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LOAD FREQUENCY CONTROL IN FOUR AREA POWER SYSTEM USING FUZZY LOGIC PI CONTROLLER

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Abstract—Variations in load bring about drifts in frequency and voltage which in turn leads to generation loss owing to the line tripping and blackouts. These drifts might be reduced to the smallest possible value by automatic generation control (AGC) also known as Automatic load frequency control (ALFC) which constitutes of two sections viz. load frequency control (LFC) along with automatic voltage regulation (AVR). Here simulation evaluation is done to know the working of LFC by building models in SIMULINK which helps us to comprehend the principle behind LFC including the challenges. The four-area system is being taken into consideration for observing Load Frequency Control in a multi-area Power System. In this project one of the modern control techniques is adopted to implement a reliable stabilizing controller. A serious attempt has been undertaken aiming at investigating the load frequency control problem in a power system consisting of four power generation units and multiple variable load units. The main aim will be to examine the robustness and reliability of using Fuzzy controller among the conventional PI controller is examined through simulation in MATLAB using SIMULINK package.

I. INTRODUCTION

Power systems are large and complex electrical networks consisting of generation, transmission, and distribution networks along with loads that are being distributed throughout the network. In the power system, the load on system keeps changing from time to time according to the needs of the consumers. So, there is a need of properly designed controllers for the regulation of the system variations in order to maintain the stability of the power system as well as guarantee its reliable operation.The rapid growth of the industries has further led to the increased complexity of the power system. Frequency mainly depends on active power and the voltage mainly depends on reactive power. So, the control difficulty in the power system may be divided into two parts. One is related to the control of the active power along with the frequency whereas the other is related to the reactive power along with the regulation of voltage. The active power control and the frequency control are generally known as the Automatic Load Frequency Control.

1.1 Concept of control area

A control is interpreted as a system where we can apply the common generation controlscheme or the load frequency control scheme. Usually, a self-governing area is made as reference to control area. Electrical interconnection is very strong in every control area when compared to the ties in the midst of the adjoining areas. Within a control area all the generators move back and forth in logical and consistent manner which is depicted by a particular frequency. Difficulty of a bulky interrelated power system have been investigated by dividing the whole system into number of control areas and termed as multi-area.

In the common steady state process, every control area must try to counterbalance the demand in power by the flow of tie-line power through the interconnected lines. Generally, the control area encompasses only restricted right to use to the information of the total grid and they are able to manage their own respective buses however they cannot alter the parameters at the unknown buses directly. But an area is alert of the dominance of its nearby areas by determining the flow in and flow out of power by the side of its boundaries which is commonly known as the tie-line power. In every area the power equilibrium equations are computed at the boundaries, taking into consideration the extra load ensuing from the power that is being exported. Later on, the areas work out on the optimization of frequency deviation.

1.2 Objectives related to control areas

The major objectives relating to control areas are as follows:

- Each control area should accomplish its individual load demand in addition to thepower transfer all the way through the tie-lines based on communal agreement.
- Every control area must have adjustable frequency according to the control.
- To take care of the required megawatt power output of a generator matching withthe changing load.
- To take care of the appropriate value of exchange of power linking control areas.
- To facilitate control of the frequency for larger interconnection.

1.3 Advantages of automatic load frequency control in multi-area system

The Automatic Load Frequency Control helps to diminish the transient deviationsin addition to making the steady state error to zero.

It also holds system frequency at a specified value.

The Automatic Load Frequency Control also collaborate in keeping the net powerinterchange between the pool members at the predetermined values.

1.4 Need for the inter-connection of areas

Earlier electric power systems were usually operated as individual units. But a needfor the interconnection was realized due to the following reasons:

- There was a demand for larger bulk of power with increased reliability so there wasinterconnection of neighboring plants.
- It is also beneficial economically since fever machines are necessary as reserve for action at peak loads (reserve capacity) and less machines are needed to be run without load to take care of sudden rise and fall in load (spinning reserve).
- Due to these reasons, several generating units relate to each other forming state grids,regional grids, and national grids respectively. Also, for the control of power flow in these grids the load dispatch centres are needed.

II. LITERATURE SURVEY

- IlhanKocaarslan&Ertugrul Cam,2005: This paper explains about theimplementation of PI and Fuzzy based picontroller only on two area systems and thetwo area systems use conventional type ofpowersystems.
- Dong-JingLee,LiWang,2008: This paper briefly talks about how tointegraterenewableenergypowersystemslike solar photo voltaic, wind, geo thermaland fuel cells to non-renewable energysourcepower systems.
- Adil Usman and BP Divakar, 2012: In this paper, a simulation study is carried out to understand the operation of load frequency controller by developing models in SIMULINK. The simulation study helps us understand the principle and challenges behind load frequency controller.
- Yogendra Arya, 2019: In this paper, it uses Fuzzy PI controller for load frequency control of Aqua ElectrolyserFuel cell units and solar PV is introduced. It connects two areas fuel cells system to solar PV, and it does not use any other non-renewable energy systems.
- Surya Prakashand S K Sinha,2012: This paper mainly focuses on load frequency control of three area and four area systems by using Fuzzy based PID controller. PID deals with higher order capacitive processes, whereas PI can be used to avoid large disturbances.
- Kritika Rajanwal, Ritu Shakya, Sanskriti Patel, Rakesh Kumar, 2014: This paper talks about the advantages and disadvantages of PI, PID and Fuzzy logic controller.
- S.M.AbdElazim , E. S. Ali, 2016: In this paper, it uses PI controllers for load frequency control of hybrid system composing of photovoltaic (PV) system and thermal generator is introduced. It integrates only PV system to thermal power system, and it does not use any other renewable energy systems.

III. DYNAMICS OF THE POWER SYSTEM

3.1 Dynamics of the power system

If the generator is connected to a number of different loads in a power system, then the generator frequency and speed changes with the governor characteristics as the load changes. If it is not required to keep the frequency constant in a power system, then the operator is not required to change the setting of the generator. But if constant frequency is required the operator can adjust the speed of the turbine by changing the governor characteristics when required. If a change in load is taken care by two generating stations running at parallel, then the complexity of the system increases. Suppose there are two generating stations (say A and B) that are connected to each other by tie line. The possibility of sharing the load by two machines is as follow:

- If the change in load is either at A or at B and the generation of A is alone asked to regulate so as to have constant frequency, then this kind of regulation is called Flat frequency regulation.
- The other possibility of sharing the load the load is that both A and B would regulate their generations to maintain the constant frequency. This is called Parallel frequency regulation.
- The third possibility is that the change in the frequency of a particular area is taken care by the generator of that area thereby the tie-line load remains the same. This method is known as Flat tie-line loading control.
- In Selective Frequency control each system in a group is takes care of the load changes on its own system and does not aid the other systems un the group for changes outside its own limits.
- In Tie-line load-bias control all the power systems in the interconnection aid in regulating frequency regardless of where the frequency change originates. The equipment consists of a master load frequency

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controller and a tie line recorder measuring the power input on the tie as for the selective frequency control.

The error signal i.e., Δf and ΔP tie are amplified, mixed and transformed to real power command signal, ΔPV which is sent to the prime mover to call for an increase in the torque. The prime mover shall bring about a change in the generator output by an amount ΔPG which will change the values of Δf and ΔP tie within the specified tolerance. The first step to the analysis of the control system is the mathematical modelling of the system's various components and control system techniques.

3.1. Mathematical modelling of various components

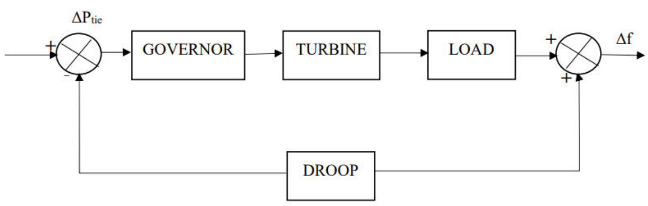

Fig. 3.1; Block diagram of Automatic load frequency control

Mathematicalmodellingofprimemover

The source of power generation is commonly known as the prime mover. It may behydraulic turbines at waterfalls, steam turbines whose energy comes from burning ofthe coal, gas and other fuels. Turbines are used in power systems for the conversion ofthe natural energy, like the energy obtained from the steam or water, into mechanicalpower (Pm) which can be conveniently supplied to the generator. There are threecategories of turbines usually used in power systems; non-reheat, reheat in addition tohydraulic turbines, each and every one of which may be modelled and designed bytransferfunctions.

When sunlight strikes on photovoltaic solar panels solar electricity is produced. That is why this is also referred to as photovoltaic solar, or PV solar.

We have non-reheat turbines which are represented as first-order units where the delayin time known as time delay takes place between the interval during switching of thevalveandproducingthetorqueintheturbine.Designofreheatturbinesisdonebyusingsecond-order units as there are different stage because of soaring and low down of thepressure of the steam. Because of the inertia of the water hydraulic turbines are treatedas non-minimum phase units.

Theturbinemodelrepresentschangesinthesteamturbinespoweroutputtovariationinthe opening of the steam valve. Here we have considered a non-reheat turbine with asinglegainfactor,1andtimeconstant,T_t.Inthemodeltherepresentationoftheturbineis related to the changes in mechanical power output ΔP_m to the changes in the steamvalveposition ΔPV.

$$\frac{\Delta Pm(s)}{\Delta Pm(s)}=\frac{1}{1+sTt}\text{...........(3.1)}$$

WhereΔPV(s)= theinput totheturbine.

$\Delta P_m(s)$=the output fromthe turbine.

3.1.2 Mathematical Modelling of Generator

Generators receive mechanical power from the turbines and then convert it to electrical power. However, our interest concerns the speed of the rotor rather than the power transformation. The speed of the rotor is proportional to the frequency of the power system. We need to maintain the balance amid the power generated and the power demands of the load because the electrical power cannot be stored in bulk amounts. When there is a variation in load, the mechanical power given out by the turbine does not counterpart the electrical power generated by the generator which results in an error which is being integrated into the rotor speed deviation (Δω). Frequency bias Δf = 2π Δω. The loads of the power can be divided into resistive loads (PL), which may be fixed when there is a change in the rotor speed due to the motor loads which change with the speed of the load. If the mechanical power does not change then the motor loads shall compensate the change in the load at a rotor speed which is completely dissimilar from the planned value. Applying the swing equation of a synchronous machine to small perturbation, we have

$$\frac{2H}{\omega}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e \text{.........(3.2)}$$

Or in terms of small deviation in speed, we have,

$$\frac{d\Delta\frac{\omega}{\omega_s}}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e) \text{............(3.3)}$$

Taking Laplace Transform, we obtain,

$$\Delta\Omega(s) = \frac{1}{2H_s}[\Delta P_m(s) - \Delta P_e(s)] \text{............(3.4)}$$

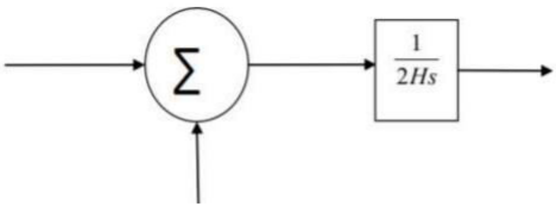

Fig.3.2: Mathematical Modelling Block diagram for Generator

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3.1.3 Mathematical Modelling of Governor

Governors are employed in power systems for sensing the bias in frequency which is the result of the modification in load and eliminate it by changing the turbine inputs such as the characteristic for speed regulation (R) and the governor time constant (Tg). If the change in load occurs without the load reference, then some part of the alteration can be compensated by adjusting the valve/gate and the remaining portion of the alteration can be depicted in the form of deviation in frequency. LFC aims to limit the deviation in frequency in the presence of changing active power load. Consequently, the load reference set point can be utilized for adjusting the valve/gate positions so as to cancel all the variations in load by controlling the generation of power rather than ensuing deviation in frequency. Mathematically,

$$\Delta Pg\ (s) = \Delta Pref(s) - \frac{1}{R}\Delta f(s) \ \ldots\ldots\ldots\ldots(3.5)$$

Where $\Delta P_g(s)$ = governor output.

$\Delta P_{ref}(s)$ = reference signal.

R = regulation constant or droop.

$\Delta F(s)$ = frequency deviation due to speed.

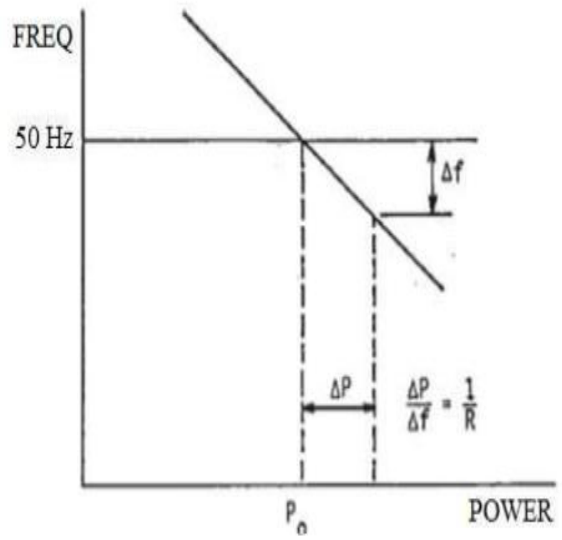

Fig.3.3: Graphical Representation of Regulation by Governor

3.1.4 Mathematical modelling of Load

The load on the power system constitutes of a diversity of electrical devices. The loads that are resistive, for example lighting purposes and also heating loads are not dependent on frequency, but the motor loads are composite of the resistive and inductive components and are responsive to frequency depending on the speed-load characteristics as shown below;

$$\Delta P_e = \Delta P_L + D\,\Delta\omega \ \ldots\ldots\ldots\ldots(3.6)$$

Where ΔP_L = non-frequency responsive load change.

$D\,\Delta\omega$ = frequency responsive load change.

$$D = \frac{\%\ \text{Change in load}}{\%\ \text{Change in frequency}} \ \ldots\ldots\ldots\ldots(3.7)$$

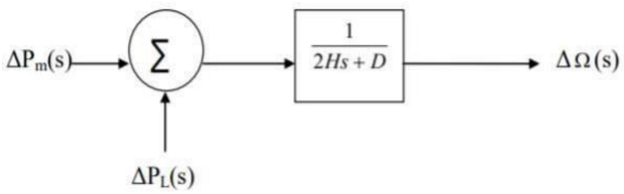

Fig.3.4: Mathematical modelling block diagram for Load

Combining all the block diagrams from earlier block diagrams for a single are system we get the following block diagram;

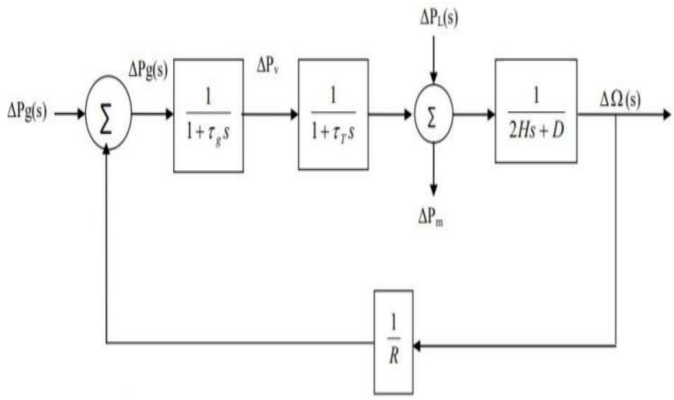

Fig.3.5: Block Diagram of single system consisting of Generator, Load, Prime Mover and Governor

3.1.5 Mathematical modelling of tie-lines

Various areas can be connected with one another by one or more transmission lines in an interconnected power grid through the tie-lines. When two areas are having totally different frequencies, then there's an exchange of power between the two areas that are linked by the tie lines. The power due to tie-line trades in area i and area j (ΔPij) and the tie-line synchronizing torque coefficient (Tij). Thus, we can also say that the integral of the divergence in frequency among the two areas is an error in the power due to tie-line. The objective of tie-lines is to trade power with the systems or areas in the neighbourhood whose costs for operation create such transactions cost-effective. Moreover, even though no power is being transmitted through the tie-lines to the neighbourhood systems/areas and it so happens that suddenly there is a loss of a generating unit in one of the systems. During such type of situations all the units in the interconnection experience an alteration in frequency and

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because of which the desired frequency is regained. Let us consider that area 1 is having surplus power and it transfers power to the area 2 by the tie-line.

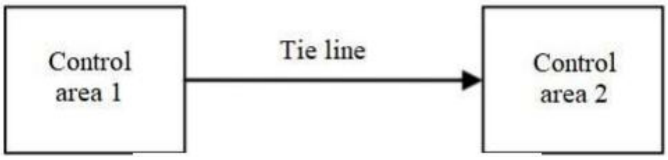

Fig.3.6: Power transfer through tie lines.

P12 = power exchanged from area 1 towards area 2 via tie lines. Then the power transfer equation of the tie-line is specified as follows;

$$P_{12} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1 - \delta_2) \; \ldots\ldots\ldots\ldots(3.8)$$

$$\Delta P_{12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1 - \delta_2)(\Delta\delta_1 - \Delta\delta_2) \; \ldots\ldots\ldots\ldots(3.9)$$

Where δ1 and δ2 = power angles of end voltages V1 and V2 of corresponding machine of the two areas.
X12 = reactance of the tie line.
|V1| and |V2| = magnitude of voltages of area 1 and area 2.
The sequence of the subscripts depicts that the flow of power due to the tie lines is positive in the direction from 1 to 2. For little deviation in the angles δ1 and δ2 changes by Δδ1 and Δδ2, the tie line power changes are as follows;

$$\Delta P_{12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1 - \delta_2)(\Delta\delta_1 - \Delta\delta_2)\ldots\ldots\ldots\ldots(3.10)$$

$$\Delta P_{12} = T^0(\Delta\delta_1 - \Delta\delta_2) \; \ldots\ldots\ldots\ldots(3.11)$$

$$\Delta P_{12}(s) = \frac{2\pi T^0}{s}[\,\Delta F_1(s) - \Delta F_2(s)\,] \; \ldots\ldots\ldots\ldots(3.12)$$

$$T^0 = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1 - \delta_2)\ldots\ldots\ldots\ldots(3.13)$$

In a control area which is isolated, the incremental power (ΔPG – ΔPD) is the rate of rise of preserved kinetic energy due to rise in the load followed by a rise in the frequency. The power due to the tie-lines for each area is as below;

$$\Delta P_1(s) = \Delta P_{12}(s) + a_{31}\Delta P_{31}(s)\ldots\ldots\ldots\ldots(3.14)$$

$$\Delta P_2(s) = \Delta P_{23}(s) + a_{12}\Delta P_{12}(s)\ldots\ldots\ldots\ldots(3.15)$$

$$\Delta P_3(s) = \Delta P_{31}(s) + a_{23}\Delta P_{23}(s)\ldots\ldots\ldots\ldots(3.16)$$

Control of tie line bias is utilized to get rid of the steady state error because of frequency plus the exchange of the power due to tie-lines. This shows that all of the control areas should put in their share in frequency control, besides dealing with their own particular total interchange of power.
Let, ACE1 = area control error of area 1
ACE2 = area control error of area 2
ACE3 = area control error of area 3
ACE1, ACE2 and ACE3 are shown as linear arrangement of frequency along with tie-line power error as follows;

$$ACE_1 = \Delta P_{12} + b_1\Delta f_1\ldots\ldots\ldots\ldots(3.17)$$

$$ACE_2 = \Delta P_{23} + b_2\Delta f_2\ldots\ldots\ldots\ldots(3.18)$$

$$ACE_3 = \Delta P_{31} + b_3\Delta f_3\ldots\ldots\ldots\ldots(3.19)$$

Where b1, b2 and b3 are known as bias in area frequency of area 1, area 2 and area 3 respectively. Area control error (ACE) is negative when the net power flow output from an area is very small or else when the frequency has dropped or both. During such situations we need to increase the generation.

3.1.6 Mathematical modelling of wind turbine

Electrical power generated by wind turbine generator rely upon wind speed. The blades of wind turbine are used to accumulate energy from wind in the form of kinetic energy. This kinetic energy drives the shaft interconnected to generator that produces electric power. Thus, it is self-evident that the electrical output confides on mechanical output which is dependent on wind speed. The mechanical output of wind turbine with reference to wind speed is outlined by a non-dimensional curve. The relation between output mechanical power and wind speed is obtained,

$$P_{wind-turbine} = \frac{1}{2}\,\rho\,\mathrm{Ar}\,\mathrm{Cp}\,V^3{}_{wind}\ldots\ldots\ldots\ldots(3.20)$$

Where Pwind-turbine denotes output mechanical power of wind turbine, ρ denotes air density, Ar denotes area swept by blades, Cp denotes power co-efficient and Vwind denotes wind speed. The transfer function of wind turbine generator is summarized as first-order lag function.

$$TF_{wind} = \frac{\Delta P_{WTG}}{\Delta P_{wind}} = \frac{K_{WTG}}{1+sT_{WTG}}\ldots\ldots\ldots\ldots(3.21)$$

where, *K*wtg is wind-turbine power fraction and *T*wtg is wind-turbine generator system time constant.

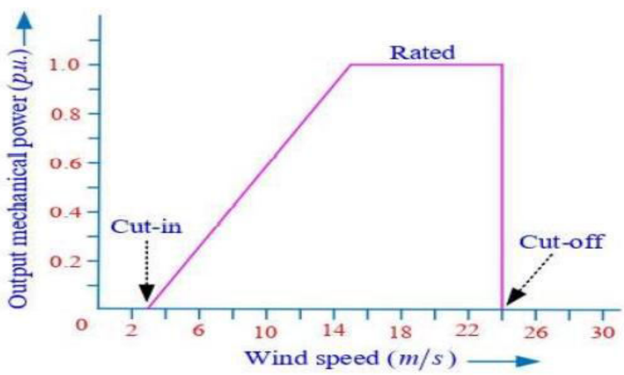

Fig.3.7: Characteristics curve of wind turbine with reference to wind speed

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3.1.7 Mathematical modelling of PV cell

The PV cell comprises of current source having non-linear voltage current characteristics altering with intensity of sunlight and temperature. The equivalent electrical circuit of solar cell is as shown consisting of current source whose magnitude is proportional to intensity of sunlight in parallel with diode along with a series contact resistance. The transfer function of PV system incorporated in power system is summarized.

$$TF_{PV} = \frac{\alpha + s\beta}{s^2 + s\gamma + \delta} \ldots\ldots\ldots\ldots(3.22)$$

where, α, β, γ and δ are PV grid parameters.

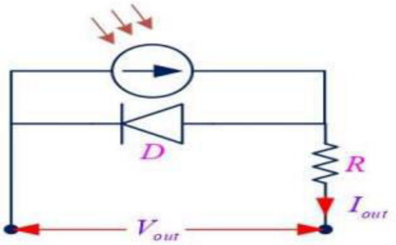

Fig.3.8: Equivalent electrical circuit of solar cell

3.1.8 Mathematical modelling of Hydrogen

Aqua Electrolyser Fuel Cell The operation of HAE-FC power system is simple and eco-friendly making it to be more efficient. Initially in HAE-FC, water is electrolyzed into hydrogen and oxygen using hydrogen aqua electrolyser. Then, the obtained hydrogen from this process is compressed, packed and finally transported to fuel cell through pipelines. In FC, hydrogen is fed to cathode and air is fed to anode while the catalyst at anode splits hydrogen molecules into electrons and protons. These electrons flow along the path in an external closed circuit developing electricity. The transfer function of HAE and FC are obtained,

$$TF_{HAE} = \frac{K_{HAE}}{1+sT_{HAE}} \ldots\ldots\ldots\ldots(3.23)$$

$$TF_{FC} = \frac{K_{FC}}{1+sT_{FC}} \ldots\ldots\ldots\ldots(3.24)$$

where, *K*hae and *K*fc are gain parameter of HAE and FC respectively, THAE and TFC are time constants of HAE and FC respectively.

3.1.9 Mathematical Modelling of Geothermal Power System

In context of electrical power generation, geothermal power is reliable as well as potential source. The characteristics of geothermal power system are much similar to that of conventional non-reheat thermal plant except that boiler component is absent. The modelling of geothermal governor and turbine drive to first order transfer function obtained as follows.

$$TF_{GTG} = \frac{1}{1+sT_{GTG}} \ldots\ldots\ldots\ldots(3.25)$$

$$TF_{GTT} = \frac{1}{1+sT_{GTT}} \ldots\ldots\ldots\ldots(3.26)$$

where, *T*gtg and *T*gtt are time constants of geothermal governor and turbine respectively.

3.2 Parallel Operation of Generators

If there are a number of units for power generation to be operational in parallel in that particular area, a counterpart generator may be created for ease. The corresponding generator inertia constant (Meq), damping constant of load (Deq) and characteristics for frequency response (Beq) may be shown. Tie line flows as well as frequency droop represented for interconnecting power areas may be combined characteristics derived from parallel action of generators. Each one of the areas could retain its speed ω = 2πf, then a load general to both areas; by superposition include the voltage at the terminal. Two generators paralleled include completely diverse governor speed-droop characteristics. Since they may be in parallel, power exchange linking them insists them to synchronize at a general frequency.

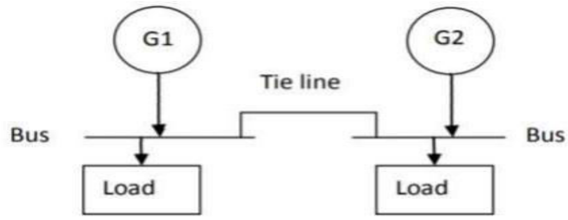

Fig.3.9: Block diagram for parallel operation of generators

3.3 Mathematical Modelling of Automatic Load Frequency Control

Modelling for the change in frequency; Let us consider an automatic load frequency control loop of a system which is isolated intended for the examination of the steady state and dynamic responses. The figure is as shown in the Fig. 3.1

3.3.1 Steady state analysis

Let ΔPref (s) be the setting for the speed changer and ΔPD(s) be the alteration in demand of the load. Considering a simple

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situation where the speed changer might have constant setting i.e., Δpref (s) = 0 as well as there is change in the load demand. This may be known to be free governor operation. For such a process the steady modification in the system frequency for a step change in load i.e.,

$$\left[\left\{\Delta P_{ref}(s) - \frac{1}{R}\Delta F(s)\right\}\frac{K_T}{(1+sT_H)(1+sT_T)} - \Delta P_D(s)\right]\frac{K_P}{(1+sT_P)} = \Delta F(s) \text{ ....(3.27)}$$

This implies that,

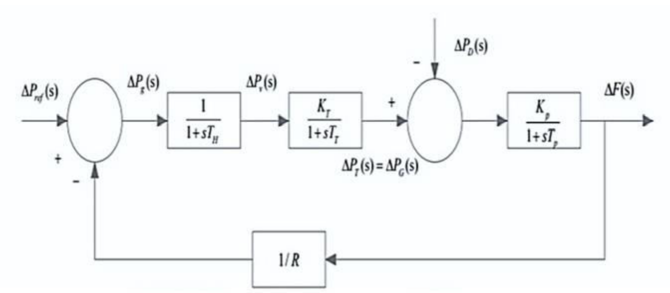


Fig.3.10: Automatic load frequency control loop

$$\Delta F(s) = \frac{\frac{-K_P\,\Delta P_D(s)}{s(1+sT_P)}}{\frac{\frac{K_T K_P}{R}}{(1+sT_H)(1+sT_T)(1+sT_P)}} \text{ ....(3.28)}$$

After simplification we get,

$$\Delta F(s) = -\frac{\Delta P_D}{\beta} \text{ ....(3.29)}$$

Where β is the area frequency response characteristics

3.3.2 Dynamic analysis

For a step change in load,

$$\Delta F(s) = \frac{\frac{-K_P\,\Delta P_D(s)}{s(1+sT_P)}}{\frac{\frac{K_T K_P}{R}}{(1+sT_H)(1+sT_T)(1+sT_P)}} \text{ ....(3.30)}$$

Assuming amplifier and turbine response to be instantaneous i.e. TT=TH=0 and KT=1, we have,

$$\Delta F(s) = \frac{-K_P}{(1+sT_P)+K_P/R}\,\frac{\Delta P_D}{s} \text{ ....(3.31)}$$

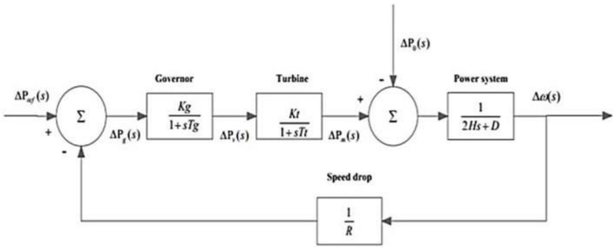
After simplification we get,

$$\Delta F(s) = \frac{-RsK_P(1+sT_H)(1+sT_T)}{Rs(1+sT_H)(1+sT_T)(1+sT_P)+(s+RK_i)K_p}\,\frac{\Delta P_D}{s} \text{ ....(3.32)}$$

IV. DESIGNMODELFORPOWERSYSTEMUSINGCONTROLLER

1.Design Model for Using Power System Controller

Fig 4.1 shows the Automatic Load Frequency Control



loop. The frequency whichchanges with load is contrasted with reference speed setting. The frequency can be setto the desired value by making generation and demand equal with the help of steamvalvecontrollerwhichregulatesteamvalveandincreasespoweroutputfromgenerators.Itservestheprimary/basicpurposeofbalancingtherealpowerbyregulatingturbineoutput (ΔP_m) according to thevariationin load demand (ΔP_D).

Fig.4.1:Modelofsingle area

The transfer function of the model of the single area system as shown in Fig 4.1 is asbelow;

$$K\,G(s)H(s) = \frac{1}{R}\,\frac{1}{(2H_s+D)(1+\tau_g s)(1+\tau_T s)} \text{ ....(4.1)}$$

$$\frac{\Delta\omega(s)}{-\Delta P_L(s)} = \frac{(1+\tau_g s)(1+\tau_T s)}{(2H_s+D)(1+\tau_g s)(1+\tau_T s)+{}^{1}/_{R}} \text{ ....(4.2)}$$

$$\Delta\omega(s) = -\Delta P_0(s)\,T(s) \text{ ....(4.3)}$$

For the case with load which is not sensitive to frequency load (D=0);

$$\Delta\omega_{ss} = (-\Delta P_0)R \text{ ....(4.4)}$$

From the above equations, we can get the steady state value of new system frequency which is less than the initial value. But we have to make the frequency drift (Δω) to zero or to an acceptable value with the help of controller (which in turn changes the ΔPref) for stable operation. This is shown above in Fig.4.1 Let us

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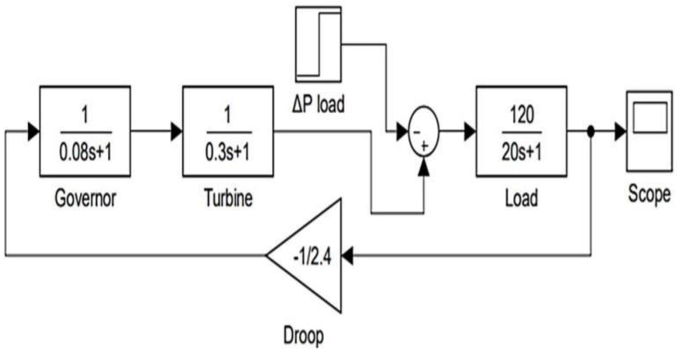
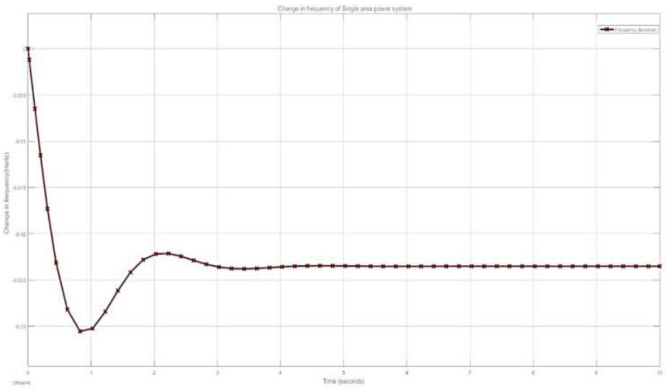


MATLABmodelof Single Area PowerSystem

Fig.4.2:MATLABmodelofsingle areapowersystem

Dueto changeinload,thereischangeinthesteadystatefrequency(Δω),sothereis aneedforcontroller apart from the existing feedback loop to convey the frequency to the initial valuebefore theloaddisturbanceoccurs.



SimulinkresultofMATLAB model

Fig.4.3: Response of Single area power system

4.1. Controllers

A controller is a mechanism that seeks to minimize the difference between the actual value of a system (i.e., the process variable) and the desired value of the system (i.e., the set point). Controllers are a fundamental part of control engineering and used in all complex control systems.

The important uses of the controllers include:

1. Controllers improve the steady-state accuracy by decreasing the steady state error.
2. As the steady-state accuracy improves, the stability also improves.
3. Controllers also help in reducing the unwanted offsets produced by the system.
4. Controllers can control the maximum overshoot of the system.
5. Controllers can help in reducing the noise signals produced by the system. 6. Controllers can help to speed up the slow response of an overdamped system.

4.1.1 Types of Controllers

There are two main types of controllers:

1.Continuous controllers

2.Discontinuous controllers

In discontinuous controllers, the manipulated variable changes between discrete values. Depending on how many different states the manipulated variable can assume, a distinction is made between two positions, three position, and multi-position controllers. Compared to continuous controllers, discontinuous controllers operate on very simple, switching final controlling elements.

The main feature of continuous controllers is that the controlled variable (also known as the manipulated variable) can have any value within the controller's output range. Now in the continuous controller theory, there are three basic modes on which the whole control action takes place, which are:

1. Proportional controllers
2. Integral controllers
3. Derivative controllers

We use the combination of these modes to control our system such that the process variable is equal to the set-point (or as close as we can get it). These three types of controllers can be combined into new controllers which are called as conventional controllers.

1. Proportional and integral controllers (PI Controller)
2. Proportional and derivative controllers (PD Controller)
3. Proportional integral derivative control (PID Controller)

4.1.2 Proportional Controller (P Controller)

All controllers have a specific use case to which they are best suited. We cannot just insert any type of controller at any system and expect a good result. There are certain conditions that must be fulfilled.

For a proportional controller, there are two conditions and are as follows.

1. The deviation should not be large i.e., there should not be a large deviation between the input and output.
2. The deviation should not be sudden.

The name itself indicates that in a proportional controller the output also called the actuating signal is directly proportional to the error signal. Now let us analyse the proportional controller

mathematically. As we know in proportional controller output is directly proportional to the error signal, writing this mathematically we have,

$A(t)\ \alpha e(t)$

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Removing the sign of proportionality, we have

$$A(t) = K_p * e(t) \ldots\ldots\ldots\ldots(4.5)$$

Where Kp is proportional constant also known as controller gain. It is recommended that Kp should be kept greater than unity. If the value of Kp is greater than unity (>1), then it will amplify the error signal and thus the amplified error signal can be detected easily.

Advantages of Proportional Controller:

1. The proportional controller helps in reducing the steady-state error, thus makes the system more stable.
2. The slow response of the overdamped system can be made faster with the help of these controllers.

Disadvantages of Proportional Controller:

1. Due to the presence of these controllers, we get some offsets in the system.
2. Proportional controllers also increase the maximum overshoot of the system.

4.1.3 Integral Controller (I Controller)

The name itself indicates that in integral controllers the output also called the actuating signal is directly proportional to the integral of the error signal. Now let us analyse integral controller mathematically. As we know in an integral controller output is directly proportional to the integration of the error signal, writing this mathematically we have,

$$A(t) \, \alpha \int_0^t e(t)\, dt$$

Removing the sign of proportionality, we have

$$A(t) = K_i * \int_0^t e(t)\, dt \ldots\ldots\ldots\ldots(4.6)$$

Where Ki is an integral constant also known as controller gain. The integral controller is also known as reset controller.

4.1.4 Derivative Controller (D Controller)

The name itself indicates that in a derivative controller the output also called the actuating signal is directly proportional to the derivative of the error signal. Now let us analyse the derivative controller mathematically. As we know in a derivative controller output is directly proportional to the derivative of the error signal, writing this mathematically we have,

$$A(t) \, \alpha \, \frac{de(t)}{dt}$$

Removing the sign of proportionality, we have

$$A(t) = K_d * \frac{de(t)}{dt} \ldots\ldots\ldots\ldots(4.7)$$

Where, Kd is proportional constant also known as controller gain. The derivative controller is also known as the rate controller.

4.1.5 Proportional and Integral Controller (PI Controller)

The name itself indicates that it is a combination of a proportional and an integral controller the output also called the actuating signal is equal to the summation of proportional and integral of the error signal. Now let us analyse proportional and integral controller mathematically. As we know in a proportional and integral controller output is directly proportional to the summation of proportional of error and integration of the error signal, writing this mathematically we have,

$$A(t) \, \alpha \, e(t) + A(t) \, \alpha \int_0^t e(t)\, dt$$

Removing the sign of proportionality, we have

$$A(t) = K_p * e(t) + K_i * \int_0^t e(t)\, dt \ldots\ldots\ldots\ldots(4.8)$$

Where, Kp and Ki are proportional constant and integral constant respectively.

Its main advantage is that it reduces steady-state error drastically, due for this reason it is one of the most widely used controllers.

It is also significant that Integral part reduces the stability, which does not mean that system will be always unstable.

4.1.6 Proportional and Derivative Controller (PD Controller)

The name itself indicates that it is a combination of a proportional and a derivative controller the output also called the actuating signal is the summation of proportional and derivative of the error signal. Now let us analyse proportional and derivative controller mathematically. As we know in a proportional and derivative controller output is directly proportional to the summation of proportional of error and differentiation of the error signal, writing this mathematically

$$A(t) \, \alpha \, e(t) + A(t) \, \alpha \int_0^t e(t)\, dt$$

we have,

Removing the sign of proportionality, we have

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$$A(t) = K_p * e(t) + K_i * \int_0^t e(t)\,dt \ldots\ldots\ldots\ldots(4.8)$$

Where Kp and Kd are proportional constant and derivative constant respectively.

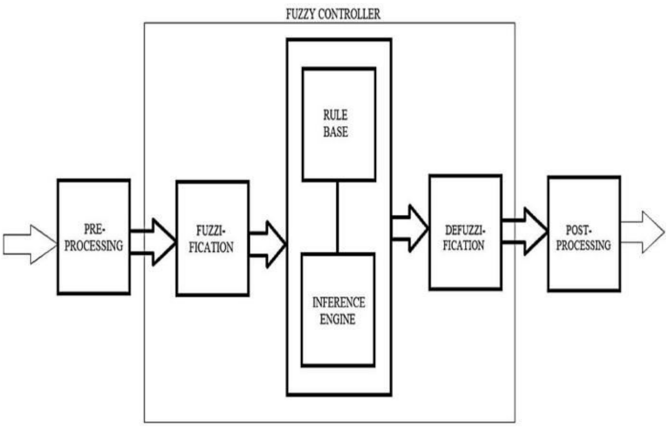
Advantages and disadvantages are combinations of advantages and disadvantages of proportional and derivative controllers. In general, it is observed that PD controller improves transient performance.

4.1.7 Proportional plus Integral plus Derivative Controller (PID Controller) A PID controller is generally used in industrial control applications to regulate temperature, flow, pressure, speed, and other process variables.

The name itself indicates that it is a combination of a proportional, an integral and a derivative controller the output also called the actuating signal is the summation of proportional, an integral and derivative of the error signal. Now let us analyse PID controller mathematically. As we know in a PID controller output is directly proportional to the summation of proportional of error signal, an integral of error signal and differentiation of the error signal, writing this mathematically we have,

$$A(t)\ \alpha\ e(t) + A(t)\ \alpha \int_0^t e(t)\,dt + A(t)\ \alpha\ \frac{de(t)}{dt}$$

Removing the sign of proportionality, we have



$$A(t) = K_p * e(t) + K_i * \int_0^t e(t)\,dt + K_d * \frac{de(t)}{dt} \ldots\ldots\ldots$$

Where Kp, Ki and Kd are proportional constant, integral constant and derivative constant respectively.

4.1.8 Fuzzy Logic controllers

Fuzzy Logic controllers are used where systems are highly non-linear. Generally, most of the Electrical systems are highly non-linear. Due to this reason, Fuzzy Logic controllers are a good choice among the controllers.

An accurate mathematical model is not needed in FLC. It works based on past experiences, can handle non-linearities and can present disturbance insensitivity greater than the most other non-linear controllers.

FLC is based on fuzzy sets, i.e., classes of objects in which the transition from membership to non-membership is smooth rather than abrupt.

In recent developments, FLC have outperformed other controllers in complex, nonlinear or undefined systems for which a good practical knowledge exists. Therefore, boundaries of fuzzy sets can be vague and ambiguous, making them useful for approximation models. The important step in the fuzzy controller synthesis procedure is to define the input and output variables based on previous experiences or practical knowledge.

This is done accordingly with the expected function of the controller. There are no general rules to select those variables, although typically the variables chosen are the states of the controlled system, their errors, error variation, and error accumulation.

A. Principles of fuzzy modelling

The general algorithm for a fuzzy system designer can be synthesized as follows:

1. Fuzzification
   - a. Normalize of the universes of discourses for the fuzzy input and output vector.
   - b. Convert crisp data into fuzzy data or membership function.
   - c. Calculate the membership function for every crisp value of the fuzzy input.

Fig4.4: ProcessBlocksofaFUZZYcontroller

2. Fuzzy Inference
   - d.Combine membership function with the rule to drive the fuzzy output.
   - e. Calculation of the membership function for every crisp value of the fuzzy input.
3. Defuzzification
   - f. Calculate the fuzzy output, using suitable defuzzification method.

i. Fuzzy membership function

Let us consider a membership function for a fuzzy set A on the universe of discourse X is defined as µA: X → [0,1], where each element of X is mapped to a value between 0 and 1. This value, called membership value or degree of membership, quantifies the grade of membership of the element in X to the fuzzy set A.

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ii. Fuzzy rules for developing FIS

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all the pieces that are described: Membership-Functions, Logical Operations and Rules.

B. System design with FLC

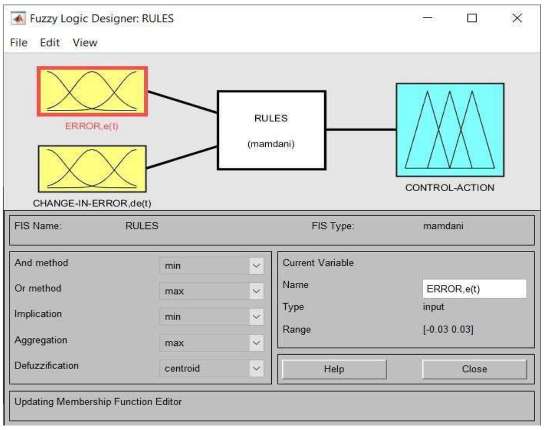

Fig 4.5; Selection of number of I/O for designing FIS for FLC

The membership functions should be chosen such that they cover the whole universe of discourse.

Now the algorithm is implemented in MATLAB with a five-member fuzzy inference system used for the input parameters i.e., error and change in error and also for the output. A Mamdani-type fuzzy inference approach is utilized. The setup is as shown in Fig 4.5

		Change in error, de(t)				
		NB	NS	ZZ	PS	PB
Error,e(t)	NB	S	S	M	M	B
	NS	S	M	M	B	VB
	ZZ	M	M	B	VB	VB
	PS	M	B	VB	VB	VVB
	PB	B	VB	VB	VVB	VVB

Table 4.1: FUZZY RULES DECISION TABLE FOR FLC

The error, e(t) and change in error, de(t) are inputs of FLC. Two input signals are converted to fuzzy numbers first in fuzzifier using five membership functions: Positive Big (PB), Positive Small (PS), Zero (ZZ), Negative Small (NS), Negative Big (NB), Small(S), Medium(M), Big(B), Very Big (VB) and Very Very Big (VVB). Triangular membership functions are usedin this FLC. Since it is easier to intercept membership degrees from a triangle. Then they are used in the rule table as shown below in Table I to determine thefuzzy number of the compensated output signal. Finally, resultant united fuzzy subsets representing the controller output are converted to the crisp values using the central ofarea defuzzifier scheme. The FLC parameters are chosen based on a trial-and-error study of the control.

The main fuzzy reasoning blocks and the defuzzification process of the FLC used in thisstudy are given inFig 4.6. The FLC used here is developed in MATLAB/Simulinkenvironmentformultipurposeuseasacontrol tool.Withsomesimplemodificationsitcanbeusedtocontrol differentsystems.

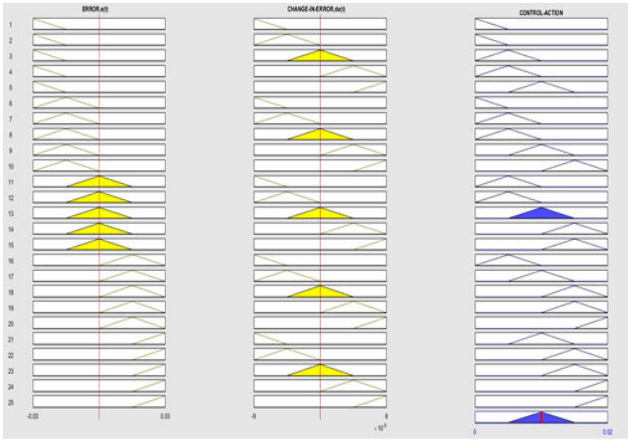

Fig 4.6; Fuzzy reasoning representing the process from fuzzification to defuzzification

FUZZY INFERENCE SYSTEM

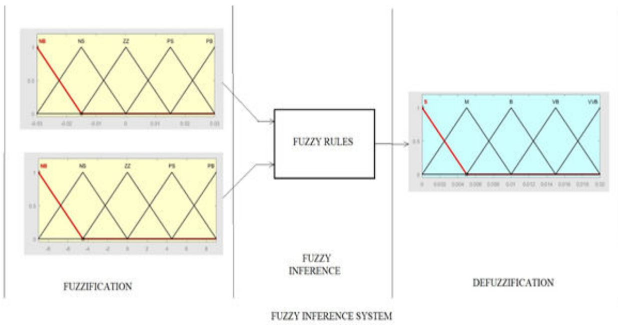

Fig 4.7: FUZZY INTERFERENCE SYSTEM

V.SIMULATION RESULTS

5.1 Simulation

Thesystemdynamicperformanceistobeobservedusingtwodifferentcontrollerstructures:

PIcontroller andFuzzyPIcontroller.

5.1 4 Area Power SystemAppendix

Let us considerthe following appendix:

Area-1

Tp1=20sec,Kp1=120,TT1=0.3sec,TG1=0.08sec,R1=2.4

Area-2

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T_{p2}= 25sec,K_{p2}=112.5,T_{T2}=0.33sec, T_{G2} = 0.072sec,R_2=2.7

Area-3

T_{p3}= 20sec,K_{p3}=125,T_{T3}=0.35sec, T_{G3}= 0.07sec,R_3=2.5

Area-4

T_{p4} = 15sec, K_{p4} = 115, T_{T4}= 0.375sec, T_{G4} = 0.085sec,
R_4= 2$T_{12}T_{13}$=T_{14}=T_{21}= T_{23}= T_{31}= T_{32}=T_{41}=0.545
T_{24}=T_{34}=T_{42}=T_{43}=0K_1=K_2= K_3=K_4=0.6
B_{S1}=B_{S2}=B_{S3}=B_{S4}=0.425a
12= a41=a23= a31= -1
K_{IPI}= -0.5, K_{PPI}= 0.05,P_D= 1%

Notations:

T_T:Turbinetimeconstant,
T_G:Governortime constant,
K_p:Power systemgain,cient,
B: Frequency bias parameter,
P_D:load disturbance,
K_i:Integrationgain.

TheMATLABmodelof4-areaPowersystemusingPIcontrollerisasshowninpreviouspage. TheSIMULINKresult of MATLABmodelisasshown in Fig 5.1

5.1 MATLAB MODEL OF 4-AREA POWER SYSTEM

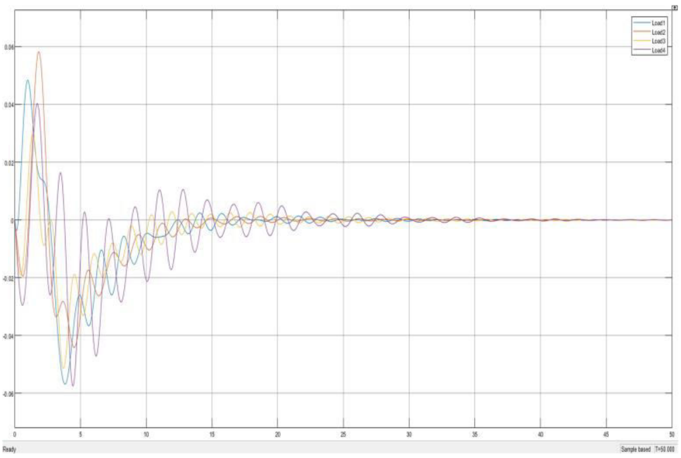

Fig5.1: SIMULINKresultof4-areaPowersystem withPIcontrollerRenewableSources

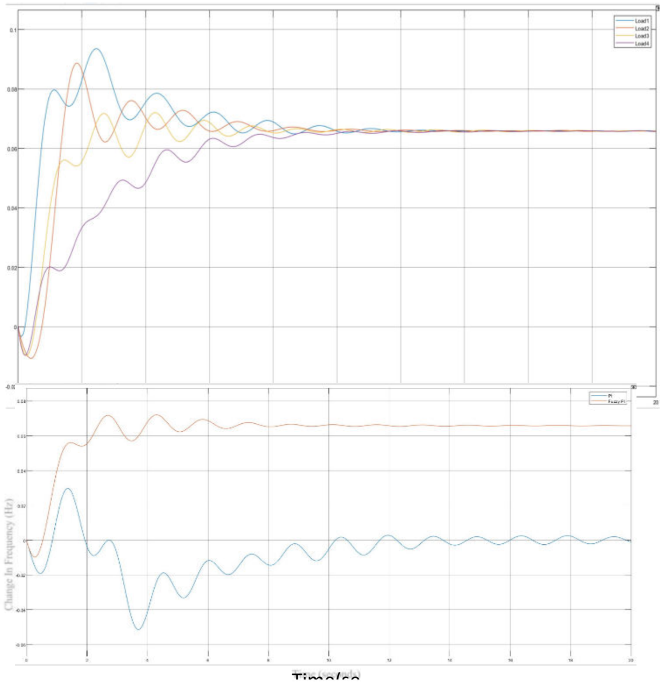

Fig 5.3: Comparison ofDynamic responseofArea-1: 1%Load

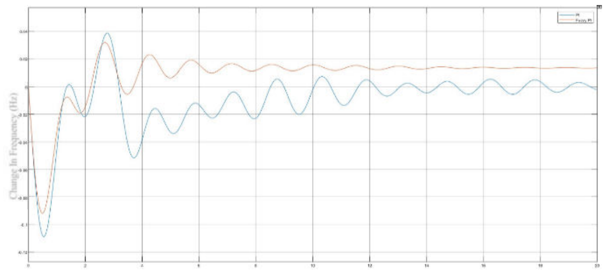

Fig.5.4: Comparison ofDynamic responseofArea-1: 5%

The graphs show comparison of dynamic frequency response of Area-1 using PI and FuzzybasedPIcontrollers. Thebluecolour representsthePIcontroller,andtheredcolourrepresentsthe Fuzzy based PI controller. From the graph compared to PI, the Fuzzy based PI controllerreduces settling time for1% and 5%changein load.

Change in frequencyfor5%changein loadisveryless whencomparedto1%changein load.

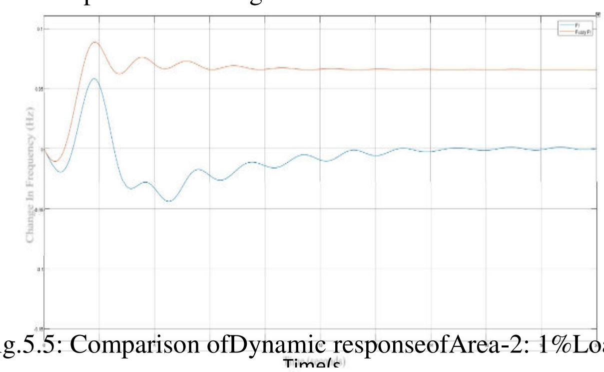

Fig.5.5: Comparison ofDynamic responseofArea-2: 1%Load.

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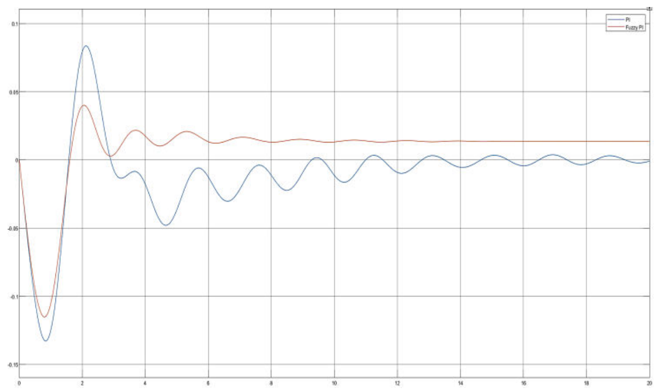

Fig.5.6: Comparison ofDynamic responseofArea-2: 5%Load

The graphs show comparison of dynamic frequency response of Area-2 using PI and FuzzybasedPIcontrollers. Theblue colour representsthePIcontroller,andtheredcolourrepresentsthe Fuzzy based PI controller. From the graph compared to PI, the Fuzzy based PI controllerreduces settling time for1% and 5%changein load.

Change in frequencyfor5%changein loadisveryless whencomparedto1%changein load.

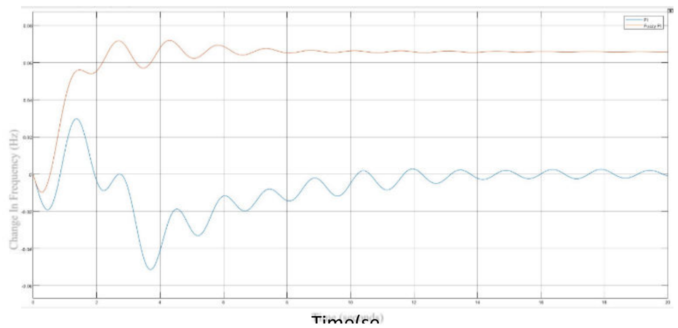

Fig.5.7: Comparison ofDynamic responseofArea-3: 1%Load.

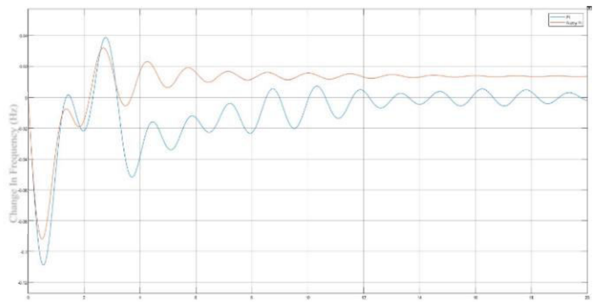

Fig.5.8: Comparison ofDynamic responseofArea-3: 5%Load.

The graphs show comparison of dynamic frequency response of Area-3 using PI and FuzzybasedPIcontrollers. Thebluecolour representsthePIcontroller,andtheredcolourrepresentsthe Fuzzy based PI controller. From the graph compared to PI, the Fuzzy based PI controllerreduces settling time for1% and 5%changein load.

Change in frequencyfor5%changein loadisveryless whencomparedto1%changein load.

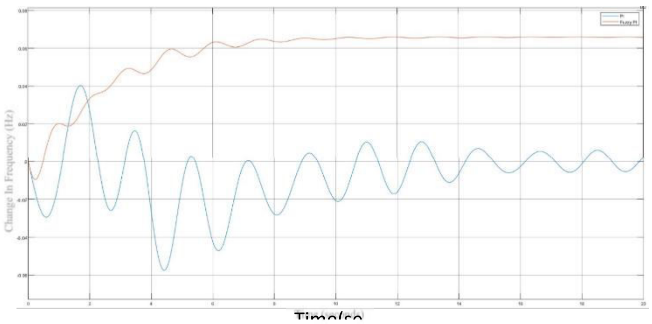

Fig.5.9: Comparison ofDynamic responseofArea-4: 1%Load

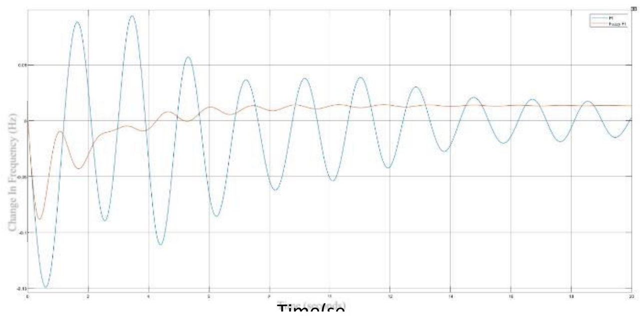

Fig.5.10: Comparison ofDynamic responseofArea-4: 5%Load.

The graphs show comparison of dynamic frequency response of Area-4 using PI and FuzzybasedPIcontrollers. Thebluecolour representsthePIcontroller,andtheredcolourrepresentsthe Fuzzy based PI controller. From the graph compared to PI, the Fuzzy based PI controllerreduces settling time for1% and 5%changein load.

Change in frequencyfor5%changein loadisveryless whencomparedto1%changein load.

5.6 OBSERVATIONSFROMSIMULATIONS:

5.6.1SimulationObservations forRenewableSources

Table5.1:Observations ofRenewable sources

Area	PeakOvershoot (Hz)	Settingtime(seconds)
1% Changein Load		
Area-1:PIcontroller	4.839e-02	18.45
Area-1: Fuzzy logic PIcontroller	9.31e-02	12.63
Area-2:PIcontroller	5.828e-02	24.44
Area-2: Fuzzy logic PIcontroller	8.876e-02	13
Area-3:PIcontroller	8.280e-06	34.43
Area-3: Fuzzy logic PIcontroller	7.208e-02	14.6
Area-4:PIcontroller	4.034e-02	37
Area-4: Fuzzy logic PIcontroller	6.604e-02	14.86

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5% Changein Load		
Area-1:PIcontroller	5.636e-02	36.6
Area-1: Fuzzy logic PIcontroller	6.577e-02	15.84
Area-2:PIcontroller	7.866e-02	33.79
Area-2: Fuzzy logic PIcontroller	4.935e-02	12.58
Area-3:PIcontroller	2.878e-02	43.27
Area-3: Fuzzy logic PIcontroller	3.336e-02	16.5
Area-4:PIcontroller	8.834e-02	48.64
Area-4: Fuzzy logic PIcontroller	1.436e-02	19.18

By varying 1% step load, the above dynamic responses reveal the steady state error.Change in frequency, settling time and peak overshoot can also be observed fromdynamicresponse.

The Fuzzy logic controller is intelligent controller and can be used for AutomaticGeneration Control for the two-area, three-area and four-area interconnected powersystems.

Performance evaluation is carried out by using Fuzzy control and conventional PIcontrolapproaches.ConventionalPIandFuzzycontrolapproach withinclusionofgainprovides better dynamic performance and reduces the steady state error and reducesoscillation of the frequency deviation and the tie line power flow in each area of four-area interconnected power system. The two models of interconnected power systemhavebeendevelopedwithtwotypesofsaidcontrollersandsimulatedusingMATLAB/SIMULINK package. The performance of the Fuzzy controllers has beencompared with the conventional PI controllers for the four-area interconnected powersystem.

VI CONCLUSION

The simplification or linearization of the non-linear system under consideration has tobe performed by the conventional control methodology like PI since its construction isbasedonlinearsystemtheory.Hence,thecontrollerdoesnotprovideanyguaranteeforgoodperformance.Theyrequirecomplexcalculationsforevaluatingthegaincoefficients. These controllers however are not recommended for higher order andcomplexsystemsasitcancausethesystemtobecomeunstable.Hence,amoreheuristicapproachisrequiredforchoiceofthecontroller parameterswhichcanbeprovidedwiththehelpoffuzzylogic,where wecandefinevariablesinasubjectiveway.Thus,wecanavoidthe numerical complicacy involvedin higherordersystems.

The performance of a well-tuned PI controller is undoubtedly ahead in terms of systemrobustness and predictability, but Fuzzy logic provides a certain level of artificialintelligence to the controllers since they try to imitate the human thought process. Thisfacilityisnotavailableintheconventionalcontrollers.Nowthe MATLAB/SIMULINKarrangementis utilisedin ordertocomparetheresponses ofthePIand thatofFLC.

6.1 SCOPEFOR FUTUREWORK

1.Various other optimization algorithmic programs can be used for optimization andtheperformancecanbecomparedwiththeresponseobtainedusingFuzzylogiccontroller.

2.Various controllers may be used to manage the frequency deviations and changes intie-linepower.

3.It may be implemented to system with multi-areas and also the performance of thesystem may be studied.

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