical Engineering

Department of Electrical Engineering and Computing Sciences

Rochester Institute of Technology - Dubai

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Dedicated to my Beloved Husband
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Abstract

Controlling thermal power systems increases the overall system efficiency and satisfies the desired requirements. In such a large system, fuel reduction of even a small percentage leads to large energy saving. Hence, power systems are gaining significant attention from engineers and scientists.

In this thesis, the uncontrolled power system for single area, two area, and three area is modelled using state space representation. Frequency deviation is simulated using MATLAB and SIMULINK. PID control is added to the system to analyze the effect of conventional control on system output response. Adaptive fuzzy logic control is added to the uncontrolled system using MATLAB Fuzzy Inference System and its effect on the system output response is measured in terms of overshoot/undershoot percentage, settling time, and steady state frequency error. Effect of adaptive fuzzy logic control is analyzed on single area, two area, and three area power system. Tie-line power exchange among areas is investigated before and after implementation of PID and adaptive fuzzy logic control.

For the purpose of comparison in this thesis, a conventional PID control and an adaptive fuzzy logic control is applied to two different thermal power systems. The simulations demonstrate that adaptive fuzzy logic control is proved to be more efficient and reliable than conventional PID control in power system control problem.
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Chapter 1: Modelling and Simulation of Power System

1.1 Introduction and background knowledge

The aim in control of thermal power system “is to make the generator’s fuel consumption or the operating cost of the whole system minimal by determining the power output of each generating unit under the constraint condition of the system load demands.”[3] Configuration of a power plant is to select the optimal operation conditions in order to satisfy the electricity demand while maximizing the net income and minimizing the total operation cost [5].

Electric loads are energy consumptions which range from household appliances to industrial machinery. In Electric power generation system, the load variation changes continuously and the objective is to ensure the generation variations match the load variations at the minimal conditions or cost. In other words, the large interconnected power system must maintain the voltage and the frequency variations within a very narrow range. When the system experiences disturbances from load changes, the generator controllers must act quickly to maintain the balance and dampen the oscillations experienced by the system [4]. Control of electric energy system in order to obtain exact matching between the generation and the load is a very complex task as load varies every hour or even every minute.

In an interconnected power system, Automatic Generation Control (AGC), there are two control loops: Load Frequency Control (LFC) and Automatic Voltage Regulator (AVR). Figures 1.1 and 1.2 show how LFC and AVR are interconnected [19]. AVR is responsible to regulate the terminal voltage and LFC is employed to control the system frequency. In this thesis, LFC is considered for careful analysis because LFC is more sensitive to changes in the load compared to AVR. LFC and AVR are decoupled and can be analyzed separately. There is only weak overlap of effect between the two control loops.
Figure 1.1: Block diagram of power system

Figure 1.2: Two main control loops of Automatic Generation Control
Figure 1.3 shows the block diagram representation of single area LFC system which consists of a speed governor, a turbine, a re-heater, and a generator [19]. In some LFC systems, no re-heat component is available. Re-heat or feed water re-heat is used to pre-heat the water that is delivered to the steam boiler. In this thesis, all the considered models have re-heat component. For computational simplicity in LFC problem, we consider the case where the thermal power generation system consists of a single boiler, a single turbine, and a single generator. In many real world power systems, the generation unit consists of multiple boilers, steam turbines, and generators. “Network Power Loss” is referred to the loss of power from one generator to another or from one turbine to another that is experienced in systems with multiple components of same type [3].

In Figure 1.3, the inputs of the system are $\Delta P_c$ representing the change in speed governor by utility and $\Delta P_d$ representing the change in load by consumer also known as disturbance. The output of LFC system is $\Delta f$ which represents the change or variation in system frequency. The objective is to have a constant output frequency which corresponds to $\Delta f$ being zero or very small. The value of speed regulation $R$ also known as droop is the ratio of frequency deviation ($\Delta f$) to change in power output of the generator.

![Figure 1.3: Block diagram of single area LFC system](image)

### 1.2 Literature review

Control of power systems has gained high level of attention from scientists and engineers over the last few decades. Controlling thermal power generation systems will reduce energy or fuel consumption. Fuel reduction of even a small percentage will lead to large energy saving [2]. Hence, many researches have been conducted to solve control problem in thermal power systems.
Performance of the uncontrolled system shown in Figure 1.3 is undesirable in terms of settling time, steady state error, and initial transient response. Proportional and Integral (PI), Proportional and Derivative (PD), or Proportional, Integral and Derivative (PID) control can be used to secure the system performance when changes occur on the power system parameters. There exist two stabilization techniques: Pole-Placement technique and Linear Quadratic Regulator (LQR) [6]. In this thesis, LQR technique is used to stabilize the system once a control is added. PID control is a powerful and well known tool to improve both transient and steady state performances. However, proper tuning of PID control can be a very complex task as there are three parameters \((K_g, K_i, K_d)\) to be properly tuned to give the desired output response [7]. In [7], instructions of PID control tuning using MATLAB are explained in details. In [6], steady state performance of a two area interconnected thermal power system is considered after implementation of PI control.

Conventional PI control is very successful in achieving zero steady state error in power system. However, the load is continuously changing. Hence, conventional PI control will no longer be suitable to solve the control problem due to dynamic nature of the system [8]. Additionally, PI control approach returns relatively undesirable dynamic performance as evident by large overshoot/undershoot and transient frequency oscillation. Furthermore, settling time achieved by PI control is relatively large [14].

The problem of controlling and optimizing a dynamic system can be addressed using Fuzzy Logic. In various applications, Fuzzy Logic (FL) has been used to solve power plant control problem because it is well suited for uncertain systems. FL has been applied to solve optimal distribution planning, generator maintenance scheduling, load forecasting, load management, and generation dispatch problem [4]. FL establishes linguistic rules, called membership rules, to determine a systematic way of describing controller actions. Reliability of FL control makes it applicable in solving wide range of control problems such as power system control.

Hence, conventional PI control can be combined with FL control to improve the system performance significantly [9]. Performance of an open loop and closed loop two area power system after implementing PI control combined with FL control have been compared in [14].
Simulation results show that the system performance is significantly improved in terms of settling time, steady state frequency deviation, and percentage undershoot.

### 1.3 Single area modelling and simulation

Open loop modelling and simulation begins with considering a single area LFC system. As shown in Figure 1.4, the output of each integrator is a state space variable. Equations 1.1-1.4 show the transfer functions developed using the state assignments shown in Figure 1.4.

**Block 1: Generator**

\[
\frac{X_1}{X_2 - \Delta P_d} = \frac{K_p}{1 + T_p S} \tag{1.1}
\]

**Block 2: Re-heat**

\[
\frac{X_2}{X_3} = \frac{1 + K_r S}{1 + T_r S} \tag{1.2}
\]

**Block 3: Turbine**

\[
\frac{X_3}{X_4} = \frac{1}{1 + T_t S} \tag{1.3}
\]

**Block 4: Governor**

\[
\frac{1}{R} \frac{X_4}{X_1 + \Delta P_c} = \frac{1}{1 + T_g S} \tag{1.4}
\]

![Figure 1.4: Block diagram of single area LFC system with state variable assignment](image)

The above system has two inputs: \(\Delta P_c\) and \(\Delta P_d\). The output of the system is \(\Delta f\) which represents change or variation in system frequency. To develop state space representation of the system shown in Figure 1.4, rate of change of each state variable is needed. Equations 1.5-1.8 are the system state equations:

**Block 1: Generator**

\[
\dot{x}_1 = \frac{-1}{T_p} x_1 + \frac{K_p}{T_p} x_2 - \frac{K_p}{T_p} \Delta P_d \tag{1.5}
\]

**Block 2: Re-heat**

\[
\dot{x}_2 = \frac{-1}{T_r} x_2 + \frac{1}{T_r} \left(1 - \frac{K_r}{T_r}\right) x_3 + \frac{K_r}{T_r T_t} x_4 \tag{1.6}
\]
Block 3: Turbine
\[ x_3 = \frac{-1}{\tau_t} x_3 + \frac{1}{\tau_t} x_4 \]  \hspace{1cm} (1.7)

Block 4: Governor
\[ x_4 = \frac{-1}{RT_g} x_1 - \frac{1}{T_g} x_4 + \frac{1}{T_g} \Delta P_c \]  \hspace{1cm} (1.8)

Then, Equations 1.5-1.8 are transformed into state space model. It is important to note that the output of the system \( \Delta f \) is the state variable \( x_1 \). State space representation of the single area LFC system shown in Figure 1.4 is:

\[ \dot{X}(t) = AX(t) + B \Delta P_c + F \Delta P_d \]  \hspace{1cm} (1.9)

\[ Y(t) = CX(t) \]  \hspace{1cm} (1.10)

\[
\begin{bmatrix}
  \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4
\end{bmatrix} =
\begin{bmatrix}
  \frac{-1}{T_p} & \frac{K_p}{T_p} & 0 & 0 \\
  0 & \frac{-1}{T_r} & \left(1 - \frac{K_r}{T_r}\right) \frac{1}{T_r} & \frac{K_r}{T_r T_r} \\
  0 & 0 & -\frac{1}{T_r} & \frac{1}{T_r} \\
  \frac{-1}{RT_g} & 0 & 0 & -\frac{1}{T_g}
\end{bmatrix}
\begin{bmatrix}
  x_1 \\ x_2 \\ x_3 \\ x_4
\end{bmatrix}
\]

\[
\begin{bmatrix}
  0 \\ 0 \\ 0 \\ \frac{1}{T_g}
\end{bmatrix} \Delta P_c +
\begin{bmatrix}
  -\frac{K_p}{T_p} \\ 0 \\ 0 \\ 0
\end{bmatrix} \Delta P_d
\]

\[ \Delta f = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \]

\( \Delta P_c \) is the speed change of the motor and \( \Delta P_d \) is the change in load/disturbance. The input matrix B shown below is formed by extracting the coefficients of \( \Delta P_d \) in Equations 1.5-1.8.
\[
B = \begin{bmatrix}
-K_p \\
T_p \\
0 \\
0 \\
0
\end{bmatrix}
\]

The corresponding parameters for the state, input, and output matrix are given in the Appendix A-1. The input \( \Delta P_d \) is a unit step function. Figure 1.5 illustrates the output response of the LFC system. Increase in load leads to decrease in frequency which corresponds to undershoot. Decrease in load leads to increase in frequency which corresponds to overshoot. The system settling time is about 180 seconds and the frequency deviation is -2.5HZ. The undershoot percentage, settling time, and the steady state error are significantly large and this leads to the necessity of having PID control added to the system.

**Figure 1.5:** Output response of single area LFC system
1.4 Two area modelling and simulation

The main reasons for utilities to interconnect control areas are:

1. To buy or sell power with neighboring control areas whose operation cost are different from theirs.
2. To improve reliability of control areas for events such as sudden loss in generation.

Total generation is divided among the control areas adequately such that the production cost is minimized. This means each control area must participate in generating electricity and regulating frequency. When power interchange scheduling among the areas is on, each control area is responsible to generate the scheduled amount of electricity and interchange some electricity with other control areas. This interchange will allow the neighboring control areas to generate sufficient amount of electricity when load changes.

In a two area interconnected power system there is tie-line power exchange flowing from area 1 to area 2, called $P_{tie,12}$. The tie-line power exchange running from area 2 to area 1 is the same as that of area 1 to area 2 in magnitude but opposite in direction. Figure 1.6 illustrates the concept of two area power system with tie-line power.

\[ P_{tie,12} = -P_{tie,21} \]

**Figure 1.6:** Two area interconnected power system

Figure 1.7 shows the block diagram representation of a two area interconnected LFC system. Area 1 and area 2 can have the same model; however, in Figure 1.7, two different areas are combined together to show a two area power system. Area 1 consists of 4 transfer function blocks and area 2 consists of 8 transfer function blocks. $\Delta P_{tie,12}$ is output of tie-line power integral block which interconnects the two area. $\Delta P_{tie,12}$ represents the incremental power change in tie-line. Hence, the entire system is modelled by 13 state variables.
Figure 1.7: Block diagram of two area LFC system

\[
A = \\
\begin{bmatrix}
-\frac{1}{T_p} & K_p & 0 & 0 & -\frac{K_p}{T_p} & 0 \\
0 & -\frac{1}{T_r} & \frac{1}{T_r} \left(1 - \frac{K_p}{T_r} \right) & \frac{K_p}{T_r T_i} & 0 & 0 \\
0 & 0 & -\frac{1}{T_i} & \frac{1}{T_i} & 0 & 0 \\
\frac{1}{R_i T_g} & 0 & 0 & -\frac{1}{T_g} & 0 & 0 \\
0 & 0 & 0 & 0 & -\frac{K_5}{T_g} & \frac{-2\pi T}{2\pi T} \\
0 & 0 & 0 & 0 & 0 & \frac{-1}{T_g} \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-K_1 T_1 T_2 T_3}{R_1 T_1 T_2 T_3} \\
0 & 0 & 0 & 0 & 0 & \frac{-K_2 T_2}{R_2 T_2} \\
0 & 0 & 0 & 0 & 0 & \frac{-K_3 T_3}{R_2 T_3} \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]
The inputs of the system are $\Delta P_{d1}$ and $\Delta P_{d2}$, respectively. Following is the input matrix of the system:

$$B = \begin{bmatrix}
-K_p & 0 \\
\frac{T_p}{T_p} & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
\frac{T_8}{T_8} & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
\frac{1}{T_1} & 0 \\
\frac{1}{T_2} & 0 \\
\frac{1}{T_3} & 0 \\
\frac{1}{T_4} & 0 \\
\frac{1}{T_5} & 0 \\
\frac{1}{T_6} & 0 \\
\frac{1}{T_7} & 0 \\
\frac{1}{T_8} & 0 \\
\frac{1}{T_9} & 0 \\
\frac{1}{T_{10}} & 0 \\
\frac{1}{T_{11}} & 0 \\
\frac{1}{T_{12}} & 0 \\
\frac{1}{T_{13}} & 0 \\
\frac{1}{T_{14}} & 0 \\
\frac{1}{T_{15}} & 0 \\
\frac{1}{T_{16}} & 0 \\
\frac{1}{T_{17}} & 0 \\
\frac{1}{T_{18}} & 0 \\
\frac{1}{T_{19}} & 0 \\
\frac{1}{T_{20}} & 0 \\
\frac{1}{T_{21}} & 0 \\
\frac{1}{T_{22}} & 0 \\
\frac{1}{T_{23}} & 0 \\
\frac{1}{T_{24}} & 0 \\
\frac{1}{T_{25}} & 0 \\
\frac{1}{T_{26}} & 0 \\
\frac{1}{T_{27}} & 0 \\
\frac{1}{T_{28}} & 0 \\
\frac{1}{T_{29}} & 0 \\
\frac{1}{T_{30}} & 0 \\
\frac{1}{T_{31}} & 0 \\
\frac{1}{T_{32}} & 0 \\
\frac{1}{T_{33}} & 0 \\
\frac{1}{T_{34}} & 0 \\
\frac{1}{T_{35}} & 0 \\
\frac{1}{T_{36}} & 0 \\
\frac{1}{T_{37}} & 0 \\
\frac{1}{T_{38}} & 0 \\
\frac{1}{T_{39}} & 0 \\
\frac{1}{T_{40}} & 0 \\
\frac{1}{T_{41}} & 0 \\
\frac{1}{T_{42}} & 0 \\
\frac{1}{T_{43}} & 0 \\
\frac{1}{T_{44}} & 0 \\
\frac{1}{T_{45}} & 0 \\
\frac{1}{T_{46}} & 0 \\
\frac{1}{T_{47}} & 0 \\
\frac{1}{T_{48}} & 0 \\
\frac{1}{T_{49}} & 0 \\
\frac{1}{T_{50}} & 0 \\
\frac{1}{T_{51}} & 0 \\
\frac{1}{T_{52}} & 0 \\
\frac{1}{T_{53}} & 0 \\
\frac{1}{T_{54}} & 0 \\
\frac{1}{T_{55}} & 0 \\
\frac{1}{T_{56}} & 0 \\
\frac{1}{T_{57}} & 0 \\
\frac{1}{T_{58}} & 0 \\
\frac{1}{T_{59}} & 0 \\
\frac{1}{T_{60}} & 0 \\
\frac{1}{T_{61}} & 0 \\
\frac{1}{T_{62}} & 0 \\
\frac{1}{T_{63}} & 0 \\
\frac{1}{T_{64}} & 0 \\
\frac{1}{T_{65}} & 0 \\
\frac{1}{T_{66}} & 0 \\
\frac{1}{T_{67}} & 0 \\
\frac{1}{T_{68}} & 0 \\
\frac{1}{T_{69}} & 0 \\
\frac{1}{T_{70}} & 0 \\
\frac{1}{T_{71}} & 0 \\
\frac{1}{T_{72}} & 0 \\
\frac{1}{T_{73}} & 0 \\
\frac{1}{T_{74}} & 0 \\
\frac{1}{T_{75}} & 0 \\
\frac{1}{T_{76}} & 0 \\
\frac{1}{T_{77}} & 0 \\
\frac{1}{T_{78}} & 0 \\
\frac{1}{T_{79}} & 0 \\
\frac{1}{T_{80}} & 0 \\
\frac{1}{T_{81}} & 0 \\
\frac{1}{T_{82}} & 0 \\
\frac{1}{T_{83}} & 0 \\
\frac{1}{T_{84}} & 0 \\
\frac{1}{T_{85}} & 0 \\
\frac{1}{T_{86}} & 0 \\
\frac{1}{T_{87}} & 0 \\
\frac{1}{T_{88}} & 0 \\
\frac{1}{T_{89}} & 0 \\
\frac{1}{T_{90}} & 0 \\
\frac{1}{T_{91}} & 0 \\
\frac{1}{T_{92}} & 0 \\
\frac{1}{T_{93}} & 0 \\
\frac{1}{T_{94}} & 0 \\
\frac{1}{T_{95}} & 0 \\
\frac{1}{T_{96}} & 0 \\
\frac{1}{T_{97}} & 0 \\
\frac{1}{T_{98}} & 0 \\
\frac{1}{T_{99}} & 0 \\
\frac{1}{T_{100}} & 0 
\end{bmatrix}$$
The system has three outputs. The first output is frequency deviation of area 1 ($\Delta f_1 = x_1$), the second output is frequency deviation of area 2 ($\Delta f_2 = x_6$), and the third output is tie-line power connecting area 1 and 2 which is represented by state variable $x_5$. Following is the output matrix of the system:

\[
C = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

Figures 1.8 and 1.9 show the output response of area 1 and area 2, respectively. Similar to the single area system, in two area system the objective is to have a system with zero steady state frequency deviation $\Delta f_1 = \Delta f_2 = 0$. By examining the responses, it can be clearly seen that the system is behaving undesirably. Output responses of area 1 and 2 take about 300 seconds to reach a steady value. This is an extremely slow settling time with about 40% frequency error. The undesirable system performance determines the necessity of integral control in the system. Integral control can significantly reduce steady state error, improve settling time, and decrease undershoot. Integral control ensures Area Control Error (ACE) is reduced to zero or nearly zero at steady state. ACE is the difference between the actual power flow out of area, and scheduled power flow.

Figure 1.10 shows the tie-line power response interconnecting area 1 and area 2. As expected, the tie-line power begins with undershoot due to presence of disturbance. The steady state value of tie-line power flow is about -0.9pu MW and the settling time is about 250 seconds.
Figure 1.8: Output response of area 1 in two area LFC system

Figure 1.9: Output response of area 2 in two area LFC system
Three area power system consists of three control areas that are interconnected through tie-lines as shown in Figure 1.11. Tie-lines are responsible to interchange the scheduled power among the control areas. $P_{tie,12}$ is the power flowing from area 1 to area 2. The power flowing from area 2 to area 1 is the same in magnitude as that of area 1 to area 2 but opposite in direction. $P_{tie,13}$ is the power flowing from area 1 to area 3 and this is the same as that of flowing from area 3 to area 1 but opposite in direction. Lastly, $P_{tie,23}$ is the power flowing from area 2 to area 3 and this is the same as that of flowing from area 3 to area 2 but opposite in direction. This means the tie-line power appears as positive load in one area and negative load in other area. The net interchange power of a control area is the power leaving the system minus the power entering the system.
Figure 1.12 shows the block diagram of three area interconnected system. Three area system is an extension of two area system with an additional control area. In Figure 1.12, area 1 and 3 are identical. Each area has a reference input as well as disturbance. Considering the disturbances or load changes to be the only inputs of the LFC system, the entire system has 3 inputs: $\Delta P_{d1}$, $\Delta P_{d2}$, and $\Delta P_{d3}$.

Output of area 1 is $\Delta f_1$ and the state variable $x_1$ is used to represent the corresponding output response. Output of area 2 is $\Delta f_2$ and the state variable $x_6$ is used to represent the corresponding output response. Output of area 3 is $\Delta f_3$ and the state variable $x_{15}$ is used to represent the corresponding output response.

An integral block is used to connect area 1 and 2. The corresponding output of this integral block is $P_{tie,12}$ which is the state variable $x_5$ shown in Figure 1.12. An integral control is used to connect area 2 and 3. The corresponding output of this block is $P_{tie,23}$ which is the state variables $x_5$.
variable \( x_{14} \). Lastly, there is an integral block connecting area 1 and 3. The corresponding output of this block is \( P_{tie,13} \) which is the state variable \( x_{19} \).

Figure 1.12: Block diagram of three area LFC system

Equations 1.11-1.32 are the transfer functions of each block used in Figure 1.12. The parameters are given in the Appendix A-1.

Block 1: Generator 1

\[
\frac{K_p}{1+T_p S} \quad (1.11)
\]

Block 2: Re-Heat 1

\[
\frac{1+K_r S}{1+T_r S} \quad (1.12)
\]

Block 3: Turbine 1

\[
\frac{1}{1+T_t S} \quad (1.13)
\]
Block 4: Governor 1
\[ \frac{1}{1+T_g S} \] (1.14)

Block 5: Tie-Line 1 and 2
\[ \frac{2\pi T}{S} \] (1.15)

Block 6: Generator 2
\[ \frac{K_5}{1+T_b S} \] (1.16)

Block 7: Re-Heat 2
\[ \frac{K_3}{1+T_b S} \] (1.17)

Block 8: Turbine Part 2
\[ \frac{K_2}{1+T_b S} \] (1.18)

Block 9: Turbine Part 1
\[ \frac{1}{1+T_4 S} \] (1.19)

Block 10: Governor Part 3
\[ \frac{1+T_{v1} S}{1+T_3 S} \] (1.20)

Block 11: Governor Part 2
\[ \frac{1+T_{v2} S}{1+T_2 S} \] (1.21)

Block 12: Governor Part 1
\[ \frac{K_1}{1+T_1 S} \] (1.22)

Block 13: Feedforward
\[ \frac{K_4}{1+T_7 S} \] (1.23)

Block 14: Tie-Line 2 and 3
\[ \frac{2\pi T}{S} \] (1.24)

Block 15: Generator 3
\[ \frac{K_p}{1+T_p S} \] (1.25)

Block 16: Re-Heat 3
\[ \frac{1+K_r S}{1+T_r S} \] (1.26)

Block 17: Turbine 3
\[ \frac{1}{1+T_t S} \] (1.27)

Block 18: Governor 3
\[ \frac{1}{1+T_g S} \] (1.28)

Block 19: Tie-Line 1 and 3
\[ \frac{2\pi T}{S} \] (1.29)

Droop 1
\[ \frac{1}{R_1} \] (1.30)
Droop 2 \[ \frac{1}{R_2} \] (1.31)

Droop 3 \[ \frac{1}{R_3} \] (1.32)

As illustrated in Figure 1.12, area 1, 2, and 3 consist of 4, 8, and 4 transfer function blocks, respectively. There are 3 integral blocks to connect the areas. Hence, there are 19 state variables in Figure 1.12. The system has 3 inputs: \( \Delta P_{d1}, \Delta P_{d2}, \) and \( \Delta P_{d3} \). The system has 6 outputs: \( \Delta f_1, \Delta f_2, \Delta f_3, \Delta P_{tie,12}, \Delta P_{tie,23}, \) and \( \Delta P_{tie,31} \).

\[
A = \begin{bmatrix}
-\frac{1}{T_p} & \frac{K_p}{T_p} & 0 & 0 & -\frac{K_p}{T_p} & 0 & 0 \\
0 & -\frac{1}{T_r} & \frac{1}{T_r} (1 - \frac{K_r}{T_t}) & \frac{K_r}{T_r} & \frac{K_r}{T_t} & 0 & 0 \\
0 & 0 & -\frac{1}{T_t} & 0 & 0 & 0 & 0 \\
-\frac{1}{R_1 T_g} & 0 & 0 & \frac{1}{T_g} & 0 & 0 & 0 \\
2\pi T & 0 & 0 & 0 & 0 & \frac{-2\pi T}{T_8} & \frac{K_5}{T_8} \\
0 & 0 & 0 & 0 & 0 & \frac{K_5}{T_8} & \frac{1}{T_6} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{K_1 T_{v1} T_{v2}}{T_1 T_2 T_3 R_2} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-K_1 T_{v2}}{T_1 T_2 R_2} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-K_1}{T_1 R_2} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-K_4}{R_2 T_7} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-2\pi T}{T_6} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]
\[
\begin{array}{cccccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_p}{T_p} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{K_1}{T_6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{T_5} & \frac{K_2}{T_9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{T_4} & \frac{1}{T_4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{-1}{T_3} & \frac{1}{T_3} & (1-\frac{T_v}{T_2}) & \frac{T_v}{T_2T_3} & (1-\frac{T_v}{T_1}) & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{1}{T_2} & \frac{1}{T_2} & (1-\frac{T_v}{T_1}) & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{-1}{T_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-1}{T_7} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{2\pi T}{T_p} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-K_p}{T_p} & \frac{-1}{T_p} & \frac{K_p}{T_p} & 0 & 0 & \frac{-K_p}{T_p} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_r} & \frac{1}{T_r} & \frac{1}{T_r} & \frac{(1-\frac{K_r}{T_r})}{T_rT_r} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_r} & \frac{1}{T_r} & \frac{1}{T_r} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{R_sT_s} & 0 & 0 & \frac{-1}{T_s} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{2\pi T} & 0 & 0 \\
\end{array}
\]
Figures 1.13-1.15 display the output response of each control area. It can be observed that the output responses begin with aggressive oscillations which are the effect of having poles on the imaginary axis. The LFC system reaches steady state value after 25 seconds. Hence, the system has undesirable response which emphasizes the need of a control in order to eliminate the frequency error as well as reducing the settling time.
Figures 1.16 and 1.17 show the tie-line power exchange. The tie-line power exchange begins at zero and experiences undershoot due to presence of disturbance. The response settles after 25 seconds at -0.5pu MW. The objective is to eliminate or minimize the steady state power exchange deviation.

Figure 1.13: Output response of area 1 in three area LFC system

Figure 1.14: Output response of area 2 in three area LFC system
Figure 1.15: Output response of area 3 in three area LFC system

Figure 1.16: Tie-line response of three area LFC system for area 1 and 2
The single area, two area, and three area systems considered in the previous sections are test cases. By analyzing the output responses of the test cases, it is concluded that the uncontrolled LFC system of size N will have unsatisfactory performance in terms of percentage overshoot/undershoot, oscillations, settling time, and steady state error. The need for control is essential in regulating the output response and improving overall performance of the system.

In an interconnected system, the control areas are connected via tie-lines. As it was illustrated in Figure 1.6 and 1.11, as number of control areas increases in LFC system, more tie-lines are needed to allow interchange of electricity among the control areas. Tie-line exchange has a nominal value to follow and any variation from the nominal value is considered as error. Hence, in LFC system analysis, it is important to consider tie-lines behavior. Figure 1.18 shows a four area interconnected system. In a four area LFC system, there exists 4 inputs/disturbances, 4 output frequency change, and 6 tie-lines. Hence, such a system will have 4 inputs and 10 outputs.
Chapter 2: Feedback Modelling and Simulation of Power System Using PID Control

2.1 Introduction to feedback analysis

The primary objective of using control in power system is to eliminate or minimize the system frequency deviation. In typical power systems, following performance specifications are recommended:

1. Steady state error should not be more than 0.01 HZ.
2. Settling time should be less than 3 seconds.
3. The maximum overshoot/undershoot should not be more than 6% which corresponds to 0.06 HZ.
4. Change in power exchange $\Delta P_{tie}$ is upon mutual agreement of the generating areas.

Each type of control has different role in a system. Proportional control is used to reduce rise time and settling time. Integral control is used to eliminate steady state error. The negative effect of integral control is creating oscillation. Derivative control is used to improve transient
response which means reducing overshoot/undershoot. Equations 2.1-2.5 show structure of most commonly used conventional controls:

Proportional (P) control: \[ U(S) = K_g E(S) \] (2.1)

Integral (I) control: \[ U(S) = \frac{K_i}{s} E(S) \] (2.2)

Derivative (D) Control: \[ U(S) = (K_d s) E(S) \] (2.3)

PI control: \[ U(S) = \left( K_g + \frac{K_i}{s} \right) E(S) \] (2.4)

PID control: \[ U(S) = \left( K_g + \frac{K_i}{s} + K_d s \right) E(S) \] (2.5)

The main objective in LFC system control problem is to improve the dynamic response of the system by minimizing or even eliminating AEC. In real life LFC systems, ACE is never zero due to instantaneous change in load. Hence, the objective is to keep AEC as close to zero as possible. Integral control is well suited in this case to meet the objective. The value of integral gain constant \( K_i \) is adjusted until the desired response is achieved. This is called tuning and is a time consuming task [6]. Figure 2.1 illustrates how a conventional PID control can be added to a system. “Process” block in Figure 2.1 is the uncontrolled system. When an integral control is added to a system, a new pole is added to the system which may cause the system to be unstable. This means a stabilizing technique is needed. LQR technique is used to stabilize the system.

![Figure 2.1: Implementation of PID control in feedback system](image)
2.2 Feedback single area modelling and simulation using PI control

For a single area closed loop system, a PI control is added in the block diagram as shown in Figure 2.2. The transfer function of the PI control is \((K_g + \frac{K_i}{S})\).

**Figure 2.2:** Block diagram of feedback single area LFC system

The system shown in Figure 2.2 has 5 transfer function blocks which corresponds to 5 state variables. Equations 2.6-2.10 show the developed transfer functions of Figure 2.2.

Block 1: Generator
\[
\frac{x_1}{x_2 - \Delta P_d} = \frac{K_p}{1 + T_p S} \quad (2.6)
\]

Block 2: Re-Heat
\[
\frac{x_2}{x_3} = \frac{1 + K_r S}{1 + T_r S} \quad (2.7)
\]

Block 3: Turbine
\[
\frac{x_3}{x_4} = \frac{1}{1 + T_t S} \quad (2.8)
\]

Block 4: Governor
\[
\frac{-1}{R} x_4 = \frac{1}{1 + T_g S} \quad (2.9)
\]

Block 5: PI Control
\[
\frac{x_5}{x_1} = \frac{K_g S + K_I}{S} \quad (2.10)
\]

Equations 2.11-2.15 show the system differential equations which corresponds to rate of change of each variable:

\[
\dot{x}_1 = -\frac{1}{T_p} x_1 + \frac{K_p}{T_p} x_2 - \frac{K_p}{T_p} \Delta P_d \quad (2.11)
\]

\[
\dot{x}_2 = -\frac{1}{T_r} x_2 + \frac{1}{T_r} \left(1 - \frac{K_r}{T_t}\right) x_3 + \frac{K_r}{T_r T_t} x_4 \quad (2.12)
\]
\[ \dot{x}_3 = \frac{-1}{\tau_t} x_3 + \frac{1}{\tau_t} x_4 \quad (2.13) \]

\[ \dot{x}_4 = \frac{-1}{r_{tg}} x_1 - \frac{1}{\tau_g} x_4 - \frac{1}{\tau_g} x_5 \quad (2.14) \]

\[ \dot{x}_5 = (K_i - \frac{K_g}{T_p}) x_1 + \frac{K_g K_p}{T_p} x_2 - \frac{K_g K_p}{T_p} \Delta P_d \quad (2.15) \]

Next, differential Equations 2.11-2.15 are transformed into state space model. The only input of the system is \( \Delta P_d \). Following is state space representation of the LFC system shown in Figure 2.2:

\[ \dot{X}(t) = A X(t) + B \Delta P_d \quad (2.16) \]

\[ Y(t) = C X(t) \quad (2.17) \]

\[
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3 \\
  x_4 \\
  x_5
\end{bmatrix} =
\begin{bmatrix}
  \frac{-1}{T_p} & \frac{K_p}{T_p} & 0 & 0 & 0 \\
  0 & \frac{-1}{T_r} & \frac{1}{T_r} & \frac{1}{T_i} & 0 \\
  0 & 0 & \frac{-1}{T_i} & \frac{1}{T_i} & 0 \\
  -\frac{1}{RT_g} & 0 & 0 & \frac{-1}{T_g} & \frac{-1}{T_g} \\
  K_i - \frac{K_g}{T_p} & \frac{K_g K_p}{T_p} & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3 \\
  x_4 \\
  x_5
\end{bmatrix} +
\begin{bmatrix}
  -\frac{K_p}{T_p} \\
  0 \\
  0 \\
  0 \\
  \frac{-K_g K_p}{T_p}
\end{bmatrix} \Delta P_d
\]

\[ \Delta f = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \]

PI tuning is a challenging task as the parameters of the control need to be changed until the desired requirements are met. For the specifications mentioned in section 2.1, the nominal values of the PI control used in Figure 2.2 are shown in Table 2.1.

<table>
<thead>
<tr>
<th>Area number (N)</th>
<th>Type of control</th>
<th>Integral gain constant (( K_i ))</th>
<th>Proportional gain constant (( K_g ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PI</td>
<td>2.85</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table 2.1**: Control parameters for feedback single LFC system
Figure 2.3 is output response of the LFC system. Based on the simulation result, the system is stable and the steady state error is very close to zero. The settling time is less than 1 second and undershoot is about 5.5%. Hence, addition of the proposed PI control improved the system performance significantly and the desired specifications outlined in section 2.1 are met.

![Graph showing frequency change over time with labels: Settling time: 1 sec, Undershoot: 0.055HZ, Error: 0HZ]

**Figure 2.3:** Output response of feedback single area LFC system with PI control

### 2.3 Feedback two area modelling and simulation using integral control

Two area power system consists of two control areas interconnected through tie-line. By analyzing Figure 1.8, 1.9, and 1.10, it was concluded that a control is essential in order to improve the system performance in terms of steady state frequency error, settling time, and transient frequency error. An integral control with appropriate integral gain is used in two area closed loop model in order to have the system behave desirably.

Figure 2.4 shows that an integral control is used for each area separately and then the two areas are connected through tie-line. The parameters of the integral controls have been tuned to
meet the specifications mentioned in section 2.1. Tuning of a conventional control is a time consuming task and numerous values have been tried. Table 2.2 lists the parameters of the controls used in Figure 2.4.

<table>
<thead>
<tr>
<th>Area number ((N))</th>
<th>Type of control</th>
<th>Integral gain constant ((K_I))</th>
<th>Frequency bias factor ((B_N))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>2.85</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>0.17</td>
<td>1.3</td>
</tr>
</tbody>
</table>

**Table 2.2:** Control parameters for feedback two area LFC system

As shown in Figure 2.4, \(ACE_1\) is the input of the integral control used in area 1 and \(ACE_2\) is the input of the integral control used in area 2.

**Figure 2.4:** Block diagram of feedback two area LFC system with integral control
The corresponding parameters for the state, input, and output matrix are given in the Appendix A-1. Area 1 and 2 consist of 4 and 8 transfer function blocks, respectively. There is an integral control for each area which corresponds to two state variables \(x_{14}\) and \(x_{15}\). Additionally, there is an integral block for the tie-line to interconnect the two areas. Hence, there are total of 15 state variables. The system has 2 inputs: \(\Delta P_{d1}\) and \(\Delta P_{d2}\) which are load disturbances. The system has three outputs and they are the frequency deviation of area 1 and area 2, and the tie-line interconnecting area 1 and area 2.

\[
\begin{bmatrix}
-\frac{1}{T_p} & K_p & 0 & 0 & 0 & -\frac{K_p}{T_p} & 0 & 0 & 0 \\
0 & -\frac{1}{T_r} & \frac{1}{T_r} (1 - \frac{K_r}{T_r}) & \frac{K_r}{T_r T_r} & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{T_i} & \frac{1}{T_i} & 0 & 0 & 0 & 0 \\
-\frac{1}{R_i T_g} & 0 & 0 & -\frac{1}{T_g} & 0 & 0 & 0 & 0 \\
2\pi T & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
K i_1 B_1 & 0 & 0 & 0 & 0 & K i_1 & 0 & 0 \\
0 & 0 & 0 & 0 & -K i_2 & K i_2 B_2 & 0 & 0
\end{bmatrix}
\]
\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_g} \\
0 & 0 & 0 & 0 & 0 & -\frac{K_5}{T_8} & 0 \\
0 & 0 & 0 & 0 & -\frac{K_6}{T_8} & 0 & 0 \\
\frac{K_2}{T_3} & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{T_4} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{T_3} & \frac{1}{T_3} & (1 - \frac{T_{v1}}{T_2}) & \frac{T_{v1}}{T_2 T_3} & (1 - \frac{T_{v2}}{T_1}) & 0 & 0 & -\frac{K_1 T_{v1} T_{v2}}{T_1 T_2 T_3} \\
0 & 0 & -\frac{1}{T_2} & \frac{1}{T_2} & (1 - \frac{T_{v2}}{T_1}) & 0 & 0 & -\frac{K_1 T_{v2}}{T_1 T_2} \\
0 & 0 & 0 & -\frac{1}{T_1} & 0 & 0 & -\frac{K_1}{T_1} \\
0 & 0 & 0 & 0 & -\frac{1}{T_7} & 0 & -\frac{K_4}{T_7} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
-\frac{K_p}{T_p} & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & -\frac{K_5}{T_8} \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]
Figure 2.5 demonstrates the output response of area 1 in two area LFC system. The steady state error is completely removed. The settling time is about 5 seconds and the undershoot percentage is about 61%. Figure 2.6 demonstrates the output response of area 2. The steady state frequency error is completely eliminated. The settling time is about 15 seconds and the undershoot percentage is 13%.

Eliminating the steady state error is one of the most important strengths of conventional controls. However, the systems with high undershoot/overshoot cannot be controlled by conventional controls. This is one of the shortcomings of conventional controls. Hence, a conventional PID control is not the most reliable control to improve the performance in time-variant systems such as LFC system.

To analyze the system behavior, the tie-line power exchange deviation is examined. Figure 2.7 illustrates $\Delta P_{tie,12}$ which is the state variable $x_5$ in Figure 2.4. The tie-line power deviation begins with 17% undershoot and settles down to zero after 10 seconds. Specifications related to tie-line power exchange are upon mutual agreement of the generating areas.

Figure 2.5: Output response of area 1 in feedback two area LFC system with integral control
Figure 2.6: Output response of area 2 in feedback two area LFC system with integral control

Figure 2.7: Tie-line response of two area LFC system with integral control
2.4 Feedback three area modelling and simulation using integral control

Three area system consists of three control areas that are connected through tie-lines. The individual control areas may or may not be the same. The system shown in Figure 2.8 consists of three control areas that are different. Area 1 and 3 are identical; however, area 2 is different. The system is changed from an open loop to a closed loop through addition of integral control to each control area. The main objective is to improve the system performance by ensuring that the specifications mentioned in section 2.1 are met.

Area 1, 2, and 3 consist of 4, 8, and 4 transfer function blocks, respectively. There is an integral block to represent tie-line between area 1 and 2. There is another integral block to connect area 2 and 3 and one to connect area 1 and 3. Hence, there are 3 integral blocks for tie-lines. Each area has an integral control which adds three additional state variables to the system. Hence, the entire system is modelled using 22 state variables The system has total of 3 inputs which are the disturbances experienced by each control area: \( \Delta P_{d1} \), \( \Delta P_{d2} \), and \( \Delta P_{d3} \).

To analyze the output response of the LFC system shown in Figure 2.8, the output of each area is considered individually. Output of area 1 is represented by state variable \( x_1 \) and is generated due to its input \( \Delta P_{d1} \). Output of area 2 is represented by state variable \( x_6 \) and is generated due to \( \Delta P_{d2} \). Finally, output of area 3 is represented by state variable \( x_{15} \) and is generated due to its input \( \Delta P_{d3} \). It is important to note that the disturbances are the only inputs of the LFC system.

Tie-line power exchange is also considered as an output in the closed loop system. The system has 3 tie-lines; hence, there are another set of 3 outputs to be analyzed. Therefore, the LFC system has total of 6 outputs to be considered.
Figure 2.8: Block diagram of feedback three area LFC system with integral control
\[
A = \begin{bmatrix}
-1 & \frac{K_p}{T_p} & 0 & 0 & -\frac{K_p}{T_p} & 0 & 0 & 0 & 0 & 0 \\
& 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{T_r} & 1 & -\frac{K_r}{T_r} & \frac{K_r}{T_r T_T} & 0 & 0 & 0 & 0 & 0 \\
& 0 & 0 & -\frac{1}{T_r} & 1 & \frac{1}{T_T} & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{R_T g} & 0 & 0 & -\frac{1}{T_g} & 0 & 0 & 0 & 0 & 0 & 0 \\
2\pi T & 0 & 0 & 0 & 0 & 0 & -2\pi T & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{K_5}{T_6} & -\frac{1}{T_8} & \frac{K_5}{T_8} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_6} & \frac{K_3}{T_6} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_5} & \frac{K_2}{T_5} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_4} & \frac{1}{T_4} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-K_4 T_{T_1 l T_{2}}}{R_2 T_1 T_2 T_3} & 0 & 0 & 0 & \frac{-1}{T_3} & \frac{1}{T_3} (1 - \frac{T_1 l}{T_2}) \\
0 & 0 & 0 & 0 & 0 & \frac{-K_4 T_{T_1 l T_{2}}}{R_2 T_1 T_2} & 0 & 0 & 0 & 0 & \frac{-1}{T_2} \\
0 & 0 & 0 & 0 & 0 & \frac{-K_1}{T_1 R_2} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-K_4}{T_2 R_2} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -2\pi T & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-2\pi T & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
K_{i1} B_1 & 0 & 0 & 0 & K_{i1} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -K_{i2} & K_{i2} B_2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]
\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & K_p & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{T_p}{T_p} & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_g} & 0 & 0 \[3pt]
0 & \frac{-K_i}{T_i} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
0 & \frac{K_i}{T_i} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
\frac{T_{s1}}{T_2T_3} (1 - \frac{T_{s2}}{T_1}) & 0 & 0 & \frac{-K_i T_{s1} T_{s2}}{T_1 T_2 T_3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
\frac{1}{T_2} (1 - \frac{T_{s2}}{T_1}) & 0 & 0 & \frac{1}{T_1} T_{s2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
\frac{-1}{T_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_i}{T_1} & 0 \[3pt]
0 & \frac{-1}{T_7} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_i}{T_7} & 0 \[3pt]
0 & 0 & 0 & 0 & 2\pi T & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & \frac{-K_p}{T_p} & \frac{-1}{T_p} & \frac{K_p}{T_p} & 0 & 0 & \frac{-K_p}{T_p} & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & \frac{-1}{T_r} & \frac{1}{T_r} \frac{(1 - K_r T_{s1})}{T_r T_i} T_{s2} & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & \frac{-1}{T_i} & \frac{1}{T_i} & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & \frac{-1}{R_i T_g} & 0 & 0 & \frac{-1}{T_g} & 0 & 0 & 0 & \frac{-1}{T_g} \[3pt]
-2\pi T & 0 & 0 & \frac{2\pi T}{T_g} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_{i2}}{T_i} & 0 & 0 & 0 & 0 \[3pt]
0 & 0 & K_{i3} & K_{i3} B_3 & 0 & 0 & 0 & K_{i3} & 0 & 0 & 0
\end{bmatrix}
\]
The parameters of the integral controls used in the system, shown in Figure 2.8, have been tuned to meet the specifications mentioned in section 2.1. Table 2.3 lists the parameters of the controls used in this section.
### Table 2.3: Control parameters for feedback three area LFC system

<table>
<thead>
<tr>
<th>Area number (N)</th>
<th>Type of control</th>
<th>Integral gain constant ($K_I$)</th>
<th>Frequency bias factor ($B_N$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>2.85</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>0.17</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>1.08</td>
<td>0.925</td>
</tr>
</tbody>
</table>

Figure 2.9 illustrates the output response of area 1 in feedback three area system due to input $\Delta P_{d1}$. The response begins with undershoot due to presence of disturbance. Undershoot percentage is about 60% and the settling time is 4 seconds. These two parameters need to be improved since they do not meet the specifications mentioned in section 2.1. The frequency error is zero. Figure 2.10 illustrates the output response of area 2 in feedback three area system due to $\Delta P_{d2}$. Undershoot percentage is about 8% and the settling time is 10 seconds. Hence, these two parameters need improvement. The frequency error is zero. Figure 2.11 illustrates the output response of area 3 in feedback three area system due to $\Delta P_{d3}$. Undershoot percentage is about 8.5% and the settling time is 10 seconds. The frequency error is zero.

![Output response of area 1 in feedback three area LFC system with integral control](image)

**Figure 2.9:** Output response of area 1 in feedback three area LFC system with integral control
Figure 2.10: Output response of area 2 in feedback three area LFC system with integral control

Figure 2.11: Output response of area 3 in feedback three area LFC system with integral control
By studying Figures 2.9-2.11, it is concluded that integral control improved the system performance significantly in terms of steady state error and settling time. However, the system experiences high undershoot – undershoot more than the specified value. This is a shortcoming of conventional PID control.

In analysis of closed loop LFC system, it is important to analyze tie-line power exchange behaviour. Figure 2.12 illustrates the deviation in tie-line power exchange between area 1 and 2. This tie line power exchange experiences 0.16pu MW undershoot and settles down after 14 seconds with zero steady state power exchange error. Figure 2.13 shows the deviation in tie-line power exchange between area 2 and 3. This tie line power exchange experiences 0.01pu MW undershoot and settles down after 20 seconds with zero steady state power exchange error. Figure 2.14 shows the deviation in tie-line power exchange between area 1 and 3. Tie-line power exchange behaviour is upon mutual agreement of the control areas.

Figure 2.12: Tie-line response of feedback three area LFC system with integral control for area 1 and 2
Figure 2.13: Tie-line response of feedback three area LFC system with integral control for area 2 and 3

Figure 2.14: Tie-line response of feedback three area LFC system with integral control for area 1 and 3
2.5 Feedback N area generalization using integral control

In this chapter, effect of integral control has been analyzed in details. Based on the analysis performed on output response of single area, two area, and three area system, it is concluded that addition of integral control can improve the system performance in terms of steady state error and settling time; however, there is an increase in undershoot/overshoot. This is one of the shortcomings of conventional PID control. The same conclusion is applied to N area LFC system. Hence, a more reliable type of control is needed since power generation system is a system with high level of complexity and uncertainties. Following is list of outputs of multiple area system:

Single Area: $\Delta f_1$

Two Area: $\Delta f_1, \Delta f_2, \Delta P_{tie,12}$

Three Area: $\Delta f_1, \Delta f_2, \Delta f_3, \Delta P_{tie,12}, \Delta P_{tie,23}, P_{tie,13}$

Four Area: $\Delta f_1, \Delta f_2, \Delta f_3, \Delta f_4, \Delta P_{tie,12}, P_{tie,13}, P_{tie,14}, P_{tie,23}, P_{tie,24}, P_{tie,34}$

Another shortcoming of conventional PID control is that the exact mathematical modelling of the system is needed in order to be able to obtain the output response. For closed loop single area system, shown in section 2.2, five state variables were needed to model the system. For closed loop two area system shown in section 2.3, fifteen state variables were needed. For closed loop three area model shown in section 2.4, twenty two state variables were needed. Hence, the number of state variables increases as more control areas are added to the power system. Deriving the mathematical model of a power system with N control areas is a challenging task and the transfer function of each block may not even be available at the time of modelling. Therefore, there is a strong need of having efficient techniques that can improve the system performance without the need of precise mathematical modelling.
Chapter 3: Feedback Modelling and Simulation of Power System Using Adaptive Fuzzy Control

3.1 Introduction to fuzzy logic

Fuzzy Logic (FL) developed by Dr. Zadeh, in 1960s, is able to provide a systematic way for the application of uncertain and indefinite models when precise definition or mathematical representation of the system is unavailable [9].

FL is used in weather forecasting system since global climate is unpredictably changing and airports need to be informed of the changes every instant of time. FL is also used in biological processes such as production of drugs. Many techniques have been used for controlling and automating biological processes; however, they were unsuccessful because of lack of information in some of the biological reactions, complexity of mathematical modelling of the systems, and unavailability of sensors. FL is used in some home appliances such as washing machines. For washing machines, sensors continually monitor conditions inside the machine and accordingly adjust the setting for the best wash result. FL is used in transportation system in Japan. Sendai trains in Japan include FL control for smart transmission, breaking system, traffic planning, predicting number of customers, and energy consumption. FL led to tremendous improvement in autonomous robotics control systems. In 1990s, Motorola produced a FL based microcontroller that was well suited for designing autonomous robots.

Power system is a time-variant system that is influenced significantly by disturbances experienced by each control area. Power system is highly affected by non-internal factors such as weather and season. Modelling a time varying system is a very challenging task [10]. FL theory based control is able to upgrade system performance without the need of mathematical modeling of the system. It is enough to have only some knowledge about the system and its behavior.

FL is strongly based on linguistic interpretation of the system. Membership functions are fundamental part of FL. Let X be a set of objects whose elements are denoted by x. Membership in a subset A of X is the membership function \( \mu_A \) [13].
Fuzzy sets are functions that map a value that might be a member of a set to a number between zero and one indicating its actual degree of membership. Fuzzy sets produce a membership curve.

\[ A = \{(x, mA(x)), x \in X\} \quad (3.1) \]

3.2 Fuzzy logic control

As it was shown in chapter 2, conventional controls could not improve the system performance significantly especially in terms of undershoot/overshoot percentage. Even though, the steady state error reduced to zero and the settling time decreased to about 2 seconds, the system behavior was still unacceptable due to high undershoot. Hence, there is need for a more reliable control method to enhance the system performance [9].

FL control can be more effective than conventional control in controlling large scale systems. FL control is used to minimize fluctuation on the system outputs [12]. Combination of the two types of controls can result in a reliable and efficient control design. There exist two types of FL control:

1. Static Fuzzy Control: This control is used when structure and parameters of the FL control are fixed and do not change during real time operation [10].
2. Adaptive Fuzzy Logic Control: This control is used when structure and parameters of FL control change during real time operation. This type of control is more expensive to implement; however, it results in better performance and less mathematical information about the system is needed [10].

Objective of using adaptive FL control is to control the system in the presence of uncertainties and unknown variations. adaptive FL control is difficult to analyze because it is time varying; however, it ensures more desired performance in comparison to static FL control.

Figure 3.1 shows block diagram of a FL control which consists of the following 4 components [10]:

1. Rule-Base: It holds knowledge in terms of set of linguistic rules defined by the user called fuzzy rules. Fuzzy rules are built using membership functions.
2. Inference Mechanism: It selects relevant rules at the current time and decides what the output of the control should be. Output of the control $u(t)$ is input of the plant.

3. Fuzzification: It converts control’s input into information that can be used in inference mechanism.

4. Difuzzification: It converts output of the control into values that can be used by the plant. Fuzzification and difuzzification are inverse processes.

![Fuzzy Logic Controller Block Diagram](image)

**Figure 3.1:** Fuzzy logic control block diagram

By analyzing Figure 3.1, it can be observed that the steady state error is $e(t) = r(t) - y(t)$.

FL control has 2 inputs as shown below:

- **Input 1:**
  \[ e(t) = y(t) - r(t) > ACE \]  

- **Input 2:**
  \[ \frac{d}{dt} e(t) = \dot{e}(t) > A\dot{C}E \]  

If reference input $r(t)$ is zero, then inputs of FL control will be:

- **Input 1:**
  \[ e(t) = y(t) > ACE \]  

- **Input 2:**
  \[ \frac{d}{dt} e(t) = \dot{e}(t) = y(t) > A\dot{C}E \]  

To create a fuzzy logic system, following steps must to be taken [13]:

1. Define input of the control:         
   - Error = process output – set point
   - Error change = current error – last error
2. Define output of the control: \[ \text{Output} = \text{control output} - \text{plant input} \]

3. Create membership functions: Membership functions are developed based on designer’s knowledge and experience about the system. Membership functions are used to define fuzzy rules.

4. Create rules: Fuzzy rules are defined using IF-THEN relationships. They need to be manually tuned or adjusted in order to obtain the desired system response.

5. Simulate the result: SIMULINK is used to simulate the output result.

### 3.3 Feedback single area modelling and simulation using adaptive fuzzy logic control

The inputs of the FL control shown in Equations 3.4 and 3.5 can be classified into membership functions. Here, the inputs are classified into 7 membership functions as described below: NB: Negative Big, NM: Negative Medium, NS: Negative Small, ZZ: Zero, PS: Positive Small, MP: Positive Medium, PB: Positive Big. These 7 membership functions lead to 49 fuzzy rules as shown in Table 3.1.

Membership functions must be symmetrical and each membership function overlaps with the adjacent functions by 50%. Membership functions are normalized in the interval \([-L, L]\) which is symmetric around zero [13]. The two inputs are combined together using AND operation. Table 3.1 is constructed based on experience and knowledge known about power systems.

<table>
<thead>
<tr>
<th>(e(t))</th>
<th>AND</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZZ</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZZ</td>
</tr>
<tr>
<td>NM</td>
<td>NB</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>NS</td>
<td>ZZ</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>NS</td>
<td>NM</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>ZZ</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>Z</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>NS</td>
<td>ZZ</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>NM</td>
<td>NS</td>
<td>ZZ</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>PM</td>
<td>NS</td>
<td>ZZ</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>PB</td>
<td>ZZ</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

**Table 3.1:** Fuzzy rules for LFC system
Fuzzy Inference System (FIS) in MATLAB is able to design a FL control based on the fuzzy rules defined in Table 3.1. Figures 3.2-3.5 show the important windows of FIS used in control design. The FL control has two inputs: $e(t)$ and $e(t)$. Centeroid method is used to defuzzificate the values. The range of each membership, shown in Figure 3.3, is defined based on human’s experience and knowledge about power system.

**Figure 3.2:** FIS - inputs and output

**Figure 3.3:** FIS - membership functions
Figure 3.4: FIS - fuzzy rules

Figure 3.5: FIS - rule viewer
To have a stable closed loop system after implementation of FL control, controllability and observability are very important factors. Fuzzy logic control guarantees a closed loop globally stable system if the corresponding open loop system is controllable, observable, and stable [13]. Hence, the system shown in Figure 1.4, which has order of 4, is checked for the above conditions:

1. The system is controllable. The rank of controllability matrix is 4.
2. The system is unobservable. The rank of observability matrix is 3.
3. The system is stable since all the four poles lie on the left half plane.

Hence, the system considered in Figure 1.4 is not a valid candidate for implementation of FL control since it is not observable. As shown in chapter 2, this system worked perfectly fine for implementation of conventional PID control; however, it will not serve the purpose for implementation of FL control. Therefore, in order to illustrate how power system can be controlled using FL control, a different system must be considered. After careful investigation, a system that meets all the above specifications is selected.

The system shown in Figure 3.6 is the open loop system used in this chapter. The LFC system is modelled using state space representation. The poles of the system are located on the left half plane which indicates the system is stable. Rank of controllability and observability matrices are both 3 which is equal to number of state variables used in the system modelling. Hence, the system is controllable, observable, and a valid candidate for FL control implementation.

**Figure 3.6:** Block diagram of open loop single area LFC system
The state space representation of the system, shown in Figure 3.6, is given as follows. The system has 2 inputs: $\Delta P_c$ and $\Delta P_d$. However, only $\Delta P_d$ is considered as input since disturbance is non-controlling factor. The input is taken as unit step function. The output of the system is frequency deviation of the generator which corresponds to the state variable $X_1$.

\[
A = \begin{bmatrix}
-0.1 & 0.1 & 0 \\
0 & -1 & 1 \\
-200 & 0 & -10
\end{bmatrix}, \quad B = \begin{bmatrix}
-0.1 \\
0 \\
0
\end{bmatrix}, \quad C = [1 \ 0 \ 0]
\]

Figure 3.7 shows the output response of the open loop single area model illustrated in Figure 3.6. The system is stable with settling time of 3.5 seconds and undershoot of 0.06HZ. The steady state error is about 0.048HZ. Based on the specifications mentioned in section 2.1, the system is expected to have steady state error of no more than 0.01HZ and settling time of less than 3 seconds. The objective in this chapter is to combine implementation of adaptive FL control with a conventional PID control to improve the LFC system performance.

\[\text{Figure 3.7: Output response of open loop single area LFC system}\]
Figure 3.8 is block diagram of the feedback single area system used in this chapter. The FL control and PI control are combined together in parallel to improve the system behavior. The system has only one input $\Delta P_d$ and one output $\Delta f$.

![Block diagram of feedback single area LFC system with adaptive FL and PI control](image)

**Figure 3.8:** Block diagram of feedback single area LFC system with adaptive FL and PI control

Parameters of the PI control have been tuned carefully to ensure the requirements are met. Table 3.2 shows the parameters of the PI control implemented in Figure 3.8.

<table>
<thead>
<tr>
<th>Area number $(N)$</th>
<th>Type of control</th>
<th>Proportional gain constant ($K_p$)</th>
<th>Integral gain constant ($K_i$)</th>
<th>Frequency bias factor ($B_N$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PI</td>
<td>-0.25</td>
<td>-3.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Table 3.2:** Control parameters for feedback single area LFC system with adaptive FL control

Figure 3.9 shows the frequency response of the feedback LFC system after implementation of FL control described in Table 3.1 combined with PI control. Reliability of FL control and efficiency of PI control are combined together to construct a well behaved closed loop system. The FL control used in this chapter is shown in details in Figures 3.2-3.5. As shown in Figure 3.9, the system settling time is reduced to 2.5 seconds and the steady state error is completely removed; this is the effect of integral control. The undershoot percentage is 0.025%. This is a well behaved controlled system since all the specifications are met.
3.4 Feedback two area modelling and simulation using adaptive fuzzy logic control

Figure 3.10 shows LFC two area system that is constructed by combining two different control areas. Order of the system is 8 since 8 state variables are needed to model the system. The rank of controllability and observability matrices is 8 which imply the open loop system is controllable and observable, respectively. All the eight poles lie on the left half plane which implies the stability of the system. The system is controllable, observable, and stable; hence, the proposed LFC system is a valid candidate for implementation of FL control.

The system, shown in Figure 3.10 has 2 inputs to be considered: \( \Delta P_d1 \) and \( \Delta P_d2 \). The system has 3 outputs: \( \Delta f_1 \), \( \Delta f_2 \), and \( \Delta P_{tie,12} \). Figures 3.11 and 3.12 illustrate the frequency change response. It is observed that the system is behaving undesirably due to high settling time and steady state error. For area 1, the settling time is about 70 seconds and for area 2, it is about 1900 seconds. Since the specifications mentioned in sections 2.1 are not met, there is strong need for implementation of adaptive FL control combined with conventional PID control. Figure 3.13 is tie-line power response of the two area LFC system with settling time of 1800 seconds.
Figure 3.10: Block diagram of open loop two area LFC system

Figure 3.11: Output response of area 1 in open loop two area LFC system
Figure 3.12: Output response of area 2 in open loop two area LFC system

Figure 3.13: Tie-line response of open loop two area LFC system
Figure 3.14 shows the block diagram of the closed loop two area LFC system. Adaptive FL and PI control are combined together to improve the system performance. Equations 3.6 and 3.7 show ACE of each area:

Area 1: \[ ACE_1 = B_1 . \Delta \omega_1 + \Delta P_{tie,12} \] (3.6)
Area 2: \[ ACE_2 = B_2 . \Delta \omega_2 - \Delta P_{tie,12} \] (3.7)

The parameters of the PI control for area 1 and area 2 are selected after numerous trials and careful considerations. Table 3.3 shows the parameters used in PI control design in this section.

<table>
<thead>
<tr>
<th>Area number (N)</th>
<th>Type of control</th>
<th>Proportional gain constant ((K_p))</th>
<th>Integral gain constant ((K_i))</th>
<th>Frequency bias factor ((B_N))</th>
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</thead>
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<tr>
<td>1</td>
<td>PI</td>
<td>-0.02</td>
<td>-1.1</td>
<td>3.5</td>
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<tr>
<td>2</td>
<td>PI</td>
<td>-1.2</td>
<td>-0.35</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 3.3: Control parameters for feedback two area LFC system with adaptive FL control

Figure 3.14: Block diagram of feedback two area LFC system with adaptive FL and PI control
Figures 3.15 and 3.16 illustrate the output response of the LFC system after implementation of adaptive FL and PI control. For area 1, the settling time is 3 seconds. The frequency error is 0.0003HZ and the undershoot percentage is 0.059%. For area 2, the settling time is 7.5 seconds. The frequency error is 0.0001HZ and the undershoot percentage is 0.11%. The frequency error and undershoot percentage meet the specifications mentioned in section 2.1. However, the settling time for area 2 needs improvement. Further tuning of FL rules and PI control parameters are required.

![Figure 3.15](image)

**Figure 3.15:** Output response of area 1 in feedback two area LFC system with adaptive FL and PI control

Figure 3.17 shows tie-line power exchange. The tie line power exchange begins with overshoot of 0.001pu MW and it settles down to zero after about 20 seconds. Specifications for the tie-line power exchange are upon mutual agreement of the control areas.
Figure 3.16: Output response of area 2 in feedback two area LFC system with adaptive FL and PI control

Figure 3.17: Tie-line response of feedback two area LFC system with adaptive FL and PI control
3.5 Feedback three area modelling and simulation using adaptive fuzzy logic control

The open loop system used in section 3.3 is expanded to create three area LFC system. Figure 3.18 represents the block diagram of the three area LFC system used in this section for adaptive FL control implementation. Area 1 and 3 are the same; they both contain non-reheat turbines. Area 2 is different from the other two areas since it contains a re-heat component. Using the state variable assignment shown in Figure 3.18, state space representation of the system is developed.

There are 3 integral blocks to show the tie-line power exchange among all the three control areas. The state variable $X_4$ represents the tie-line power exchange between area 1 and 2. The state variable $X_9$ represents the tie-line exchange between area 2 and 3. The state variable $X_{13}$ represents the tie-line power exchange between area 1 and 3. The system has total of 3 inputs: $\Delta P_{d1}$, $\Delta P_{d2}$, and $\Delta P_{d3}$. The system has total of 6 outputs: $\Delta f_1$, $\Delta f_2$, $\Delta f_3$, $\Delta P_{tie,12}$, $\Delta P_{tie,23}$, and $\Delta P_{tie,13}$.

After developing the state space representation of the system, the system is checked against the requirements to ensure it is valid for implementation of adaptive FL control. All the 13 poles of the system are located on the left half plane which implies stability of the system. The open loop system is controllable and observable. Therefore, addition of FL control to this system will create a stable closed loop system.

Figures 3.19-3.21 show open loop output response of the system and Figures 3.22 and 3.23 show the tie-line power exchange. Output response of area 1 has undershoot percentage of 0.025%, steady state error of 0.00005HZ, and settling time of 4 seconds. Output response of area 2 has undershoot percentage of 0.075%, steady state error of 0.00005HZ, and settling time of 12 seconds. Output response of area 3 has undershoot percentage of 0.03%, steady state error of 0.00005HZ, and settling time of 4 seconds. In Figures 3.22 and 3.23, the overshoot percentage is 0.1% and the tie line power exchange variation is 0 pu MW. In both cases, the tie line power exchange settles down after about 20 seconds.
Figure 3.18: Block diagram of open loop three area LFC system

Figure 3.19: Output response of area 1 in open loop three area LFC system
Figure 3.20: Output response of area 2 in open loop three area LFC system

Figure 3.21: Output response of area 3 in open loop three area LFC system
Figure 3.22: Tie-line response of open loop three area LFC system for area 1 and 2

Figure 3.23: Tie-line response of open loop three area LFC system for area 2 and 3
In order to improve the system performance, adaptive FL control and conventional PID control are combined together for each area. The objective is to reduce frequency error, settling time, and undershoot/overshoot percentage. Equations 3.8-3.10 are the control errors associated with each area:

Area 1: \[ ACE_1 = B_1 \Delta \omega_1 + \Delta P_{tie,12} - \Delta P_{tie,13} \] \hspace{1cm} (3.8)

Area 2: \[ ACE_2 = B_2 \Delta \omega_2 + \Delta P_{tie,23} - \Delta P_{tie,12} \] \hspace{1cm} (3.9)

Area 3: \[ ACE_3 = B_3 \Delta \omega_3 + \Delta P_{tie,23} + \Delta P_{tie,13} \] \hspace{1cm} (3.10)

The parameters of the conventional PID control for area 1, area 2, and 3 are selected after numerous trials and careful considerations. Table 3.4 shows the type of control and the corresponding parameters used in this section.

<table>
<thead>
<tr>
<th>Area number (N)</th>
<th>Type of control</th>
<th>Proportional gain constant (K_p)</th>
<th>Integral gain constant (K_i)</th>
<th>Frequency bias factor (B_N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PI</td>
<td>-0.5</td>
<td>-1.1</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>PI</td>
<td>-1.5</td>
<td>-0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>--</td>
<td>-1.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 3.4: Control parameters for feedback three area LFC system with adaptive FL control

Figure 3.24 is the block diagram of feedback three area LFC system after implementation of adaptive FL and conventional PID control. For area 1 and 2, PI control is used and for area 3, only integral control is used. Implementation of additional component is costly. Therefore, proportional control is not added to area 3 since it is unnecessary.

Figures 3.25-3.27 show the output response of each area. Based on Figure 3.25, the settling time of $\Delta f_1$ is 3 seconds; the frequency error is 0.00021 HZ, and the percentage undershoot is 0.05%. Based on Figure 3.26, the settling time of $\Delta f_2$ is 7 seconds; the frequency error is 0.0003 HZ, and the percentage undershoot is 0.11%. Based on Figure 3.27, the settling time of $\Delta f_3$ is 3 seconds; the frequency error is 0.00015 HZ and the percentage undershoot is 0.05%. The specifications outlined in section 2.1 related to frequency error and percentage undershoot are completely satisfied. However, there is still room for improvement in settling time and that can be achieved by further tuning the PI and I control parameters.
Figure 3.24: Block diagram of feedback three area LFC system with adaptive FL and PI control

Figure 3.25: Output response of area 1 in three area LFC system with adaptive FL and PI control

Settling time: 3sec

Error: $2.5 \times 10^{-4}$ HZ

Undershoot: $5 \times 10^{-4}$ HZ
Figure 3.26: Output response of area 2 in three area LFC system with adaptive FL and PI control

Figure 3.27: Output response of area 3 in three area LFC system with adaptive FL and PI control

Figure 3.28 shows the tie line power exchange between area 1 and 2 denoted by $\Delta P_{tie,12}$. The overshoot is 0.14% and the steady state error is 0.0014 pu MW. Figure 3.29 shows the tie line power exchange between area 2 and 3 denoted by $\Delta P_{tie,23}$. The overshoot percentage is
0.14% and the steady state error is 0.0014 pu MW. Lastly, Figure 3.30 shows the tie-line power exchange between area 1 and 3 denoted by \( \Delta P_{tie,13} \). In this tie line, the overshoot percentage is 0.005% and the steady state error is 0.00005 pu MW.

**Figure 3.28:** Tie-line response of feedback three area LFC system for area 1 and 2

**Figure 3.29:** Tie-line response of feedback three area LFC system for area 2 and 3
3.6 Feedback N area generalization using adaptive fuzzy logic control

Number of tie-lines and outputs increases as number of control areas increases. Table 3.5 shows the relationship between number of control areas and total number of outputs associated with each LFC system.

<table>
<thead>
<tr>
<th>Number of control areas</th>
<th>Number of tie-lines ($\Delta P_{tie}$)</th>
<th>Number of frequency outputs</th>
<th>Total number of outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>6</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 3.5: Relationship between number of control areas and number of outputs
In section 1.6, Figure 1.18 illustrated in details tie-lines for four area power system. Figures 3.31 and 3.32 show total number of outputs for five area and six area power system.

**Figure 3.31:** Five area interconnected power system

**Figure 3.32:** Six area interconnected power system
Chapter 4: Comparison of Conventional PID and Adaptive Fuzzy Logic Control

4.1 Effect of conventional PID control

In chapter 2, conventional controls such as PI and I controls were added to single area, two area, and three area LFC system. LQR technique was used to stabilize the system. LQR technique guarantees a stable system as long as the uncontrolled/open loop system is controllable. In chapter 2, it was shown that the system performance improved significantly in terms of settling time, frequency error, and undershoot/overshoot percentage.

Conventional PID controls are not the most effective controls to be used in time-variant systems. One of the shortcomings of conventional PID controls is that accurate mathematical modelling of the system is required in order to find state space representation of the system. Power system is a dynamic system and mathematical model may not be known accurately. Hence, a more practical and effective control is needed to control the system.

4.2 Effect of adaptive fuzzy logic control

As number of control areas increases in power system, number of outputs and tie-lines increase. This means that the system level of complexity increases as more control areas are added to the system. Once the system exceeds a certain threshold of complexity, the system will become very difficult to be modelled mathematically. Hence, conventional PID controls are no longer effective. FL control is most suitable type of control for systems that involve high level of complexity and uncertainty.

In chapter 3, adaptive FL control was introduced and applied to single area, two area, and three area power system. FL rules introduced in Table 3.1 were developed based on general knowledge of control designer about power system. In this chapter, conventional PID and adaptive FL control were combined together to ensure most effective result. It was observed that the system performance improved significantly.
No exact mathematical modelling of the system is required in FL control design. Figure 4.1 shows how FL system accepts impression and uncertainty to provide decisions [11].

![Fuzzy Logic System](image)

Figure 4.1: Fuzzy logic system

### 4.3 Comparison of conventional PID and adaptive fuzzy logic control

In chapter 2, PI and I controls were used to improve system performance in terms of frequency error, settling time, and undershoot/overshoot percentage. The parameters of the controls were tuned manually to achieve the desired response. In chapter 3, adaptive FL and conventional PID control were combined together to improve system performance in single area, two area, and three area LFC system. LF control guarantees a stable controlled/close loop system if the corresponding uncontrolled/open loop system is stable, controllable, and observable. Hence, the uncontrolled system poles, rank of controllability matrix, and rank of observability matrix need to be checked before implementation of FL control.

Table 4.1 shows the output response comparison between uncontrolled and controlled LFC system. From Table 4.1, it is concluded that adaptive FL control advances the system output behavior significantly by reducing frequency error, settling time, and undershoot/overshoot percentage. Among different types of conventional controls, PI and integral controls were chosen in chapter 3. Following specifications are recommended for a typical power system:

1. Steady state error should not be more than 0.01HZ.
2. Settling time should be not be more than 3 seconds.
3. The maximum overshoot/undershoot should not be more than 6% which corresponds to 0.06HZ.

According to Table 4.1, the settling time is reduced from 3.5 seconds to 2.5 seconds for single area LFC system. The steady state error is reduced from 0.048HZ to 0HZ and the undershoot is reduced from 0.06HZ to 0.0025HZ. Adaptive FL control met all the above specifications except
the settling time in area 2 of two area and area 2 in three area LFC system. Further tuning of PI control parameters and FL base rules are needed to enhance the system output performance. However, it is important to consider physical limitations and constraints of the system before further tuning of the parameters.

<table>
<thead>
<tr>
<th>Area</th>
<th>Single Area</th>
<th>Two Area</th>
<th>Three Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled</td>
<td>$\Delta f_1 = 2.5$ HZ, $t_s_1 = 180$ sec, $U_1 = -13$HZ</td>
<td>$\Delta f_1 = 0.5$ HZ, $t_s_1 = 300$ sec, $t_s_2 = 300$ sec, $U_1 = -3.5$HZ, $U_2 = -1.1$HZ</td>
<td>$\Delta f_1 = 1.2$ HZ, $t_s_1 = 25$ sec, $t_s_2 = 25$ sec, $U_1 = -3.5$HZ, $U_2 = -0.6$HZ</td>
</tr>
<tr>
<td>Conventional PID control</td>
<td>$\Delta f_1 = 0$ HZ, $t_s_1 = 1$ sec, $U_1 = -0.05$HZ</td>
<td>$\Delta f_1 = 0$ HZ, $t_s_1 = 5$ sec, $t_s_2 = 15$ sec, $U_1 = -6.1$HZ, $U_2 = -0.13$HZ</td>
<td>$\Delta f_1 = 0$ HZ, $t_s_1 = 4$ sec, $t_s_2 = 10$ sec, $U_1 = -0.6$HZ, $U_2 = -0.08$HZ</td>
</tr>
<tr>
<td>Adaptive FL combined with conventional PID control</td>
<td>$\Delta f_1 = 0.048$ HZ, $t_s_1 = 3.5$ sec, $U_1 = -0.06$HZ</td>
<td>$\Delta f_1 = 0.043$ HZ, $t_s_1 = 70$ sec, $U_1 = -0.06$HZ</td>
<td>$\Delta f_1 = 0.00005$ HZ, $t_s_1 = 4$ sec, $U_1 = 0.00025$HZ</td>
</tr>
<tr>
<td>Controlled:</td>
<td>$\Delta f_1 = 0$ HZ, $t_s_1 = 2.5$ sec, $U_1 = 0.00025$HZ</td>
<td>$\Delta f_2 = 0.02$ HZ, $t_s_2 = 1900$ sec, $U_2 = -0.024$HZ</td>
<td>$\Delta f_2 = 0.00005$ HZ, $t_s_2 = 12$ sec, $U_2 = -0.00075$HZ</td>
</tr>
<tr>
<td>Controlled:</td>
<td>$\Delta f_1 = 0.0003$ HZ, $t_s_1 = 3$ sec, $U_1 = 0.059%$</td>
<td>$\Delta f_2 = 0.0001$ HZ, $t_s_2 = 7.5$ sec, $U_2 = 0.11%$</td>
<td>$\Delta f_3 = 0.00005$ HZ, $t_s_3 = 4$ sec, $U_3 = -0.0003$HZ</td>
</tr>
<tr>
<td>Controlled:</td>
<td>$\Delta f_1 = 0.00021$ HZ, $t_s_1 = 3$ sec, $U_1 = -0.0005$HZ</td>
<td>$\Delta f_2 = 0.0003$ HZ, $t_s_2 = 7$ sec, $U_2 = -0.0011$HZ</td>
<td>$\Delta f_3 = 0.00015$ HZ, $t_s_3 = 2.5$ sec, $U_3 = -0.0005$HZ</td>
</tr>
</tbody>
</table>

**Table 4.1**: Comparison of output response of uncontrolled vs controlled LFC system
Chapter 5: Conclusion and future work

5.1 Conclusion

In this thesis, uncontrolled/open loop and controlled/closed loop single area, two area, and three area LFC system were considered. The system inputs, $\Delta P_{di}$, were the disturbances experienced by each control area. The system outputs were the frequency deviation, $\Delta f_i$, of each area and tie-line power exchange, $\Delta P_{tie,ij}$. Tie-line power exchange was used to interconnect the control areas when the LFC system consisted of more than one area. In chapter 2, appropriate conventional PID control was selected for each area and tuning of the control parameters was done manually to ensure the required specifications are met. In chapter 2, it was noticed that controlling systems with uncertain and unpredictable behavior such as power systems is a challenging task and a more efficient and reliable type of control was needed to control the system. In chapter 3, adaptive FL control was combined with conventional PID control to improve the system output performance. FL controls are well suited to control time-variant systems without the need to know accurate mathematical modelling of the system. FL uses FL base rules to predict the system output based on some knowledge about the nature of the system. In section 3.6, it was shown that as number of areas increases, number of tie-lines and number of outputs increase. This adds to level of complexity and uncertainty of the system.

By carefully studying Table 4.1, it is concluded that adaptive FL control combined with conventional PID control improves system performance considerably in terms of frequency error, settling time, and undershoot/overshoot percentage. Adaptive FL control combined with conventional PID control is the most efficient and reliable type of control for systems with high level of complexity such as power systems that have uncertain and unpredictable behavior.

Comparing the results of this thesis to the work in [9], it can be concluded that undershoot for area 1 in two area LFC system has improved from 0.027HZ to 0.00059HZ which corresponds to 97.8% improvement. In the same area, the settling time has improved from 4 seconds to 3 seconds which corresponds to 25% improvement in settling time.
5.2 Conventional vs restructured power system

In the conventional environment, there is one single authority/company responsible for generation, transmission, and distribution of electricity over a given geographical area. This kind of utility is called vertically integrated structure and is shown in Figure 4.2 [20].

![Figure 4.2: Vertically integrated structure](image)

In restructured or deregulated environment, there are three independent companies or authorities responsible for generating, transmitting, and distributing electricity. The generating company that owns a plant or collection of plants to generate electricity is called Genco. Transmission company owns transmission networks such as lines, cables, and relevant devices. They do not own generation plants or distribution networks. Distribution company, called Disco, owns and operates distribution networks and has control over the sale of electricity for the entire geographical region. In a competitive open market, Disco has the freedom to contract with any available Genco. There can be various combinations of Genco and Disco. Each Genco is responsible for tracking its own load and honoring tie-line power exchange with its neighboring Genco [21]. An open competitive market encourages Gencos to provide more care to their plants. Additionally, it encourages Discos to be more efficient in distribution process. Lastly, it prevents consumers to pay unnecessary cost [20]. Figure 4.3 shows how restructured or de-regulated environment is structured [20].

In vertically integrated environment, it is assumed that each control area has the necessary control and frequency regulation equipment to ensure frequency error is minimized. Currently, the electric power industry is transferring from vertically integrated environment to
restructured/deregulated environment which leads to have competitive companies sell unbounded power at lower rates. In restructured/deregulated environment, generation companies may or may not participate in LFC tracking. LFC tracking is referred to tracking of load variation while maintaining frequency and tie-line power interchange as close as possible to nominal values. These changes introduce major uncertainties in LFC system and make control of frequency a very difficult task. Here comes the need for novel control strategies for maintaining reliability and minimizing the frequency error [22]. FL is well suited to control such unpredictable systems and it can be applied to both vertically integrated as well as restructured environment. Figure 4.4 shows an example of deregulated three area power system.

![Figure 4.3: Restructured/deregulated environment](image)

![Figure 4.4: Example of three area deregulated power system](image)
5.3 Future work

In this thesis, systems that were controllable, observable, and stable were considered for FL control implementation. These kinds of systems guarantee a globally stable controlled system after implementation of FL control. This work can be expanded by considering systems that are unobservable, uncontrollable, or unstable. For unobservable systems, observers or sensors can be implemented initially to ensure all the state variables are accessible. Then, the uncontrolled system will become a valid candidate for execution of FL control. For uncontrollable systems, controllers can be implemented first to ensure all the outputs are accessible before implementing FL control. Pole-placement and LQR stabilization techniques can be used to stabilize unstable systems before implementation of FL control.

This work can be expanded by introducing more FL base rules. In this thesis, 7 membership functions were used which led to 49 fuzzy rules. More membership functions and more FL base rules will develop more accurate system output response.

The physical layout of a system is a fundamental part of control problems. To be able to design a well behaved control, it is important to understand the physical limitations and constraints of the system under study. This includes knowledge about the system energy consumption, material used in the system, speed of machines used in the system, and production cost.

Design of conventional PID control in this thesis was based on manual tuning. Further tuning of the control parameters can improve the system output performance.
References


Appendix

Appendix A - Table of Constants

<table>
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<tr>
<th>Symbol</th>
<th>Values</th>
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<tr>
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<td>0.5 sec</td>
</tr>
<tr>
<td>$T_r$</td>
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</tr>
<tr>
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</tr>
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<td>0.6 sec</td>
</tr>
<tr>
<td>$T_7$</td>
<td>0.006 sec</td>
</tr>
<tr>
<td>$T_8$</td>
<td>0.354 sec</td>
</tr>
<tr>
<td>$T_{v1}$</td>
<td>0.19 sec</td>
</tr>
<tr>
<td>$T_{v2}$</td>
<td>0.12 sec</td>
</tr>
<tr>
<td>$T$</td>
<td>0.086 sec</td>
</tr>
<tr>
<td>$K_r$</td>
<td>0.5</td>
</tr>
<tr>
<td>$K_p$</td>
<td>125</td>
</tr>
<tr>
<td>$R_1$</td>
<td>2.5 Hz/p.u MW</td>
</tr>
<tr>
<td>$R_2$</td>
<td>3.0 Hz/p.u MW</td>
</tr>
<tr>
<td>$R_3$</td>
<td>2.5 Hz/p.u MW</td>
</tr>
<tr>
<td>$K_1$</td>
<td>0.024</td>
</tr>
<tr>
<td>$K_2$</td>
<td>20</td>
</tr>
<tr>
<td>$K_3$</td>
<td>10.6</td>
</tr>
<tr>
<td>$K_4$</td>
<td>0.077</td>
</tr>
<tr>
<td>$K_5$</td>
<td>1.4286</td>
</tr>
<tr>
<td>$a_{12}$</td>
<td>-1</td>
</tr>
<tr>
<td>$K_{i1}$</td>
<td>2.85</td>
</tr>
<tr>
<td>$K_{i2}$</td>
<td>0.17</td>
</tr>
<tr>
<td>$K_{i3}$</td>
<td>1.08</td>
</tr>
<tr>
<td>$B_1$</td>
<td>1.2</td>
</tr>
<tr>
<td>$B_2$</td>
<td>1.3</td>
</tr>
<tr>
<td>$B_3$</td>
<td>0.925</td>
</tr>
</tbody>
</table>
Appendix B – Selected MATLAB file

% Feedback modelling and simulation of three area LFC system with integral control
% Created on June 10th, 2017
% Last modified September 22nd, 2017
% ---------------------------------------------------------------------------
close all
clear all
c1c
%--------------------------------THREE AREA--------------------------------

% Define the system parameters:
Tg=0.4;   % Model 1: Area 1 and 3
Tt=0.5;
Tr=10;
Tp=20;
Kr=0.5;
Kp=125;
R1=2.5;
R3=2.5;
K1=0.024; % Model 2: Area 2
K2=20;
K3=10.6;
K4=0.077;
K5=1.4286;
Tv1=0.19;
Tv2=0.12;
T1=0.27;
T2=0.08;
T3=0.04;
T4=0.087;
T5=0.1;
T6=0.6;
T7=0.006;
T8=0.354;
R2 =3.0;
T=0.086;

% Integral Control Parameters:
Ki1=2.85;   % integral gain constant of area 1.
B1=1.2;
Ki2=0.17;   % integral gain constant of area 2.
B2=1.3;
Ki3=1.08;   % integral gain constant of area 3.
B3=0.925;

% System State Space Representation:
A3=[-1/Tp Kp/Tp 0 0 -Kp/Tp 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 -1/Tr (1/Tr)*(1-(Kr/Tt)) Kr/(Tr*Tt) 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 -1/Tt 1/Tt 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; -1/(R1*Tg) 0 0 -1/Tg 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1/Tg 0 0; 2*pi*T 0 0 0 0 -2*pi*T 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 K5/T8 -1/T8 K5/T8 0 0 0 0 0 -K5/T8 K5/T8 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 -1/T6 K3/T6 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];
% Effect of deltaPd is to introduce disturbance of -1. Hence, we expect undershoot. The inputs that output is trying to track are deltaPd1, deltaPd2, & deltaPd3.

B3=[ -Kp/Tp 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 -K4/T7 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 -Kp/Tp ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ; 0 0 0 ];

C3=[ 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ];

sys_op3=ss(A3,B3,C3,0);

% Poles of A2: The system is unstable.
EigenValuesOfA3=eig(A3);

% Controllability and observability matrix:
RankofQc=rank(ctrb(A3,B3));
RankofQo=rank(obsv(A3,C3));

% ------------------------LQR STABILIZATION METHOD-------------------------
% LQR method is needed to stabilize the system.
% K: Feedback controller gain.
% P: Riccati Equation solution called Riccati matrix.
% eig_cl: Eigen values of closed loop system A-BK.

% Error weighted matrix > simplest case is identity matrix. Change Q11 since X1, X6, and X15 are the main output of the system (the most important state variables).
Q11=15.3;
Q=[Q11 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ; 0 0 0 0 0 Q11 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ];
% Control weighted matrix > positive definite. Must have as many columns as B. Must be a square matrix. Hence, it must be a 3x3 matrix.

R11=16.2;
R=[R11 0 0; 0 R11 0; 0 0 R11];

% LQR control design using Matlab built-in function:
[K,P,eig_cl]=lqr(A3,B3,Q,R);

% Define the closed loop system after stabilization is done added:
sys_cl=ss(A3-(B3*K),B3,C3,0);

% Extract columns of the matrix in order to plot each output individually:
t=0:0.05:20;
[-~,~,X] = step(sys_cl,t);
X1=X(:,1);  %Output of area 1
X6=X(:,6);  %Output of area 2
X15=X(:,15);  %Output of area 3
X5=X(:,5);  %Tie-line power of area 1 and 2 > Ptie,12
X14=X(:,14);  %Tie-line power of area 2 and 3 > Ptie,23
X19=X(:,19);  %Tie-line power of area 1 and 3 > Ptie,13

figure;plot(t,X1)
ylabel('Frequency Change (HZ)');
xlabel('Time (Seconds)');
figure;plot(t,X6)
ylabel('Frequency Change (HZ)');
xlabel('Time (Seconds)');
figure;plot(t,X15)
ylabel('Frequency Change (HZ)');
xlabel('Time (Seconds)');
figure;plot(t,X5)
ylabel('Power Change (pu MW)');
xlabel('Time (Seconds)');
figure;plot(t,X14)
ylabel('Power Change (pu MW)');
xlabel('Time (Seconds)');
figure;plot(t,X19)
ylabel('Power Change (pu MW)');
xlabel('Time (Seconds)');
Comprehensive Approach towards Modelling and Simulation of Single Area Power Generation System Using PI Control and Stability Solution Using Linear Quadratic Regulator

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Abstract - In this paper, the open loop single area power generation system is modelled using state space representation. The output response which is frequency deviation at steady state is simulated using MATLAB. Then, Proportional Integral (PI) controller is added to the system to understand the effect of a conventional controller on system steady state output response. The controlled system is stabilized through design of Linear Quadratic Regulator (LQR). The performance of system steady state output response is measured in terms of undershoot percentage, settling time, and steady state error. The controlled system simulation at the end of this paper shows that PI control is an efficient, reliable, and robust technique to solve power generation system optimization problem. The output response of the considered controlled system has settling time of 0.7 second, zero steady state error, and undershoot of 5.45%.

Key Words: Optimization, Single Area Power Generation System, LQR Technique, PI Controller, Steady State Response

1 INTRODUCTION

An interconnected system called Automatic Generation Control (AGC) consists of two sub-systems: Load Frequency Control (LFC) and Automatic Voltage Regulator (AVR). AVR is responsible to regulate the terminal voltage and LFC is employed to control the system frequency. In this paper, modelling and simulation of LFC is considered for careful analysis since LFC is more sensitive to changes in load compared to AVR. LFC and AVR are decoupled and can be analyzed separately. There is only weak overlap of effect between the two sub-systems [1].

Optimizing thermal power generation system will reduce energy or fuel consumption. Fuel reduction of even a small percentage will lead to large energy saving which results into saving the environment [2]. Hence, many researchers have been interested to solve optimization problem in thermal power generation systems. In order to optimize power generation system, the plant has to operate at desired operating level which corresponds to operating at nominal frequency.

2 OPEN LOOP ANALYSIS

Figure 1 shows the SIMULINK generated block diagram of an uncontrolled generating unit which consists of a speed governor, a turbine, a re-heat, and a generator [1]. The inputs of the system are $\Delta P_t$ representing the change in speed generation by utility and $\Delta P_d$ representing the change in load by consumer also known as disturbance. Since user has no control over load changes, $\Delta P_d$ is considered the only input of the system. The effect of $\Delta P_t$ will be disappeared when a controller is added to the system.

The fact that the frequency changes with load generation imbalance gives an accurate way to regulate the imbalance. Hence, frequency deviation $\Delta f$ is considered as a regulation signal to study the system performance. The output of LFC is $\Delta f$ which represents the change or variation in steady state frequency. The objective is to have a constant output frequency which corresponds to $\Delta f$ being zero or very small. The value of Speed Regulation $R$ also known as Droop is the ratio of frequency deviation ($\Delta f$) to change in power output of the generator. Table 1 shows the constants used for single area power system in Figure 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_g$</td>
<td>Governor Time Constant</td>
<td>0.4 sec</td>
</tr>
<tr>
<td>$T_r$</td>
<td>Turbine Time Constant</td>
<td>0.5 sec</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Re-heat Time Constant</td>
<td>10 sec</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Generator Time Constant</td>
<td>20 sec</td>
</tr>
<tr>
<td>$K_r$</td>
<td>Re-heat Gain Coefficient</td>
<td>0.5</td>
</tr>
<tr>
<td>$K_g$</td>
<td>Generator Gain Coefficient</td>
<td>125</td>
</tr>
<tr>
<td>$R$</td>
<td>Speed Regulation</td>
<td>2.5 Hz/p.u MW</td>
</tr>
</tbody>
</table>
The output of each integrator in Figure 1 is a state variable. Hence, state variable matrix A must be a 4x4 matrix. Equations 1-4 show the developed transfer functions:

Generator
\[
\frac{x_1}{x_2} = \frac{k_p}{1 + T_p s} \tag{1}
\]

Re-heat
\[
\frac{x_3}{x_4} = \frac{1 + k_s s}{1 + T_s s} \tag{2}
\]

Turbine
\[
\frac{x_3}{x_4} = \frac{1}{1 + T_s s} \tag{3}
\]

Governor
\[
\frac{x_4}{x_1} = \frac{1}{1 + T_p s} \tag{4}
\]

To develop state space representation of the system shown in Figure 1, rate of change of each state variable is needed. Therefore, Inverse Laplace Transform of the transfer functions shown in Equations 1-4 is taken and the equations are re-arranged into equations 5-8:

\[
x_1 = -\frac{1}{T_p} x_1 + \frac{k_p}{T_p} x_2 - \frac{k_p}{T_p} \Delta P_d \tag{5}
\]

\[
x_2 = -\frac{1}{T_r} x_2 + \frac{1}{T_r} \left( 1 - \frac{k_p}{T_p} \right) x_3 + \frac{k_r}{T_p T_r} x_4 \tag{6}
\]

\[
x_3 = -\frac{1}{T_r} x_3 + \frac{1}{T_r} x_4 \tag{7}
\]

\[
x_4 = -\frac{1}{T_g T_r} x_1 - \frac{1}{T_g} x_4 \tag{8}
\]

Then, Equations 5-8 are transformed into state space model. It is important to note that the output of the system \( \Delta f \) is the state variable \( x_1 \). Hence, the output matrix \( C \) will be a row matrix of size 1x4. The input matrix \( B \) is a matrix of size 4x1. State Space representation of any system follows the following structure:

\[
\dot{x}(t) = Ax(t) + B \Delta P_d \tag{9}
\]

\[
y(t) = C x(t) \tag{10}
\]

Following is state space representation of LFC shown in Figure 1:

\[
A = \begin{bmatrix}
-1 & \frac{k_p}{T_p} & 0 & 0 \\
0 & -1 & \frac{1 - \frac{k_p}{T_r}}{T_r} & \frac{k_r}{T_p T_r} \\
0 & 0 & -1 & \frac{1}{T_r} \\
0 & 0 & 0 & -1 \frac{1}{T_s}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{-k_p}{T_p} \\
0 \\
0 \\
0
\end{bmatrix}
\]

\[
C = \begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}
\]

Figure 2 illustrates the output response of the LFC model generated in MATLAB. The input \( \Delta P_d \) is a unit step function. The output response begins with oscillations and damps at steady state. Since there is increase in load, undershoot is expected. Increase in load leads to decrease in frequency which corresponds to undershoot. Decrease in load leads to increase in frequency which corresponds to overshoot. The settling time of the system is 150 seconds and the steady state value is 2.5 Hz. The undershoot percentage, settling time, and the steady state value are significantly large and this leads to the necessity of having a controller added to the system.
3 CONVENTIONAL CONTROLLERS

The primary objective of having a controller in power system is to eliminate the steady state frequency deviation. In any reliable power system, following specifications are expected to be met:

1. Steady state frequency error should not be more than ±0.01Hz.
2. Settling time should be less than 1 second.
3. The maximum undershoot should not be more than 6% which corresponds to transient frequency of ±0.06Hz.

Each controller has different role. Proportional controller is used to reduce rise time and settling time. Integral controller is used to eliminate steady state error. The negative effect of integral controller is creating oscillation. Derivative controller is used to improve transient response which means reducing overshoot/undershoot. Equations 11-15 show structure of most commonly used conventional controllers where $U(s)$ is the controller output and $E(s)$ is the controller input.

Proportional (P): $U(s) = K_p E(s)$  \hfill (11)

Integral (I): $U(s) = \frac{K_i}{s} E(s)$  \hfill (12)

Derivative (D): $U(s) = (K_dS) E(s)$  \hfill (13)

PI: $U(s) = (K_p + \frac{K_i}{s}) E(s)$  \hfill (14)

PID: $U(s) = (K_p + \frac{K_i}{s} + K_dS) E(s)$  \hfill (15)

Area Control Error (ACE) is the difference between actual power flow out of area and scheduled power flow. Ideally, the main objective in optimization problem is to improve the dynamic response of the system by minimizing or even eliminating AEC. In other words, the main objective is to lead each utility to constantly change its generation to follow the ACE. In real life power systems, it is rare to have no ACE due to instantaneous change in load. Hence, the objective is to keep AEC close to zero as possible. Integral control is well suited in this purpose.

4 FEEDBACK ANALYSIS

For single area closed loop system, a Proportional Integral (PI) controller is added to the system as shown in Figure 3. Equation 14 shows the transfer function of the PI controller used in this section.

The system shown in Figure 3 has 5 integral blocks which corresponds to 5 state variables. Equations 16-20 show the transfer functions of each integral block in Figure 3 where $K_g$ is the proportional constant and $K_i$ is the integral constant.

Generator $\frac{x_1}{x_2-\Delta P_d} = \frac{K_p}{1+\tau_p S}$  \hfill (16)

Re-Heat $\frac{x_2}{x_3} = \frac{1+K_p s}{1+\tau_p S}$  \hfill (17)

Turbine $\frac{x_3}{x_4} = \frac{1}{1+\tau_s S}$  \hfill (18)

Governor $\frac{x_4}{x_5} = \frac{1}{1+\tau_g S}$  \hfill (19)

PI Control $\frac{x_5}{x_1} = \frac{K_p S + K_i}{s}$  \hfill (20)

Inverse Laplace Transform of Equations 16-20 are taken and the equations are re-arranged into differential Equations 21-25 to find rate of change of each state variable.

\begin{align*}
\dot{x}_1 &= \frac{-1}{\tau_p} x_1 + \frac{K_p}{\tau_p} x_2 - \frac{K_p}{\tau_p} \Delta P_d \quad \hfill (21) \\
\dot{x}_2 &= \frac{-1}{\tau_t} x_2 + \frac{1}{\tau_t} \left(1 - \frac{K_p}{\tau_t}ight) x_3 + \frac{K_p}{\tau_t} x_4 \quad \hfill (22) \\
\dot{x}_3 &= \frac{-1}{\tau_t} x_3 + \frac{K_p}{\tau_t} x_4 \quad \hfill (23) \\
\dot{x}_4 &= \frac{-1}{K_p} x_1 - \frac{1}{\tau_g} x_4 - \frac{1}{\tau_g} x_5 \quad \hfill (24) \\
\dot{x}_5 &= \left(K_i - \frac{K_p}{\tau_p} x_1 + \frac{K_g K_p}{\tau_p} x_2 - \frac{K_p K_p}{\tau_p} \Delta P_d \right) \quad \hfill (25)
\end{align*}

\[ \text{Fig-3: Block Diagram Representation of Feedback Single Area Power Generating Unit} \]
Next, Equations 21-25 are transformed into state space model. The only input of the system is $\Delta P_g$ which is a unit step function. Following is state space representation of LFC shown in Figure 3:

$$A_{closed} = \begin{bmatrix}
-1 & \frac{K_p}{T_p} & 0 & 0 \\
0 & 1 & \frac{1}{T_r} & \frac{1}{T_r} \\
0 & 0 & -1 & 1 \\
\frac{1}{R T_i} & 0 & 0 & -1 & -1 \\
K_i - \frac{K_p}{T_p} & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$B_{closed} = \begin{bmatrix}
-\frac{K_p}{T_p} \\
0 \\
0 \\
0 \\
-\frac{K_p}{T_p}
\end{bmatrix}

C_{closed} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}

PI tuning is a challenging task as the parameters of the controller need to be changed until the desired requirements are met. Table 2 shows the nominal values of the PI controller used in Figure 3.

**Table 2: Controller Parameters for Feedback Single Area Generating Unit**

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>Integral Constant ($K_i$)</th>
<th>Proportional Constant ($K_p$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>2.85</td>
<td>6</td>
</tr>
</tbody>
</table>

Therefore, it is crucially important to check controllability of the system before optimizing it.

To check controllability of the system, rank of controllability matrix must be checked using Equation 26.

$$Q_c = \begin{bmatrix} B & AB & A^2B & A^3B & A^4B \end{bmatrix}$$

Rank of the matrix shown in Equation 26 is 5 which is equal to the size of the system. Hence, the system is controllable and Linear Quadratic Regulator (LQR) technique guarantees stability.

In optimization using LQR method, The Error Weighted Matrix $Q(t)$ and The Control Weighted Matrix $R(t)$ need to be selected wisely such that the system given specifications are satisfied. $Q(t)$ and $R(t)$ are symmetric matrices. The simplest way to choose $Q(t)$ matrix is to start with an identity matrix. The size of the identity matrix depends on the number of state variables used in the system modelling. Power system is an output regulator system since the objective is to keep the output $\Delta f$ close to zero. Hence, in $Q(t)$ matrix the most important element is the element that is directly related to the output. The $R(t)$ matrix is related to input of the system. A system with $n$ inputs requires $R(t)$ matrix of size $n \times n$. Increasing value of $R$ will increase the implementation cost. Hence, it is important to choose a small value for $R(t)$. Once $Q(t)$ and $R(t)$ matrices are selected, MATLAB can design the controller.

$$Q(t) = \begin{bmatrix} 14.8 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

$$R(t) = [0.2]$$

Matrix $K$ is the feedback gain matrix generated by Matlab.

$$K = \begin{bmatrix} -2.565 & -0.305 & 0.431 & 1.125 & -2.322 \end{bmatrix}$$

The optimal control law shown in Equation 27 will generate a new state matrix as shown in Equation 26 [3].

$$U(t) = K X(t)$$

$$A_{optimized} = A_{closed} - B_{closed}K$$

$A_{optimized}$ generates a feedback stable system with the following eigenvalues: -99.5547 + 0.0000i, -2.7414 + 0.1183i, -2.7414 + 0.6461i, -2.7414 + 0.6461i, -2.7414 + 0.6461i, -2.6055 + 0.0000i, -0.1183 + 0.0000i. Since all the five poles are located on the left-half plane, the closed loop system is a stable system.
6 RESULTS

Figure 4 is MATLAB generated output response of the optimized system modelled in Figure 3. Based on the simulation result, the system is stable and the steady state error is very close to zero. The settling time is 0.7 second and the percentage undershoot is about 5.54%. Hence, addition of the proposed PI controller improved the system performance significantly and the desired specifications outlined in section 3 are all met.

**Fig-4: Feedback System Output Response**

For easier comparison of the controlled and uncontrolled system, the two output responses are shown in subplots shown in Figure 5.

**Fig-5: Comparison of Controlled vs Uncontrolled Output Response**

7 CONCLUSION

In this paper, a single area power generation system was considered and its performance in terms of settling time, steady state frequency deviation and undershoot was analyzed in depth. In order to improve the open loop system performance, a conventional controller is needed to feedback the output to the input of the system. Each type of conventional controller is suitable for a specific purpose. Based on the specifications given for power generation system, a PI controller has been selected. The parameters of the controller which are integral gain and proportional gain have been tuned in MATLAB till the desired response is achieved. LQR method was used to stabilize the controlled system. Response of the controlled system had settling time of 0.7 second, undershoot of 5.45%, and zero steady state error.

REFERENCES


BIOGRAPHIES

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Advanced Optimization of Single Area Power Generation System Using Adaptive Fuzzy Logic and PI Control

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Abstract - In this paper, the open loop single area power generation system is modelled using state space representation. The output response which is frequency deviation at steady state is simulated using MATLAB. Then, Proportional Integral (PI) controller combined with Adaptive Fuzzy Logic (FL) controller is added to the system to understand the effect of conventional and modern control on system steady state output response. The performance of the system steady state output response is measured in terms of undershoot percentage, settling time, and steady state error. Simulation of the controlled system shows that PI controller combined with Adaptive FL controller are considered the most efficient, reliable, and robust type of controller in addressing power generation optimization problem. The output response of the controlled system has settling time of 2.5 second, zero steady state error, and undershoot of 0.03%.

Key Words: Optimization, Single Area Power Generation System, Adaptive Fuzzy Logic Control, PI Control, Steady State Output Response, Frequency Deviation

1 INTRODUCTION

An interconnected system called Automatic Generation Control (AGC) consists of two sub-systems: Load Frequency Control (LFC) and Automatic Voltage Regulator (AVR). AVR is responsible to regulate the terminal voltage and LFC is employed to control the system frequency. In this paper, modelling and simulation of LFC is considered for careful analysis since LFC is more sensitive to load changes compared to AVR. There is only weak coupling between the two sub-systems; hence, the overlap of load frequency and excitation voltage is negligible and the two-sub-systems can be analyzed independently. Figure 1 illustrates how AVR and LFC are interconnected in AGC system [1].

Optimizing thermal power generation system will reduce energy or fuel consumption. Fuel reduction of even a small percentage will lead to large energy saving which results into saving the environment [2]. Hence, many researchers have been interested to solve optimization problem in thermal power generation systems. There are many papers on optimization of two and three area thermal and solar power generation systems. This paper is focused exclusively on optimization of single area thermal power generation system.

2 OPEN LOOP ANALYSIS

Figure 2 shows SIMULINK generated block diagram representation of an uncontrolled generating unit which consists of a speed governor, a turbine, and a generator [1].

In some generating units, no re-heat component is available. Re-heating or feed water re-heating is used to pre-heat the water that is delivered to the steam boiler. In this paper, the considered model does not have re-heat component.

For computational simplicity in optimization problem, the case where the thermal power generation system consists of a single boiler, a single turbine, and a single generator is considered. In many real world power generation systems, the generation unit consists of multiple boilers, steam turbines, and generators. “Network Power Loss” is
referred to the loss of power from one generator to another or from one turbine to another. This loss of power is experienced in systems with multiple components of same type [3].

The inputs of the system shown in Figure 2 are \( \Delta P_c \) representing the change in speed generation by utility and \( \Delta P_d \) representing the change in load by consumer also known as disturbance. Since user has no control over load changes, \( \Delta P_d \) is considered as the only input of the system. Effect of \( \Delta P_c \) diminishes once a controller is added to the system.

The output of LFC is \( \Delta f \) which represents the change or variation in steady state frequency. The objective is to have a constant output frequency which corresponds to \( \Delta f \) being zero or very small. The value of Speed Regulation \( R \) also known as Droop is the ratio of frequency deviation (\( \Delta f \)) to change in power output of the generator.

The uncontrolled system shown in Figure 2 is modelled using state space representation shown in Equation 1 and 2 where A is the state matrix, B is the input matrix, and C is the output matrix. \( \dot{x}(t) \) is a column vector representing the state variables used in system modelling.

\[
\dot{x}(t) = Ax(t) + B \Delta P_d \quad (1)
\]

\[
y(t) = Cx(t) \quad (2)
\]

The system shown in Figure 2 has 3 integral blocks which corresponds to 3 state variables. Therefore, state matrix A must be of size 3x3. Since the system has only one input which is \( \Delta P_d \), the input matrix B must be a column vector of size 3x1. The input is taken as unit step function. The output of the system is frequency deviation of the generator which corresponds to the state variable \( x_1 \) as shown in Figure 2. The output matrix C is a row vector of size 1x3.

To obtain state space representation of the system, following transfer functions are developed:

Generator: \[
\frac{x_1}{x_2 - \Delta P_d} = \frac{1}{10s+1} \quad (3)
\]

Turbine: \[
\frac{x_2}{x_3} = \frac{1}{0.3s+1} \quad (4)
\]

Governor: \[
\frac{x_3}{\Delta P_c - 200x_4} = \frac{1}{0.1s+1} \quad (5)
\]

Inverse Laplace Transform of Equations 3-5 is taken in order to derive the differential equations 6-8.

Generator: \[
\dot{x}_1 = -0.1 \ x_1 + 0.1 \ x_2 - 0.1 \Delta P_d \quad (6)
\]

Turbine: \[
\dot{x}_2 = \frac{-1}{0.3} \ x_2 + \frac{1}{0.3} \ x_3 \quad (7)
\]

Governor: \[
\dot{x}_3 = 200 \ x_1 \cdot 10 \ x_3 \quad (8)
\]

Following is the state space representation of the uncontrolled system shown in Figure 2.

\[
A = \begin{bmatrix}
-0.1 & 0.1 & 0 \\
0 & -1 & 1 \\
-200 & 0 & -10
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
-0.1 \\
0 \\
0
\end{bmatrix}
\]

\[
C = [1 \ 0 \ 0]
\]

Figure 3 shows the steady state frequency deviation of the uncontrolled single area model illustrated in Figure 2. The system has settling time of 3 seconds, undershoot of 6% which corresponds to transient frequency of -0.06Hz, and steady state error of -0.048Hz. The system performance can definitely be improved especially with steady state frequency deviation. Hence, addition of a controller is required to control the system output response.
3 INTRODUCTION TO FUZZY LOGIC

Many industrial systems such as power generation system are time-variant and are influenced significantly by external disturbances. These disturbances cause changes in system performance. The issue of controlling and optimizing a dynamic system can be addressed using Fuzzy Logic (FL). FL has been applied to power plant optimization problems in many different ways such as optimal distribution planning, generator maintenance scheduling, load forecasting, load management, and generation dispatch problem [4].

Fuzzy Logic (FL) by Dr. Zadeh is able to provide a systematic way for the application of uncertain and indefinite models when precise definition or mathematical representation of the system is unavailable [5]. Power system is a stochastic system that is highly affected by non-internal factors such as weather and change of seasons. Modelling a stochastic and time varying system is a very challenging task [6]. FL control is able to enhance system performance without the need of mathematical modeling of the system. It is enough to have only some knowledge about the system and its behavior. This is considered as the most important advantage of FL.

FL is strongly based on linguistic interpretation of the system. It establishes linguistic rules called membership rules to determine a systematic way of modelling the power system. Membership rules or membership functions are fundamental part of FL. Let X be a set of objects whose elements are denoted by x. Membership in a subset A of X is the membership function \(\mu_A\) [7].

\[
A = \{(x, mA(x)), x \in X\}
\]  

(9)

Fuzzy sets are functions that map a value that might be a member of a set to a number between zero and one indicating its actual degree of membership. Fuzzy sets produce a membership curves.

4 DESIGN OF FUZZY LOGIC CONTROL

There exist two types of FL control:

1. Static Fuzzy Control: This controller is used when structure and parameters of the FL controller are fixed and do not change during real time operation [6].

2. Adaptive Fuzzy Logic Control: This controller is used when structure and parameters of FL controller change during real time operation. This type of controllers is more expensive to implement; however, it results in better performance and less mathematical information about the system is needed [6].

The Objective of using Adaptive FL control in optimization problem is to minimize or maximize an objective function \(f(x)\) in the presence of uncertainties, unknown variations, and constraints. Adaptive FL control is difficult to analyze because it is time varying; however, it ensures more desired performance in comparison to Static FL control.

Figure 4 shows block diagram of a FL controller which consists of the following 4 components [6]:

1. Rule-Base: It holds knowledge in terms of set of linguistic rules called fuzzy rules defined by the user. Fuzzy rules are built using membership functions.

2. Inference Mechanism: It selects relevant rules at the current time and decides what the output of the controller should be. Output of the controller \(u(t)\) is input of the plant. In power system, the plant is the uncontrolled/open loop system.

3. Fuzzification: It converts controller’s input into information that can be used in inference mechanism.

4. Defuzzification: It converts the output of the controller into values that can be used by the plant. Fuzzification and defuzzification are inverse processes.

![Fuzzy Logic Controller Block Diagram]

Fig-4: Fuzzy Logic Controller Block Diagram

From Figure 4 it can be observed that FL controller has two inputs as shown below:

\[
e(t) = r(t) - y(t) > ACE
\]  

(10)

\[
\frac{d}{dt} e(t) = e'(t) > A\dot{C}E
\]  

(11)

If reference input \(r(t)\) is zero, then inputs of FL controller will be:

\[
e(t) = -y(t) > ACE
\]  

(12)
\[
\frac{d}{dt} e(t) = e(t) = -\dot{y}(t) > A\dot{CE}
\] (13)

To create a FL controller, following steps must be taken [7]:

1. Define the controller inputs:
   Error = set point – process output
   Error change = current error – last error
2. Define the controller output:
   Output = controller output – plant input
3. Create membership functions:
   Membership functions are developed based on designer’s knowledge and experience about the system. Membership functions are used to define fuzzy rules.
4. Create fuzzy rules:
   Fuzzy rules are defined using IF-THEN relationships. They need to be manually tuned or adjusted in order to obtain the desired system response.
5. Simulate the results:
   SIMULINK can be used to simulate the steady state output response.

The inputs of FL control shown in Equation 12 and 13 can be classified into membership functions. In this paper, the inputs are classified into 7 membership functions:

NB: Negative Big, NM: Negative Medium, NS: Negative Small, ZZ: Zero, PS: Positive Small, MP: Positive Medium, PB: Positive Big. These 7 membership functions lead to 49 fuzzy rules as shown in Table 1.

Membership functions must be symmetrical and each membership function overlaps with the adjacent functions by 50%. Membership functions are normalized in the interval [-L, L] which is symmetric around zero [6].

The two inputs are combined together using AND operation. Table 1 is constructed based on experience and knowledge known about power generation systems.

### Table-1: Fuzzy Logic Membership Rules

<table>
<thead>
<tr>
<th>(e(t))</th>
<th>AND</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZZ</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZZ</td>
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<td>ZZ</td>
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<td>ZZ</td>
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<td>PB</td>
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<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

Fuzzy Inference System (FIS) in MATLAB is used to design a FL controller based on the fuzzy rules defined in Table 1. The controller output is the input of the plant. Centeroid method is used to defuzzificiate the values. The range of each membership function is defined based on human’s experience and knowledge about power generation system. There are various types of membership functions used in FIS such as triangular, trapezoidal, PI-curve, bell-shaped, and S-curved [8]. In this paper, triangular membership functions are used.

### 5 FEEDBACK ANALYSIS

To have a stable system after implementation of FL controller, controllability and observability are very important factors. Implementation of FL controller guarantees a closed loop globally stable system if the corresponding open loop system is controllable, observable, and stable [6]. Hence, the system shown in Figure 2 which has order of 3 is checked for the above conditions:

1. The system is controllable. The rank of controllability matrix is 3.
2. The system is observable. The rank of observability matrix is 3.
3. The system is stable since all the three poles lie on the left half plane. The poles are \(-10.8290 + 0.0000i\), \(-1.3022 + 2.1837i\), \(-1.3022 - 2.1837i\).

FL controllers are reliable and PI controllers are robust. Combination of the two types of controllers can result in a reliable, efficient, and robust controller design. Figure 5 is the block diagram representation of the feedback single area system generated in SIMULINK. The Adaptive FL and PI controller are combined together in parallel to improve the system behavior. This controller is called Adaptive FL and PI controller. The system shown in Figure 5 has only one input \(\Delta P_d\) and one output \(\Delta f\).
Parameters of the PI controller have been tuned carefully to ensure performance improvement. Table 2 shows the parameters of the PI controller implemented in Figure 5. Equation 14 shows the transfer function of a PI controller where $U(S)$ is the controller output, $E(S)$ is the controller input, $K_p$ is the controller proportional constant, and $K_i$ is the controller integral constant.

$$\frac{U(S)}{E(S)} = K_p + \frac{K_i}{s} \quad (14)$$

**Table-2: PI Controller Parameters for Feedback Single Area Generating Unit Combined with Adaptive FL Controller**

<table>
<thead>
<tr>
<th>Proportional Constant ($K_p$)</th>
<th>Integral Constant ($K_i$)</th>
<th>Integral Gain ($K_g$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.25</td>
<td>-3.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

6 RESULT

Figure 6 shows the steady state frequency response of the controlled system after implementation of Adaptive FL controller described in Table 1 combined with PI controller described in Table 2.

Reliability of FL controller and robustness of PI controller are combined together to construct a well behaved controlled system. As shown in Figure 6, the system settling time is reduced to 2.5 seconds and the steady state error is completely removed; this is the effect of integral controller. The undershoot percentage is about 0.03%. This is a well behaved system since all the parameters have been improved significantly.

The primary objective of having controller in a power generation system is to eliminate or minimize the steady state frequency deviation. In power generation system, followings are considered as standard performance specifications of a well-behaved system:

1. Steady state frequency error should not be more than $\pm 0.01$HZ.
2. Settling time should be less than 3 seconds.
3. The maximum overshoot/undershoot should not be more than 6% which corresponds to transient frequency of $\pm 0.06$HZ.

**Fig-6: Steady State of Feedback Single Area Model after Implementation of FL Control**

7 CONCLUSION

Adaptive FL controller and a suitable PI controller have been combined to improve the system performance of a single area power generation system. The membership functions for Adaptive FL controller and the parameters of PI controller have been tuned to ensure the specifications are met.

Adaptive FL controller is robust, reliable, and most commonly used in solving optimization problems. Table 3 compares the performance factors of uncontrolled vs controlled single area system.
Table-3: Comparison of Uncontrolled vs. Controlled Power Generation System

<table>
<thead>
<tr>
<th></th>
<th>Settling Time (Sec)</th>
<th>Steady State Error (HZ)</th>
<th>Undershoot (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled</td>
<td>3</td>
<td>-0.048</td>
<td>6</td>
</tr>
<tr>
<td>Controlled</td>
<td>2.5</td>
<td>0</td>
<td>0.03</td>
</tr>
</tbody>
</table>

BIOGRAPHIES

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