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Research Article

Load Frequency Control of Power System

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ARTICLE INFO | **ABSTRACT**

In this paper present decentralized control scheme for Load Frequency Control in a multi-area Power System by appreciating the performance of the methods in a single area power system. A number of modern control techniques are 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 two power generation unit and multiple variable load units. The robustness and reliability of the various control schemes is examined through simulations

keywords: fuzzy set, fuzzy logic, power system, load frequency.

1. Introduction

For large scale power systems which consists of inter-connected control areas, load frequency then it is important to keep the frequency and inter area tie power near to the scheduled values. The input mechanical power is used to control the frequency of the generators and the change in the frequency and tie-line power are sensed, which is a measure of the change in rotor angle. A well-designed power system should be able to provide the acceptable levels of power quality by keeping the frequency and voltage magnitude within tolerable limits. Changes in the power system load affects mainly the system frequency, while the reactive power is less sensitive to changes in frequency and is mainly dependent on fluctuations of voltage magnitude. So, the control of the real and reactive power in the power system is dealt separately. The load frequency control mainly deals with the control of the system frequency and real power whereas the automatic Voltage regulator loop regulates the changes in the reactive power and voltage magnitude. Load frequency control is the basis of many advanced concepts of the large-scale control of the power system.

2. Reasons for the Limits on Frequency

Following are the reasons for keeping a strict limit on the system frequency variation:
1. The speed of the alternating current motors depends on the frequency of the power supply. There are situations where speed consistency is expected to be of high order.
2. The electric clocks are driven by the synchronous motors. The accuracy of the clocks is not only dependent on the frequency but also is an integral of this frequency error.
3. If the normal frequency id 50 Hertz and the system frequency falls below 47.5 Hertz or goes up above 52.5 Hertz then the blades of the turbine are likely to get damaged so as to prevent the stalling of the generator.
4. The under-frequency operation of the power transformer is not desirable. For constant system voltage if the frequency is below the desired level than the normal flux in the core increases. This sustained under frequency operation of the power transformer results in low efficiency and over-heating of the transformer windings.
5. The most serious effect of subnormal frequency operation is observed in the case of Thermal Power Plants. Due to the subnormal frequency operation the blast of the ID and FD fans in the power stations get reduced and thereby reduce the generation power in the thermal plants. This phenomenon has got a cumulative effect and in turn is able to make complete shutdown of the power plant if proper steps of load shedding technique is not engaged. It is pertinent to mention that, in load shedding technique a sizable chunk of load from the power system is disconnected from the generating units so as to restore the frequency to the desired level.

3. Load Frequency Control and Mathematical Modelling of Various Components

If the system is connected to a number of different loads in a power system, then the system frequency and speed change with the governor characteristics as the load changes. If it is not required to keep the frequency constant in a 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 characteristic as and when required. If a change in load is taken care by two generating stations running at parallel then the complexity of the system increases. The possibility of sharing the load by two machines is as follow:

1. Suppose there are two generating stations that are connected to each other by tie line. 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.**
2. 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.**
3. The third possibility is that the change in the frequency of a particular area is taken care of by the generator of that area thereby the tie-line loading remains the same. This method is known as **flat tie-line loading control**.
4. 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.
5. 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 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 ΔPtie 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 ΔPtie within the specified tolerance. The first step to the analysis of the control system is the mathematical modeling of the system's various components and control system techniques.

4. Mathematical Modelling of Generator

Applying the swing equation of a synchronous machine to small perturbation, we have:

$$\frac{2H}{\omega}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e$$

Or in terms of small deviation in speed

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

Taking Laplace Transform, we obtain

$$\Delta\Omega(s) = \frac{1}{2H_s}(\Delta P_m(s) - \Delta P_e(s))$$

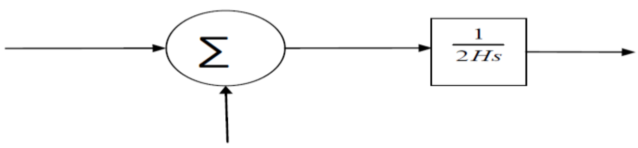

Fig.1 Mathematical modeling block diagram for generator

5. Mathematical Modelling of Load

The load on the power system consists of a variety of electrical drives. The equipment used for lighting purposes are basically resistive in nature and the rotating devices are basically a composite of the resistive and inductive components. The speed-load characteristic of the composite load is given by:

$$\Delta P_e = \Delta P_L + D\Delta\omega$$

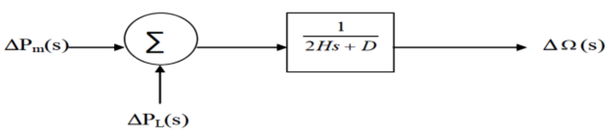

Fig.2 Mathematical modeling Block Diagram for Load Where ΔPL is the non-frequency- sensitive load change, DΔω is the frequency sensitive load change. D is expressed as percent change in load by percent change in frequency.

6. Mathematical Modelling for Prime Mover

The source of power generation is commonly known as the prime mover. It may be hydraulic turbines at waterfalls, steam turbines whose energy comes from burning of the coal, gas andother fuels. The model for the turbine relates the changes in mechanical power output ΔP_m to the changes in the steam valve position ΔP_V.

$$G_T = \frac{\Delta P_m(s)}{\Delta P_v(s)} = \frac{1}{1 + \tau_J s}$$

Where G_T,the turbine constant is, in the range of 0.2 to 2.0 seconds.

7. Mathematical Modelling for Governor

When the electrical load is suddenly increased then the electrical power exceeds the mechanical power input. As a result of this the deficiency of power in the load side is extracted from the rotating energy of the turbine. Due to this reason the kinetic energy of the turbine i.e. the energy stored in the machine is reduced and the governor sends a signal to supply more volumes of water or steam or gas to increase the speed of the prime-mover so as to compensate speed deficiency.

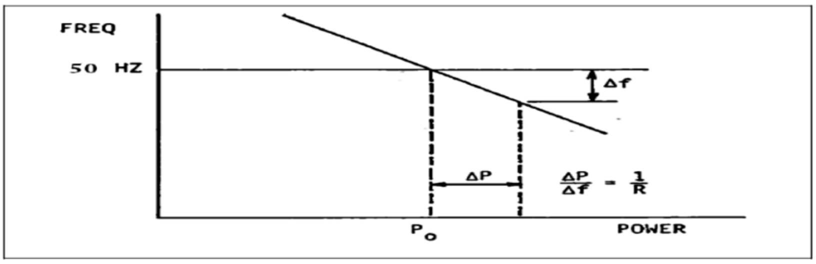

Fig. 3: Graphical Representation of speed regulation by governor

The slope of the curve represents speed regulation R. Governors typically has a speed regulation of 5-6 % from no load to full load.

$$\Delta P_g = \Delta P_{ref} - \frac{1}{R}\Delta f$$

Or in s- domain

$$\Delta P_g(s) = \Delta P_{ref} - \frac{1}{R}\Delta\Omega(s)$$

The command ΔPg is transformed through hydraulic amplifier to the steam valve position command ΔPV. We assume a linear relationship and consider simple time constant we have the following s-domain relation: τ_g

$$\Delta P_V(s) = \frac{1}{1 + \tau_g}\Delta P_g(s)$$

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

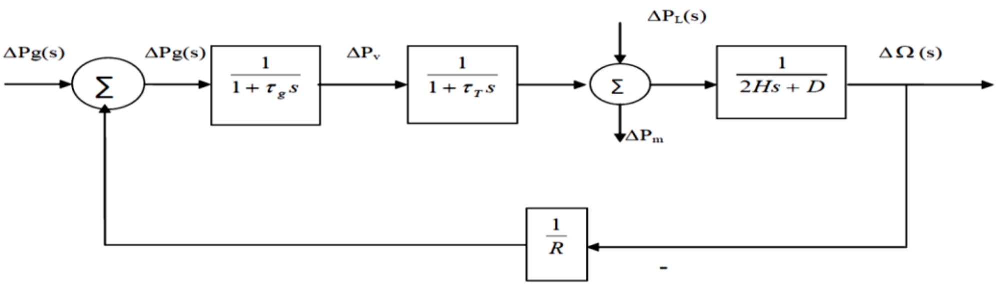

Fig.4: Mathematical Modelling of Block Diagram of single system consisting of Generator, Load, Prime Mover and Governor.

8. Automatic Generation Control

If the load on the system is increased suddenly then the turbine speed drops before the governor can adjust the input of the steam to the new load. As the change in the value of speed diminishes the error signal becomes smaller and the position of the governor and not of the fly balls gets closer to the point required to maintain the constant speed. One way to restore the speed or frequency to its nominal value is to add an integrator on the way. The integrator will unit shall monitor the average error over a period of time and will overcome the offset. Thus as the load of the system changes continuously the generation is adjusted automatically to restore the frequency to the nominal value. This scheme is known as automatic generation control. In an interconnected system consisting of several pools, the role of the AGC is to divide the load among the system, stations and generators so as to achieve maximum economy and reasonably uniform frequency.

8.1 AGC in a Single Area:

With the primary LFC loop a change in the system load will result in a steady state frequency deviation, depending on the governor speed regulation. In order to reduce the frequency deviation to zero we must provide a reset action by introducing an integral controller to act on the load reference setting to change the speed set point. The integral controller increases the system type by 1 which forces the final frequency deviation to zero. The integral controller gain must be adjusted for a satisfactory transient response

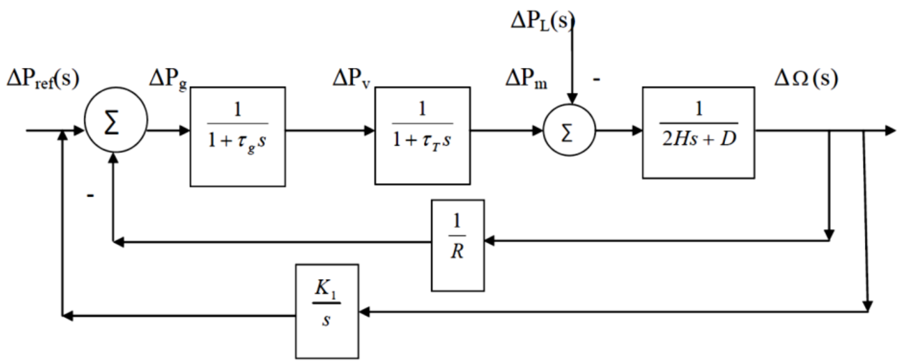

Fig.5 Mathematical modeling of AGC for an isolated power system

The closed loop transfer function of the control system is given by:

$$\frac{\Delta\Omega(s)}{-\Delta P_L(s)} = \frac{s(1+\tau_g s)(1+\tau_T s)}{s(2Hs+D)(1+\tau_g s)(1+\tau_T s) + K_1 + {}^{s}/_{R}}$$

8.2 AGC in the multi area System:

In many cases a group of generators are closely coupled internally and swing in unison. Furthermore, the generator turbines tend to have the same response characteristics. Such a group of generators are said to be coherent. Then it is possible to let the LFC loop represent the whole system and the group is called the control group. For a two area system, during normal operation the real power transferred over the tie line is given by

$$P_{12} = \frac{|E_1||E_2|}{X_{12}} \sin\delta_{12}$$

Where $X_{12} = X_1 + X_{tie} + X_2$ and $\delta_{12} = \delta_1 - \delta_2$

For a small deviation in the tie-line flow

$$\Delta P_{12} = \left|\frac{dP_{12}}{d\delta_{12}}\right|_{\delta_{12}} \Delta\delta_{12} = P_s\Delta\delta_{12}$$

The tie-line power deviation then takes on the form

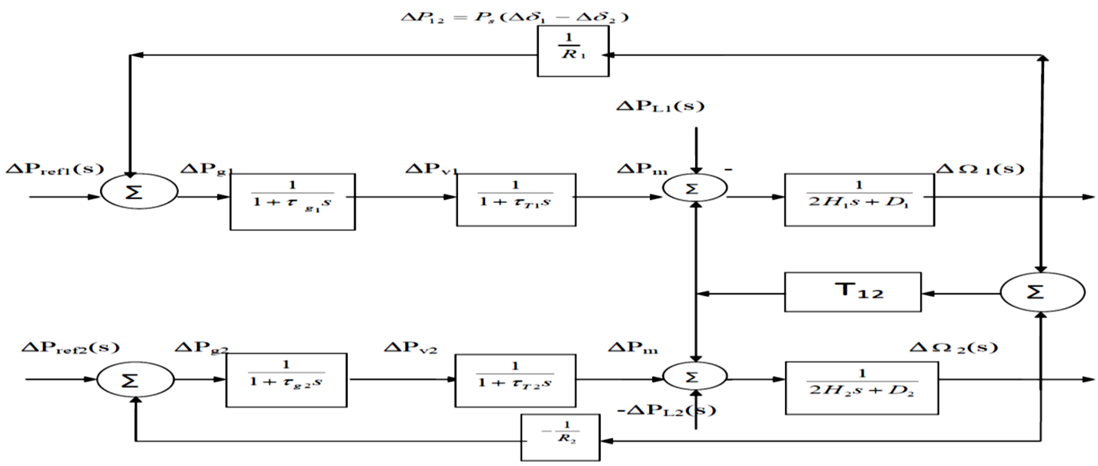

Fig.6 Two area system with primary loop LFC

Modern Control design is especially based on the multivariable state vector system. In this design algorithm we make use of the state variable parameters that can be obtained from thesystem. For the systems where all the state variables are not available a state estimator is designed.
Various Methodologies to implement the Feedback control:
(J) Pole Placement Technique:
The control is achieved by feedback the state variables through a regulator with constant gains. Consider the system in the state variable form:

$$X(t) = A_X(t) + B_u(t)$$
$$Y(t) = C_X(t)$$

The pole placement design allows all the roots of the system characteristic equation to be placed in desired location, which eventually results in a regulator with constant gain vector K.

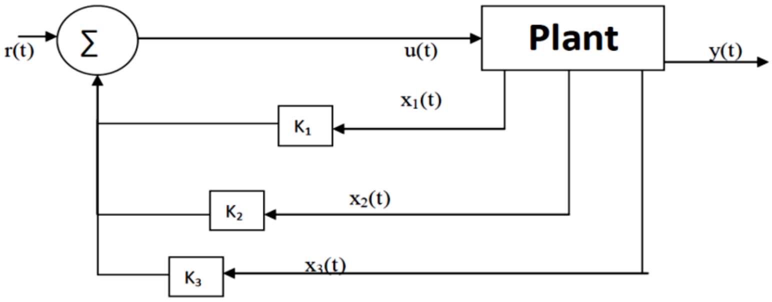

Fig.7 Control Design via Pole Placement

Now if we consider the Figure 7 above, the block diagram with the following state feedback control

$$U(t) = -K_X(t)$$

where K is a 1×n vector of constant feedback gains. The control system input r(t) is assumed to be zero. The purpose of the method is to reduce all the values of the state variables to be zero when the states have been perturbed. Substituting the compensated system state variable representation becomes

$$X(t) = (A - BK)\,X(t) = A_f X(t)$$

The compensated system characteristic equation is

$$|sI - A + BK| = 0$$

The function [K,A_f]= placepol (A,B,C,p) is developed for the pole placement design. The matrices A,B,C are the system matrices and p is row matrix containing the desired closed-loop poles. The function returns the gain matrix K and the closed-loop matrix A_f. For a multi input system K= place(A,B,p), which uses a more reliable algorithm.

9. Optimal Control System

It is a technique applied in the control system design that is executed by minimizing the performance index of the system variables. In this section we discuss the design of the optimal controllers for the linear systems with quadratic performance index, which is also referred to as the linear quadratic regulator. The objective of the optimal regulator design is to determine a control law **u*(x,t)** which can transfer the system from its initial state to the final state by minimizing the performance index. The performance index that is widely used is the quadratic performance index and is based on the minimum energy criterion.
Consider the plant as discussed:

$$X(t) = A_X(t) + B_u(t)$$

The problem is to find the vector **K** of the control law

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

Which minimizes the value of the quadratic performance index **J** of the form?

$$J = \int_{t0}^{tf} (x'Qx + u'Ru)dt$$

Where Q is a positive semi definite matrix and **R** is real symmetric matrix. **Q** is a positive definite matrix if all its principal minors are non-negative. The choice of the elements of **Q** and **R** allows the relative weighting of the individual state variables and individual control inputs.
To obtain the solution we make use of the method of Langrange multipliers using an n vector of the unconstrained equation

$$[x, \lambda, u, t] = (x'Qx + u'Ru) + \lambda'(Ax + Bu - x')$$

The optimal values determined are found by equating the partial derivative to zero.

$$\frac{\partial L}{\partial \lambda} = Ax' + Bu' - x'' = 0 \;\Rightarrow x'' = Ax' + Bu'$$

$$\frac{\partial L}{\partial u} = 2Ru' + \lambda' B = 0 \Rightarrow u' = -\frac{1}{2}R^{-1}\lambda' B$$
$$\frac{\partial L}{\partial x} = 2x'' + \lambda' + \lambda' A = 0 \implies \lambda' = 2Qx' - A'\lambda$$

Assuming that there exists a symmetric, time varying positive definite matrix **p(t)** satisfying

$$\lambda = 2p(t)X'$$

Substituting we get

$$U'(t) = -R^{-1}B'p(t)x'$$

Obtaining the derivative of (20) we get

$$\lambda = 2(px' + p'x)$$

Finally, we equate (19) and (22)

$$p(t) = -p(t)A - A'p(t) - Q + p(t)BR^{-1}B'p(t)$$

The above equation is known as the Riccati equation.
Compensators are generally used to satisfy all the desired specifications in a system. But in most of the cases the system needs to fulfill some more specifications that are difficult to attain in case of a compensated system. As an alternative to this we mainly use Optimal Control system. The trial-and-error system for the compensated design system makes it cumbersome for the designers to attain the specifications. This trial-and-error procedure works well for the system with a single input and a single output. But for a multi-input-multi-output system the trial-and-error method is done away and replaced with Optimal Control design method where the trial-and-error uncertainties are eliminated in parameter optimization method. It consists of a single performance index specially the integral square performance index. The minimization of the performance index is done using the Lyapunov stability theorem in order to yield better system performance for a fixed system configuration. The values of Q and R has to carefully selected and if the responses are unsuitable then some other values of Q and R has to be selected. K is automatically generated and the closed loop responses are found.

10. Two Area Modelling of a Power System

Take into consideration an i^{th} area power system and we write the differential equation governing the operation under normal condition where we assume that the disturbances in the system are zero.
Differential Equation of the governor:

$\Delta x'_{vi} = -\frac{1}{T_{gi}}\Delta x_{vi}(t) - \frac{1}{T_{gi}R_i}\Delta f_i(t) + \frac{1}{T_{gi}}\Delta p_{ci}(t)$

For Turbine Generator:

$\Delta p'_{gi} = -\frac{1}{T_{ti}}\Delta p_{gi}(t) + \frac{1}{T_{ti}}\Delta x_{vi}(t)$

For Power System:

$\Delta f'_i(t) = -\frac{D_i f_0}{2H_i}\Delta f_i(t) + \frac{f_0}{2H_i}(\Delta p_{tie,i} - \Delta p_{gi})$

Tie Line Power Equation:

$\Delta p'_{tie,i}(t) = \sum T_{ij}\,(\Delta f_i - \Delta f_j)$

Developing the state space model, we need the matrices A and B.

$$A = \begin{bmatrix} 0 & T_{12} & 0 & 0 & 0 & -T_{12} & 0 \\ -\frac{f_0}{2H_1} & -\frac{f_0 D_1}{2H_1} & \frac{f_0}{2H_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{g1}R_1} & 0 & -\frac{1}{T_{g1}} & -\frac{1}{T_{g1}} & 0 & 0 \\ -\frac{f_0}{2H_2} & 0 & 0 & 0 & 0 & -\frac{f_0 D_2}{2H_2} & \frac{f_0}{2H_2} \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{g2}R_2} & -\frac{1}{T_{t2}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}; \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{T_{g1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{g2}} \end{bmatrix}$$

$$X = \begin{bmatrix} \Delta p_{tie}(t) \\ \Delta f_1(t) \\ \Delta p_{g1}(t) \\ \Delta x_{v1}(t) \\ \Delta f_2(t) \\ \Delta p_{g2}(t) \\ \Delta x_{v2}(t) \end{bmatrix}; \quad U = \begin{bmatrix} \Delta p_{c1}(t) \\ \Delta p_{c2}(t) \end{bmatrix}$$

Where $\Delta x_{vi}(t)$ = Incremental change in the valve position;
$\Delta p_{gi}(t)$ = Incremental change in the power generation;
$\Delta p_{ci}(t)$ = Incremental change in the speed changer position;

And rest of the symbols used has their usual meanings as in the case of the isolated system. The subscript I denotes the area under consideration.

11. Simulations, Results and Discussions

Pole Placement Technique and Optimal Control Technique for Isolated System

11.1 Pole Placement Technique for an Isolated Area System:

A. Compensated System Response

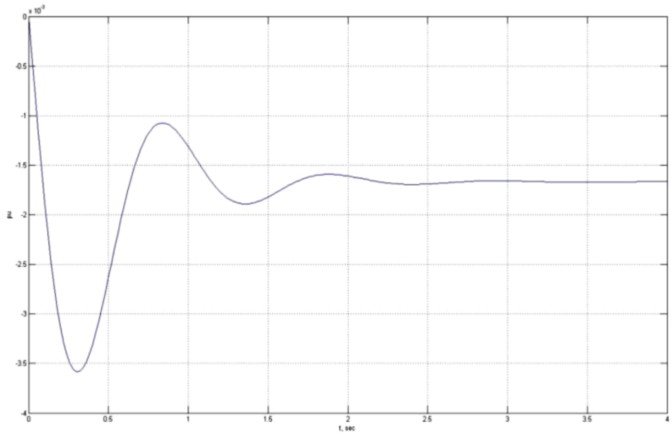

Fig.8 Step response for compensated System

B. Uncompensated system Response

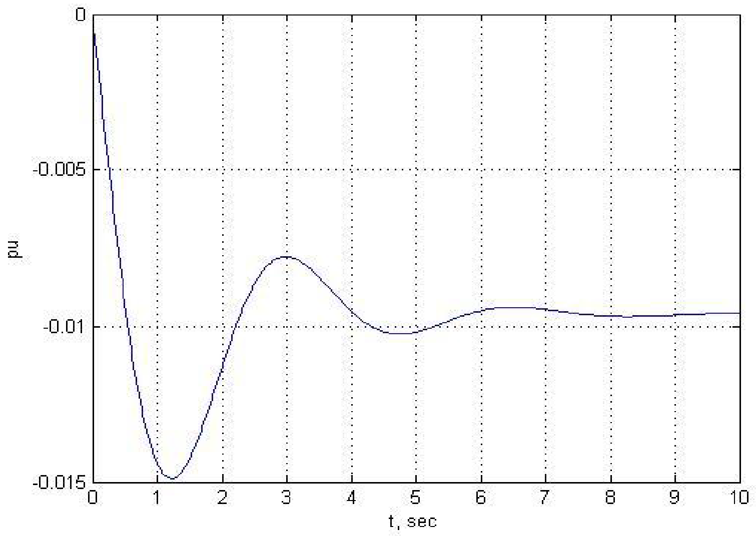

Fig.9 Step response for Uncompensated System

Results: For Pole Placement Design of the single isolated Area System.
Feedback gain vector
K=[4.2 0.8 0.8]
Compensated system closed-loop
Transfer function:

$$\frac{-0.1s^2 - 0.7s - 1}{s^3 + 7s^2 + 52s + 120}$$

Uncompensated Plant
Transfer function:

$$\frac{-0.1s^2 - 0.7s - 1}{s^3 + 7.08s^2 + 10.56s + 20.8}$$

*Compensated system matrix A-B*K=*

$$\begin{bmatrix} -5 & 0 & -100 \\ 2 & -2 & 0 \\ 0.42 & 0.18 & 0 \end{bmatrix}$$

Settling time for the uncompensated system is 4seconds and that for a compensated system is 2.5 seconds.
Optimal control Design for single area isolated System:

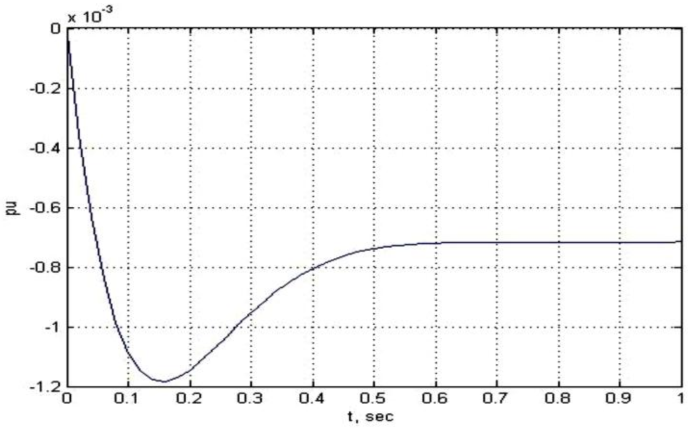

Fig.10: Frequency Deviation Step response for optimal control design of a single area isolated system

Q = [20 0 0;0 10 0;0 0 5]
K = [6.4128 1.1004 -112.6003]

$$P = \begin{bmatrix} 1.5388 & 0.3891 & -9.6192 \\ 0.3891 & 2.3721 & -1.6506 \\ -9.6192 & -1.6506 & 168.9 \end{bmatrix}$$

$$Af = \begin{bmatrix} -5 & 0 & -100 \\ 2 & -2 & 0 \\ 0.6143 & 0.21 & -11.34 \end{bmatrix}$$

Settling time is 0.6 seconds

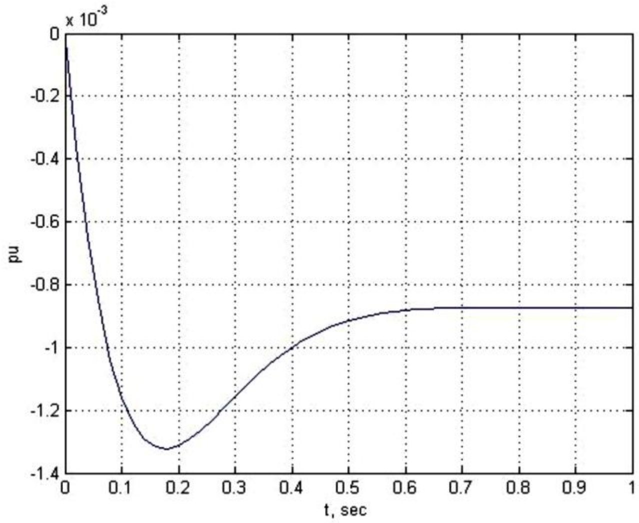

Fig.11: Frequency Deviation Step response for optimal control design of a single area isolated system

For Q = [15 0 0;0 5 0;0 0 1]
K= [5.1995 0.2944 -101.2115]

$$P = \begin{bmatrix} 1.1768 & 0.2057 & -7.7993 \\ 0.2057 & 1.2247 & -0.4415 \\ -7.7993 & -0.4415 & 151.87 \end{bmatrix}$$

$$Af = \begin{bmatrix} -5 & 0 & -100 \\ 2 & -2 & 0 \\ 0.52 & 0.1294 & -10.202 \end{bmatrix}$$

Settling time is 0.6seconds.

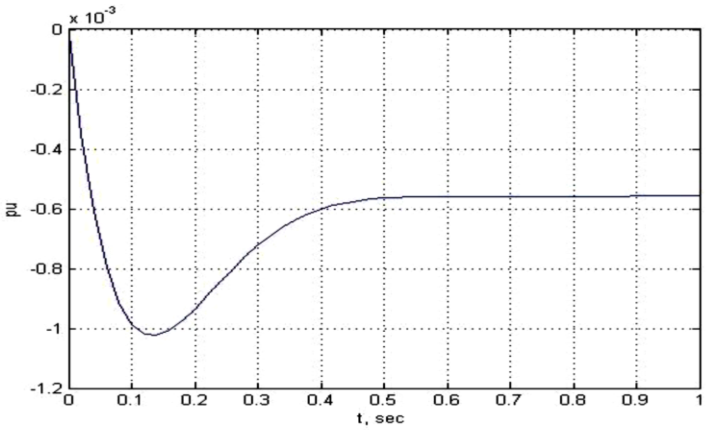

Figure 12: Frequency Deviation Step response for optimal control design of a single area isolated system

For Q = [30 0 0;0 20 0;0 0 5]
K = [8.4546 2.3265 -129.3656]

$$P = \begin{bmatrix} 2.2150 & 0.7181 & -12.6818 \\ 0.7181 & 4.6226 & -3.4897 \\ -12.6818 & -3.4897 & 194.05 \end{bmatrix}$$

$$Af = \begin{bmatrix} -5 & 0 & -100 \\ 2 & -2 & 0 \\ 0.8455 & 0.3326 & -13.0166 \end{bmatrix}$$

Settling time is 0.5 seconds.

Discussion

From the above simulations it is clear that the set of figures (Figure 8 & 9) which depicts the deviation in frequency of the isolated system has more ripples and its counterpart in Figure 10,11and 12 has less ripples. It is clearly obvious from the graphical representation of the step response that the settling time is more uncompensated system than that for a compensated system while using pole placement technique. When we look into the step response in the Optimal Controller design then its clear that the settling time is less. The system reaches equilibrium faster than that for the controllers using pole placement design. In general there are two situations where compensation is required. The first case is when the system is unstable. The second case is when the system is stable but the settling time is to reach faster. Hence using pole placement technique is nothing but using the compensation scheme to reduce the settling time of the system. It is clearly shown that the system reached faster to a steady state in compensated system than for an uncompensated system.

11.2 Optimal Control Design of two area power System

A. Simulation results when 2nd area input is changed.

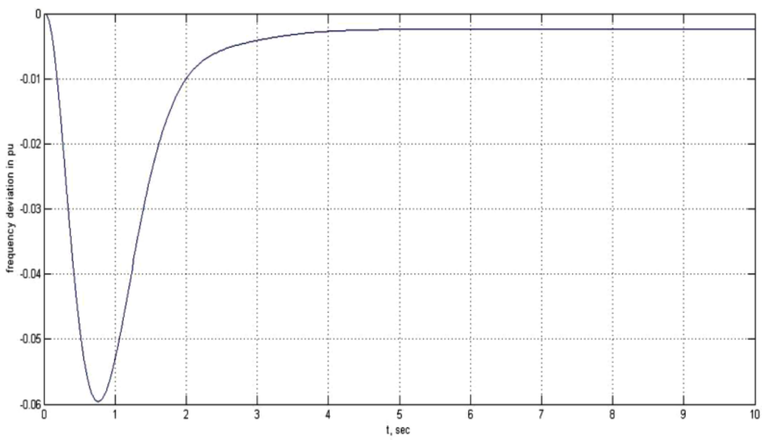

Fig.13 Frequency deviation Δf1

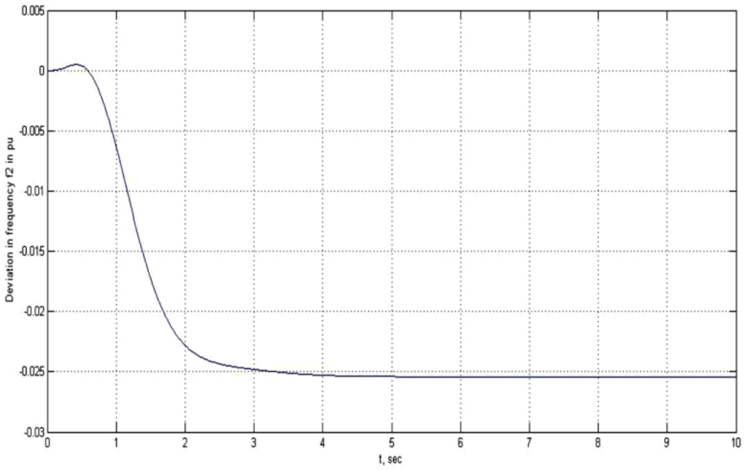

Fig.14 Frequency deviation Δf2

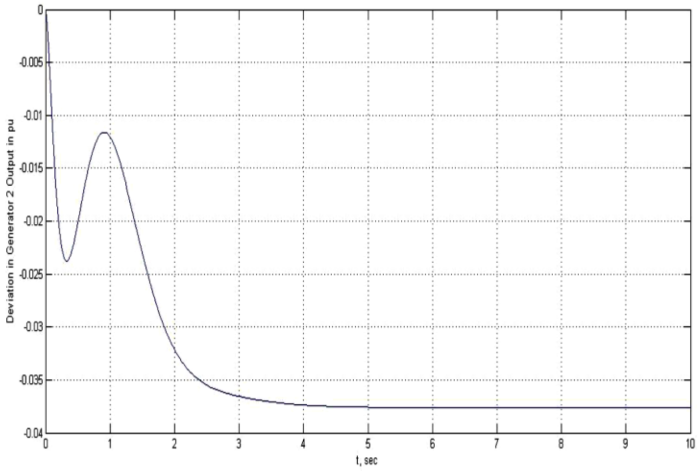

Fig.15 Deviation in Generator 2 Output Pg2

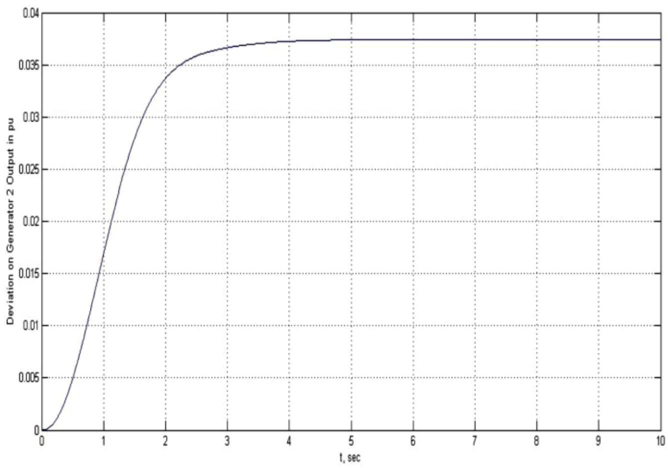

Fig.16 Deviation in Generator 1 Output Pg1

B. Simulation Results when Input to Area 1 is varied.

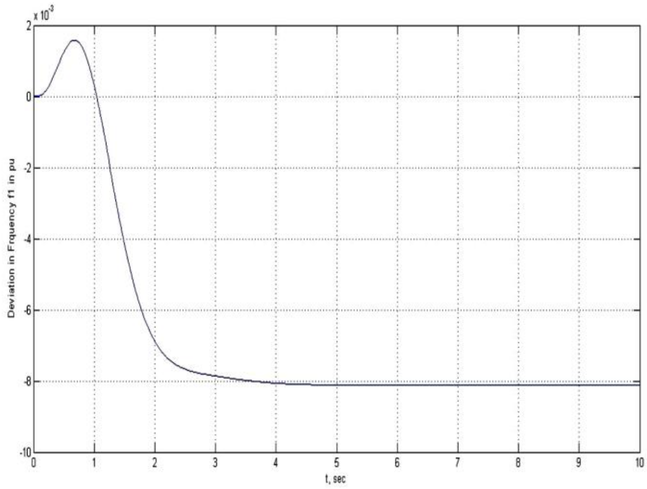

Fig.17 Frequency Deviation Δf1

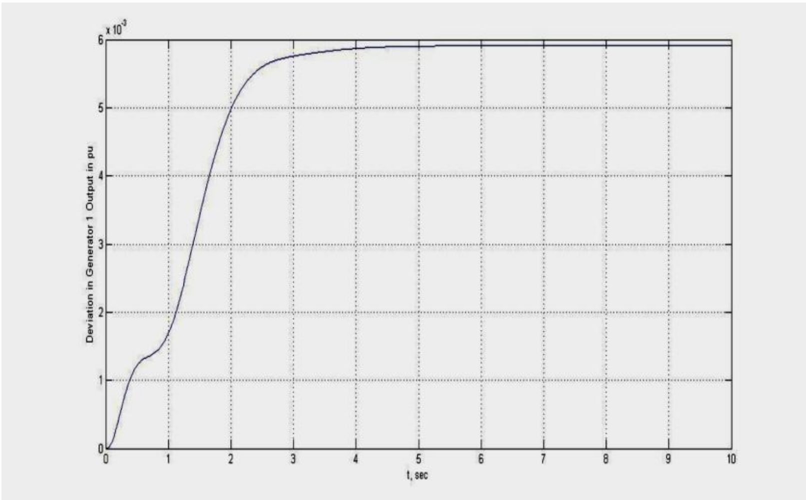

Fig.18 Deviation in Generator 2 Output Pg2

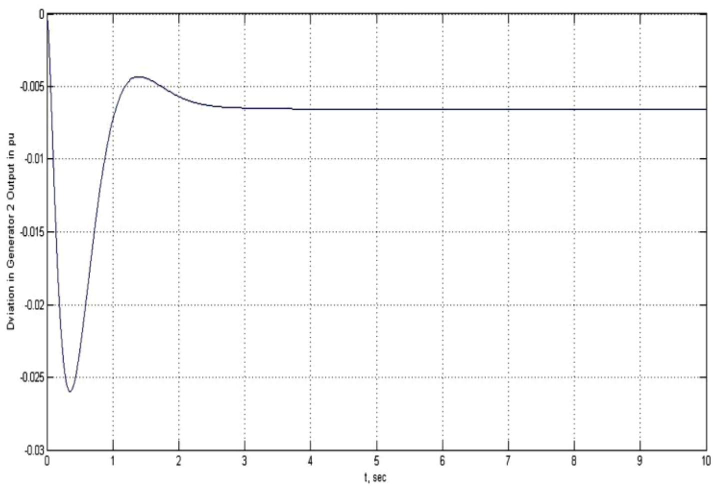

Fig.19 Deviation in Generator 1 Output Pg1

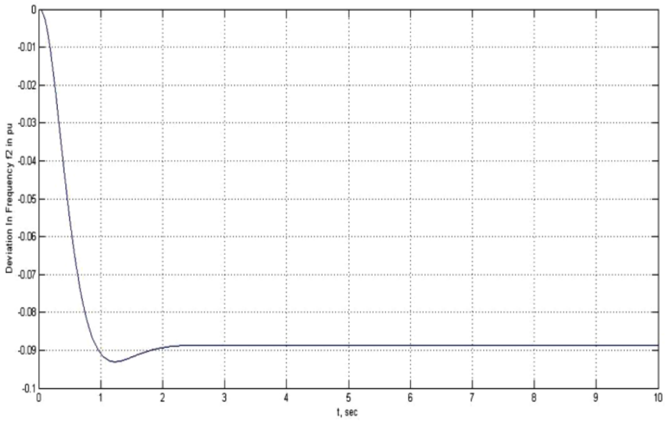

Fig.20 Frequency deviation Δf2

Discussion

Figures 16 ,17 ,18 ,19 denote the variation the frequencies and power generation of the two-area power system when there is a variation in the input parameters of area 1. Similarly, the Figures 20, 21, 22, 23 denote the variation of the above quantities when a variation in the input to the area 2 occurs, which clearly suggests that a decentralized control of the load frequency is achievable through Optimal Control Technique. Whenever the speed regulation to the area 2 generation is negative the load demand increases with respect to that of area 1, hence the frequency of area 2 deceases and the generation of power by the generator 2 also decreases. Inorder to meet the load demand the generator 1 has to increase generation and since the load has increased slightly with respect to the generation capacity it follows a slight deviation in the system frequency is ought to occur that is evidently shown in the simulations.
Similarly, when we look into the system in another way by changing the parameters in the input of generator 1 then the load demand increases with respect to the generation. As a result of which the frequency in the 1st area decreases and the generation capacity also decreases. In order to balance the generation and supply the generator in the second area must generate more power but since the load is slightly more than that of the generation capacity the system frequency decreases slightly, which is verified from the above simulation results.

Conclusion

In this paper we present a case study of designing a controller that can bear desirable results in a two-area power system when the input parameters to the system is changed. Two methods of Load Frequency Control were studied taking an isolated power system into consideration. It was seen that the Optimal controller design bore better results and achieved desired reliability under changes in the input parameter. Hence an attempt was made to extend the Optimal Control design to a two-area network. The assumptions taken under consideration strictly followed that the system operation was normal throughout and the simulations were obtained without the presence of the integral controllers. Lyapunov stability study revealed that by minimizing the system performance index the optimal controller can be designed that improves the system stability and performance drastically over the pole placement method with extensively depended on trial-and-error process. In fact, there is a huge scope of improvement in this area where the power system study can be extended to a multi-area system that shall ensure stability in closed loop system.

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