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Load Frequency Control of Two Area Power System using Optimal Controller

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ABSTRACT: *Incase of an interconnected power system, any small sudden load change in any of the areas causes the fluctuation of the frequencies of each and every area and also there is fluctuation of power in tie line. The main goals of Load Frequency control (LFC) are, to maintain the real frequency and the desired power output (megawatt) in the interconnected power system and to control the change in tie line power between control areas. So, a LFC scheme basically incorporates an appropriate control system for an interconnected power system, which is heaving the capability to bring the frequencies of each area and the tie line powers back to original set point values or very nearer to set point values effectively after the load change. This is achieved by the use of conventional controllers. But the conventional controllers are heaving some demerits like; they are very slow in operation, they do not care about the inherent nonlinearities of different power system component, it is very hard to decide the gain of the integrator setting according to changes in the operating point. Advance control system has a lot of advantage over conventional integral controller. They are much faster than integral controllers and also they give better stability response than integral controllers. In this paper advanced control techniques like optimal controller, optimal compensator has been applied for LFC of two area power system.*

KEYWORDS: Load Frequency Control, Area Control Error(AEC),Two Area Power System, Linear Quadratic Regulator(LQR),Kalman Filter, Linear Quadratic Gaussian (LQG), Optimal Compensator.

INTRODUCTION: Recent times there are several approaches developed for the LFC of multi area power system. In this a paper a two area interconnected power system model is taken for controlling the frequency

The two main objective of Load Frequency Control (LFC) are

1. To maintain the real frequency and the desired power output (megawatt) in the interconnected power system.
2. To control the change in tie line power between control areas.

If there is a small change in load power in a single area power system operating at pre-defined value of frequency creates mismatch in power both for generation and demand. This mismatch problem must be solved for maintaining the quality of supplied power. Initially solved by kinetic energy extraction from the system, as a result declining of system frequency occurs. As the frequency gradually decreases, power consumed by the old load also decreases. After the introduction of governors action the system frequency is still different its predefined value, by another different control strategies it is needed the frequency to bring back to its predefined value. Conventionally Integral Controllers are used for this purpose. This control is called a secondary control (which is operating after the primary control operation) which brings the system frequency to its predefined value or close to it. Whereas, integral controllers are generally slow in operation.

Implementation of advanced control technique provides great help in LFC of power systems. Advance control techniques are having the ability to provide high adaption for changing conditions. They are having the ability for making quick decisions. Optimal control pole placement, Linear Quadratic Regulator, Linear Quadratic Gaussian, Robust Control, sliding mode control, Internal Model Control are some examples of advanced control techniques. LQR, LQG has been used here for LFC of power system.

Concordia [1] and Cohn [2] have described the basic importance of frequency and tie line power and tie line bias control in case of interconnected power system.

The revolutionary concept of optimal control (optimal regulator) for LFC of an interconnected power system was first started by Elgerd[3]. There was a recommendation from the North American Power Systems Interconnection Committee (NAPSIC) that, each and every control area should have to set its frequency bias coefficient is equal to the Area Frequency Response Characteristics (AFRC). But Elgerd and Fosha [3-4] argued seriously on the basis of frequency bias and by the help of optimal control methods thy presented that for lower bias settings, there is wider stability margin and better response. They have also proved that a state variable model on the basis of optimal control method can highly improvise the stability margins and dynamic response of the load frequency control problem.

R. K. Green [13] discussed a new formulation of LFC principles. He has given sa Concept of transformed LFC, which is heaving the capability to eliminate the requirement of bias setting, by controlling directly the set point frequency of each unit.

The standard definitions of the different terms for LFC of power system are heaving the approval by the IEEE STANDARDS Committee in 1968 [5]. The dynamic model suggestions were described thoroughly by IEEE PESworking groups [7-8]. On the basis of experiences with real implementation of LFC schemes, various modifications to the ACE definition were suggested time to time to cope with the changing environment of power system [10, 12, 13, 15].

MATHMATICAL MODELLING: According to the diagram presented in Fig.1 the equations has been derived [3] and the parameters of the Two area Power System are shown in Table 1.

$$\Delta\dot{f}_1 = -\frac{1}{T_{p1}}\Delta f_1 + \frac{K_{p1}}{T_{p1}}\Delta P_{t1} - \frac{K_{p1}}{T_{p1}}\Delta P_{tie(1,2)} - \frac{K_{p1}}{T_{p1}}\Delta P_{d1} \tag{1}$$

$$\Delta\dot{P}_{t1} = -\frac{1}{Tt_1}\Delta P_{t1} + \frac{1}{Tt_1}\Delta P_{g1} \tag{2}$$

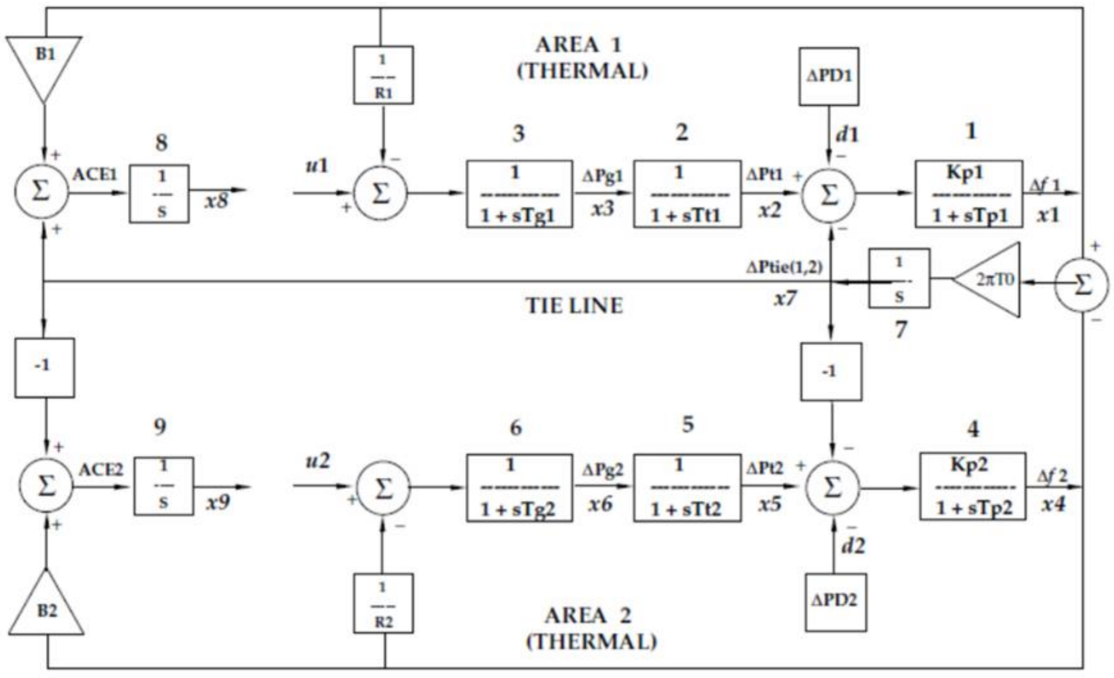

Fig.1: Block diagram model of a two area power system

Table1. Physical parameters of two area power system

Symbol	**Parameter**	**Value**
R_1& R_2	Regulations of Governors in Areas 1, 2	2.4
K_{P1}&K_{P2}	Power System Constants in Areas 1&2	120
T_{P1}&T_{P2}	Power System Time Constants in Areas 1& 2	20
B_1& B_2	Tie Line Frequency Bias in Areas 1&2	0.425
T_0	Synchronizing Coefficient for Tie Line for Two Area Systems	0.07069
T_{g1}& T_{g2}	Governor Time Constants for Thermal Areas 1 & 2	0.08
T_{t1} & T_{t2}	Governor Time Constants for Thermal Areas 1 & 2	0.4

$$\Delta\dot{P}_{g1} = -\frac{1}{R_1 Tg_1}\Delta f_1 - \frac{1}{Tg_1}\Delta P_{g1} + \frac{1}{Tg_1}u_1 \quad (3)$$

$$\Delta\dot{f}_2 = -\frac{1}{T_{p1}}\Delta f_2 + \frac{K_{p2}}{T_{p2}}\Delta P_{t2} + \frac{K_{p2}}{T_{p2}}\Delta P_{tie(1,2)} - \frac{K_{p2}}{T_{p2}}\Delta P_{d2} \quad (4)$$

$$\Delta\dot{P}_{t2} = -\frac{1}{Tt_2}\Delta P_{t2} + \frac{1}{Tt_2}\Delta P_{g2} \quad (5)$$

$$\Delta\dot{P}_{g2} = -\frac{1}{R_2 Tg_2}\Delta f_2 - \frac{1}{Tg_2}\Delta P_{g2} + \frac{1}{Tg_2}u_2 \quad (6)$$

$$\Delta P_{tie(1,2)} = 2\pi T^0 \Delta f_1 - 2\pi T^0 \Delta f_2 \quad (7)$$

$$\dot{\int} AEC_1 dt = B_1\Delta f_1 + \Delta P_{tie(1,2)} \quad (8)$$

$$\dot{\int} AEC_2 dt = B_2\Delta f_2 - \Delta P_{tie(1,2)} \quad (9)$$

The above mathematical model given by the equations (1-9) are linearized across an equilibrium point X_0

X_0=[0 0 0 0 0 0 0 0 0]

The state and output vector here are given by

$$X = [\Delta f_1 \;\; \Delta P_{t1} \;\; \Delta P_{g1} \;\; \Delta f_2 \;\; \Delta P_{t2} \;\; \Delta P_{g2} \;\; \Delta P_{tie(1,2)} \;\; \int AEC_1 dt \;\; \int AEC_2 dt]^T$$

$$Y = [\Delta f_1 \;\; \Delta f_2 \;\; \Delta P_{tie(1,2)}]$$

The Two Area Power System state space model is represented below

$$\dot{X} = AX + Bu + \Gamma d \quad (10)$$

$$Y = CX \quad (11)$$

The system considered here consists of nine states, two control inputs and three outputs. The system matrix can be obtained by linearizing is as below.

$$A = \begin{bmatrix} -0.05 & 6 & 0 & 0 & 0 & 0 & -6 & 0 & 0 \\ 0 & -2.5 & 2.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ -5.2083 & 0 & -12.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.05 & 6 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2.5 & 2.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & -5.2083 & 0 & -12.5 & 0 & 0 & 0 \\ 0.4442 & 0 & 0 & -0.4442 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0.425 & 0 & 0 & -1 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 12.5 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 12.5 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

DESIGN OF OPTIMAL CONTROLLER (LQR): The quadratic form of PI is taken as

$$PI = \frac{1}{2}\int_0^{\infty} (x^T Q x + u^T R u)dt \tag{12}$$

Where, ‘Q’ is the ‘State Weighing Matrix’ which is real, symmetric and positive semi definite in nature and ‘R’ is the ‘Control Weighing Matrix’ heaving real, symmetric and positive definite character.The two matrices Q and R obtained according to the below system requirements.

So the matrices’Q’ and ‘R’ arefound by heat and trial method:

$$Q = \begin{bmatrix} 0.180625 & 0 & 0 & 0 & 0 & 0 & 0.425 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.180625 & 0 & 0 & -0.425 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & -0.425 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The optimal control law is given by

$$u = -Kx \tag{13}$$

The feedback gain matrix ‘K’ is given by

$$K = R^{-1}B^T S \tag{14}$$

Where ’S’ is a real, symmetric and positive definite matrix which is obtained by solving the matrix Riccatti Equation given by:

$$A^T S + SA - SBR^{-1}B^T S + Q = 0 \quad (15)$$

So, the overall closed loop equation with state feedback control is:

$$\dot{X} = AX + B(-KX) = (A - BK)X = A_c X \quad (16)$$

$A_c = (A - BK)$ is a matrix calledclosed loop system matrix**.** The Eigen values of A_c will show the stability of the system with state feedback controller.After the MATLAB program ran the calculated values K and $A_c$are obtained as follows:

$$K = \begin{bmatrix} 0.4226 & 0.8294 & 0.1538 & -0.063 & -0.1156 & -0.02 & -0.2737 & 1 & 0 \\ -0.063 & -0.1156 & -0.02 & 0.4226 & 0.8294 & 0.1538 & 0.2737 & 0 & 1 \end{bmatrix}$$

$$A_c = \begin{bmatrix} -0.05 & 6 & 0 & 0 & 0 & 0 & -6 & 0 & 0 \\ 0 & -2.5 & 2.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 10.4908 & -10.3673 & -14.423 & 0.7871 & 1.4444 & 0.2504 & 3.4208 & -12.5 & 0 \\ 0 & 0 & 0 & -0.05 & 6 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2.5 & 2.5 & 0 & 0 & 0 \\ 0.7871 & 1.4444 & 0.2504 & -10.4908 & -10.3673 & -14.423 & -3.4208 & 0 & 0 \\ 0.4442 & 0 & 0 & -0.4442 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0.425 & 0 & 0 & 0 & -1 & 0 \end{bmatrix}$$

STATE ESTIMATION BY KALMAN FILTER: To design a control system on the basis of stochastic (non-deterministic) plant we cannot depend on full state feedback as we could not predict the state vector X(t) for the stochastic plant.

Hence, there is requirement of an observer which can estimate the state vector on the basic of measured output Y(t) and present known input u(t). By the use of pole placement method an observer can be designed, that has poles at the desired location. But due to some demerits of pole placement method it is not applicable for this case. The fact here is that the measured output of the plant Y(t) and the plant state vector X(t) are random (measured for infinite time) vectors. So, an observer is required that can estimate the state vectors on the basis of statistical description plant state and plant output vector. Kaman filter is such an observer. It is an optimal observer which is minimizing the statistical measure of estimation error given by:

$$e_0(t) = x(t) - x_0(t) \quad (17)$$

$e_0(t)$ is the estimated error and $x_0(t)$ is the state vector estimated.The state equation for kalman filter of a time invariant observer is written below

$$x_0(t) = Ax_0(t) + Bu(t) + L[y(t) - Cx_0 - Du(t)] \quad (18)$$

'L' is the Kalman filter gain matrix.

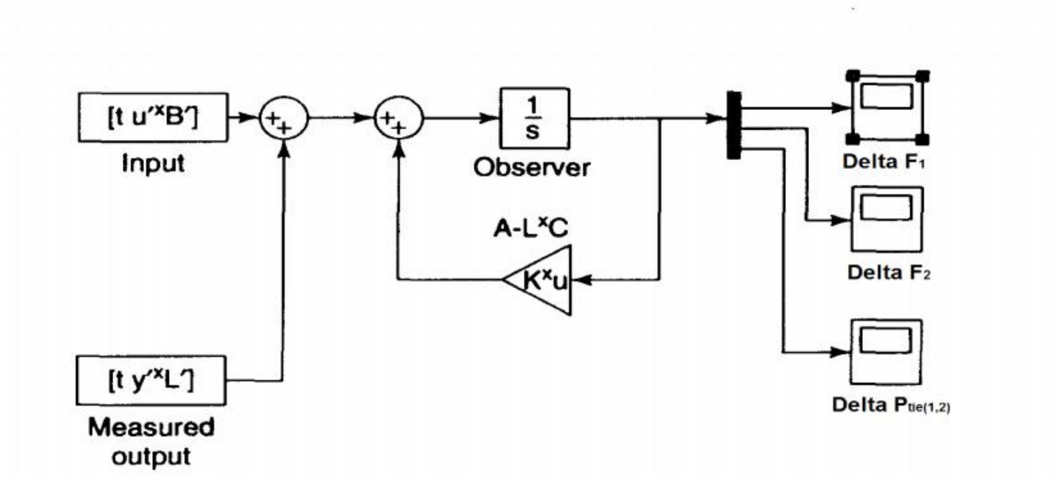

Fig.2: Simulation diagram of kalman filter

The plant considered here is heaving the following linear time invariant state space representation as follow:

$$\dot{x}(t) = Ax(t) + Bu(t) + Fv(t) \quad (19)$$

$$y(t) = Cx(t) + Du(t) + z(t) \quad (20)$$

Where v(t) and z(t) are the process and measurement noise respectively . The state equation of the optimal estimation error can be written as:

$$\dot{e}_0(t) = (A - LC)e_0(t) + Fv(t) - Lz(t) \quad (21)$$

As v(t) and z(t) both are white noises, the vector below can also be a white noise:

$$w(t) = Fv(t) - Lz(t) \quad (22)$$

So, the abbreviation of the state equation of the optimal estimation error can be written as:

$$\dot{e}_0(t) = A_0 e_0(t) + w(t) \quad (23)$$

$$A_0 = A\text{-}LC \quad (24)$$

So, after a lot of mathematical calculation a riccatic equation equation will be derived for the linear time invariant plant is

$$\frac{dR_e^0(t,t)}{dt} = AR_e^0(t,t) + R_e^0(t,t)A^T - R_e^0(t,t)C^T Z^{-1}(t)CR_e^0(t,t) + FV(t)F^T \quad (25)$$

Where Z(t)and V(t) are the power spectral densities of process and measurement noise.As the system here is a time invariant system so the riccatic equation can be written as:

$$A_G R_e^0 + R_e^0 A_G^T - R_e^0 C^T Z^{-1} C R_e^0 + FV_G F^T = 0 \quad (26)$$

$$A_G = A - F\varphi Z^{-1}C \text{ and } A_G = A - F\varphi Z^{-1}C \quad (27)$$

From the matrix riccatic equation the value of R_e^0 is found out and then the value of' L' is found out by the below equation:

$$L = R_e^0 C^T Z^{-1} \quad (28)$$

After analyzing in MATLAB the matrices L and A_0 are found

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$$L\ X\ \begin{array}{ccc} 2.8977 & -0.2973 & -0.2890 \\ 0.3659 & 0.1359 & 0.1452 \\ -0.3279 & 0.1247 & 0.1106 \\ -0.2973 & 2.8977 & 0.2890 \\ 0.1359 & 0.3659 & -0.1452 \\ 0.1247 & -0.3279 & -0.1106 \\ -0.2890 & 0.2890 & 0.5653 \\ -0.6409 & -0.0206 & -0.0218 \\ -0.0206 & -0.6409 & 0.0218 \end{array}$$

$$A_0\ X\ \begin{array}{ccccccccc} -2.9477 & 6 & 0 & 0.2973 & 0 & 0 & -5.7110 & 0 & 0 \\ -0.3659 & -2.5 & 2.5 & -0.1359 & 0 & 0 & -0.1452 & 0 & 0 \\ -4.8804 & 0 & -12.5 & -0.1247 & 0 & 0 & -0.1106 & -12.5 & 0 \\ 0.2973 & 0 & 0 & -2.9477 & 6 & 0 & 5.7110 & 0 & 0 \\ Z0.1359 & 0 & 0 & -0.3659 & -2.5 & 2.5 & 0.1452 & 0 & 0 \\ Z0.1247 & 0 & 0 & -4.8804 & 0 & -12.5 & 0.1106 & 0 & -12.5 \\ 0.7332 & 0 & 0 & -0.7332 & 0 & 0 & -0.5653 & 0 & 0 \\ 1.0659 & 0 & 0 & 0.0206 & 0 & 0 & 1.0218 & 0 & 0 \\ 0.0206 & 0 & 0 & 1.0659 & 0 & 0 & -1.0218 & 0 & 0 \end{array}$$

OPTIMAL COMPENSATOR(LQG): In this an optimal regulator (LQR) and an optimal observer (kalman filter) are designed separately for Load Frequency Control (LFC) of a two area power system. At first The Linear Quadratic Regulator is designed which is the cause of minimization of the quadratic objective function. Than an optimal observer (Kalman filter) is introduced for LFC with presence of noise (process and measurement noise) considered as white noises. The combination of optimal regulator with the optimal observer forms anoptimal compensator which is called as Linear Quadratic Gaussian (LQG).

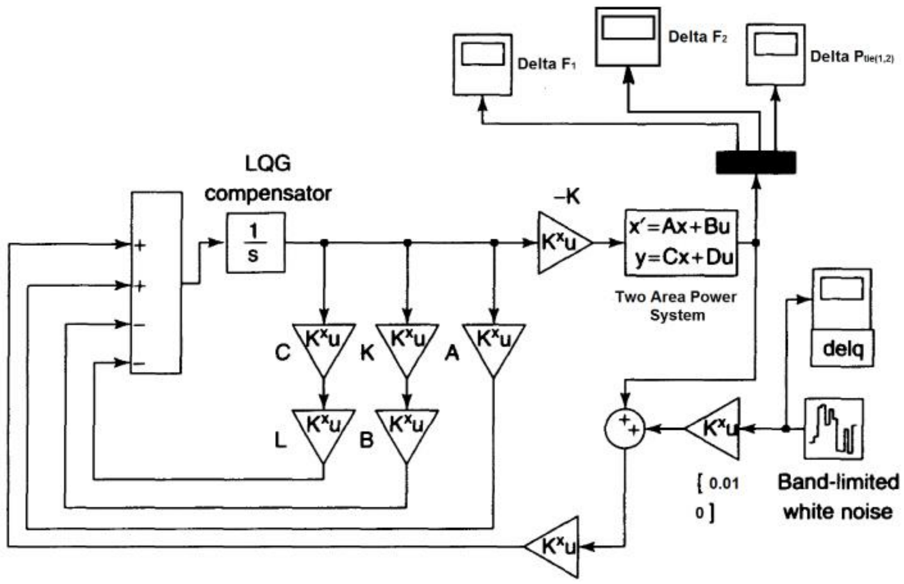

Fig.3: Simulink diagram of LQG operating on LFC of two area power system

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A state space representation of the compensator operating a noisy plant is written below which represents the state and output equations:

$$\acute{x}_0(t)\,X(A\,ZBK\,ZLC\,\Gamma\,LDK)x_0(t)\,\Gamma\,Ly(t) \quad (29)$$

$$u(t)\,XZKx_0(t) \quad (30)$$

Where ‘L’ and ‘K’ are the kalman filter and optimal regulator gain matrices respectively.

SIMULATION AND RESULT: Fig.4to Fig.6 are showing the estimated states of deviation in frequency for both the areas ($\zeta f_1, \zeta f_2$) and the power deviation in tie line ($\zeta P_{tie(1,2)}$) for a power system heaving two control areas with thermal non-reheat turbines.The change in load powers which are the input disturbances are taken as, $d_1 = 0.01$ pu , $d_2 = 0.00$ pu..

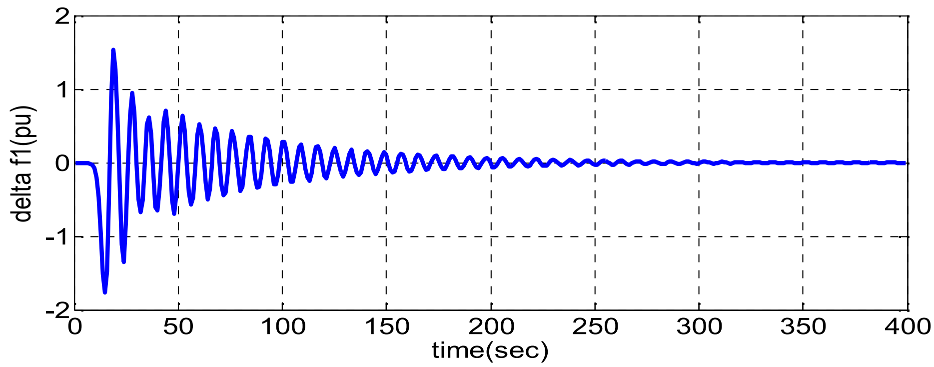

Fig.4: change in frequency V/S time in area-1 for 0.01 step load change in area-1

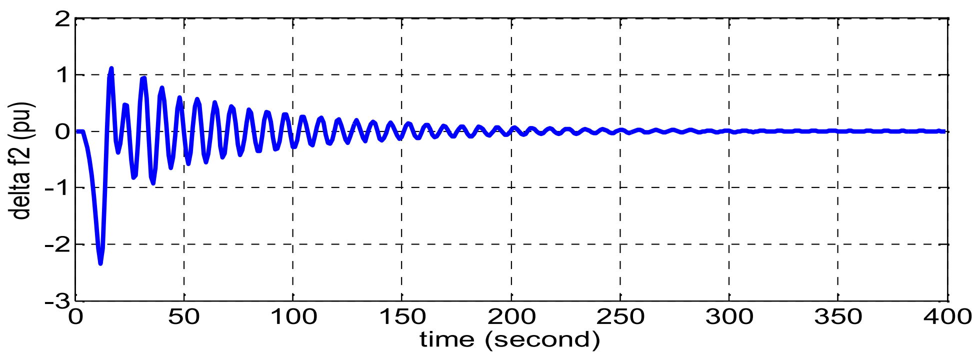

Fig.5: change in frequency V/S time in area-2 for 0.01 step load change in area-1

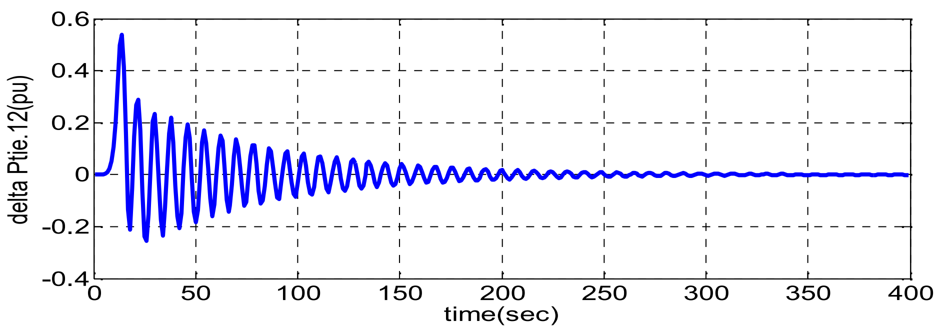

Fig.6: change in tie line power V/S time for 0.01 step load change in area-1

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These states are estimated by an optimal observer Kalman filter at the presence of process and measurement noise taken as white Gaussian noise. The figures shows that the estimated states of frequency deviation and tie line power deviation are stable due to governor action. But the responses are oscillatory in nature.

Fig.7 to Fig.9 are showing the dynamic responses of deviation in frequency for both the areas ($\zeta f_1, \zeta f_2$) and the power deviation in tie line ($\zeta P_{tie(1,2)}$) for a power system heaving two control areas with thermal non-reheat turbines. The change in load powers which are the input disturbanceare taken as $d_1 = 0.01$ pu , $d_2 = 0.00$ pu. The figures shown here represents the performances of optimal compensator compared with the performance of optimal regulator, applied for LFC of a two area power system which proves the system stability with less settling time.

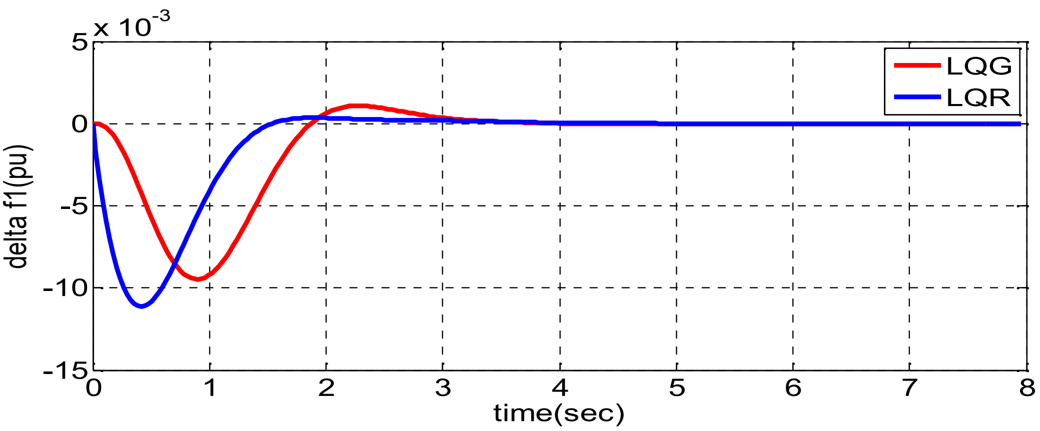

Fig.7: change in frequency V/S time in area-2 for 0.01 step load change in area-1

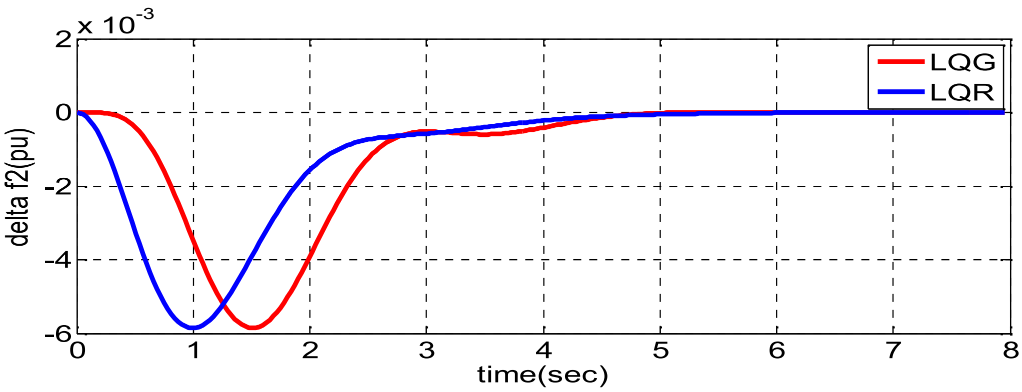

Fig.8: change in frequency V/S time in area-2 for 0.01 step load change in area-1

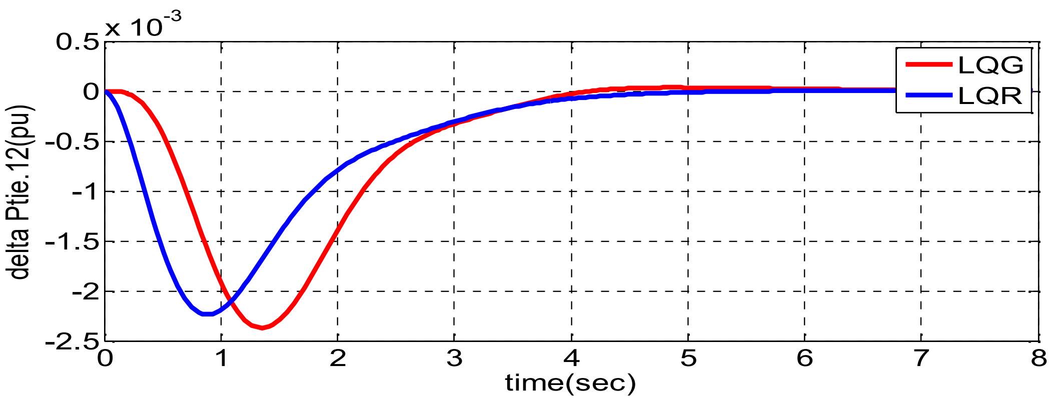

Fig.9: change in tie line power V/S time for 0.01 step load change in area-1

The figures here are comparing the results of LQR with the results of LQG for a two area power system. They show that the responses of LQG are around same as the responses of LQR. From the figures we can clearly see that, LQG recovers the performance of LQR from noise environment.

Appendix:

Δf_1&Δf_2: Frequency Deviations in Areas 1&2
$\Delta P_{tie(1,2)}$: Tie Line Power Deviation in Two Areas Systems
u_1 & u_2 : Control Inputs in Areas 1& 2
ΔP_{g1} & ΔP_{g2} : Deviations in Governor Power Outputs in Thermal Areas 1 & 2
ΔP_{t1}& ΔP_{t2} : Deviations in Turbine Power Outputs in Thermal Areas 1 & 2
ΔP_{D1} &ΔP_{D2}: Load Disturbances in Areas 1& 2

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