LOAD FREQUENCY CONTROL OF POWER SYSTEM

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By

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C E R T I F I C A T E

This is to certify that the thesis entitled ***"LOAD FREQUENCY CONTROL OF POWER SYSTEM"*** *being submitted by* ***Mr. Niranjan Behera****, to the National Institute of Technology, Rourkela (Deemed University) for the award of degree of Master of Technology in* ***Electrical Engineering*** *with specialization in* ***"Control and Automation"****, is a bonafide research work carried out by him in the* ***Department of Electrical Engineering****, under my supervision and guidance. I believe that this thesis fulfils a part of the requirements for the award of degree of Master of Technology. The research reports and the results embodied in this thesis have not been submitted in parts or full to any other University or Institute for the award of any other degree or diploma.*

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ABSTRACT

In case 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 a 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 proposed research work advanced control technique (optimal controller, optimal compensator) and IMC-PID control technique has been applied for LFC of two area power systems. The optimal controllers and compensators are capable of working without full state feedback and at the presence of process and measurement noise. The IMC-PID controller is capable of giving better response and is applicable under different nonlinearities.

TABLE OF CONTENTS

TITLE .... PAGE

ACKNOWLEDGEMENTS.. (i)

ABSTRACT.. (ii)

TABLE OF CONTENTS... (iii)

LIST OF SYMBOLS... (v)

LIST OF FIGURES...(vi)

CHAPTER 1: INTRODUCTION.. 1

1.1 Load Frequency Control Problem...1

1.2 Interconnected Power Systems...2

1.2.1 Advantages of Interconnection...3

1.3 Two -Area Power System...3

1.4 Major Drawbacks of Conventional Integral Controller.................................4

1.5 Need of Advance Control Technique..4

1.6 Objectives...5

1.7 Literature Review..5

1.7.1 Overview of LFC schemes and Review of Literature..........................5

1.7.2 Literature on LFC Related Power System Model...............................6

1.7.3 Literature Review on LFC Related to Control Techniques...................6

1.8 Organization of Thesis..7

CHAPTER 2: MODELLING OF POWER SYSTEM FOR LFC..8

2.1 Introduction..8

2.2 Model of a Two Area Thermal Non-Reheat Power System............................8

2.3 State Space Representation of Two Area Power System..............................10

2.4 Four-Area Power System...13

CHAPTER 3: DESIGN OF OPTIMAL REGULATOR AND

OPTIMAL COMPENSATOR 15

3.1 Introduction... 15

3.2 Linear Quadratic Regulator..15

3.2.1 Design of Optimal Controller (LQR)...15

3.2.2 Determination of Feedback Gain Matrix (K)......................................16

3.2.3 Analysis of System Using MATLAB...18

3.3 State Estimation by Kalman Filter..20
3.3.1 Derivation of Kalman Gain Matrix (L)...22
3.3.2 Analysis using MATLAB 23
3.4 Linear Quadratic Gaussian (LQG)...24
CHAPTER 4: TUNING OF PID LOAD FREQUENCY CONTROLLER VIA IMC...........27
4.1 Introduction..27
4.2 IMC Design..27
4.3 LFC PID Design..29
4.3.1 LFC Design without drop characteristic..30
4.3.2 LFC Design with Drop Characteristic..32
4.4 Two-Area Extension..32
CHAPTER 5: RESULT AND DISCUSSION... 35
5.1 Introduction..35
5.2 Results and Discussion..35
5.2.1 Results of LQR for LFC of Two Area Power System.........................35
5.2.2 Results of LQR for a Four Area Power System..................................38
5.2.3 Estimated States for LFC of Power System by Kalman Filter............39
5.2.4 Results of LQG for LFC of Two Area Power System........................40
5.2.5 Results of IMC-PID Controller for LFC of Two-Area Power System...41
CHAPTER 7: CONCLUSIONS AND SCOPE FOR FURTHER WORK.............................42
6.1 Conclusions..42
6.2 Scope for Future Work..43
REFERENCES...44

LIST OF SYMBOLS

$\Delta f_1 \& \Delta f_2$	: Frequency Deviations in Areas 1&2
$\Delta P_{tie(1,2)}$	: Tie Line Power Deviation in Two Areas Systems
R_1 & R_2	: Regulations of Governors in Areas 1, 2
K_T	: Integral Controller Gain in Thermal Areas
K_H	: Integral Controller Gain in Hydro Area
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_{G1}	: Deviation in Governor (stage 1) Power Output in Hydro Area
ΔP_{G2}	: Deviation in Governor (stage 2) Power Output in Hydro Area
ΔP_{t1} & ΔP_{t2}	: Deviations in Turbine Power Outputs in Thermal Areas 1 & 2
ΔP_{D1} &ΔP_{D2}	: Load Disturbances in Areas 1& 2
K_{P1}&K_{P2}	: Power System Constants in Areas 1&2
T_{P1}&T_{P2}	: Power System Time Constants in Areas 1& 2
B_1 & B_2	: Tie Line Frequency Bias in Areas 1&2
T_0	: Synchronizing Coefficient for Tie Line for Two Area Systems
T_{12}	: Synchronizing Coefficients for Tie Lines between Pair of Areas For the Two-Area System
T_{g1} & T_{g2}	: Governor Time Constants for Thermal Areas 1 & 2
T_{t1} & T_{t2}	: Turbine Time Constants for Thermal Areas 1 & 2
a_{12}	: Ratio of Rated Powers of a Pair of Areas in the Two Area System

LIST OF FIGURES

Fig. 2.1: Two area thermal (non reheat) power system with integral controller........................9

Fig. 2.2: State space model of two area power system (thermal no reheat).............................10

Fig. 3.1: Simulation diagram of Kalman filter...23

Fig. 3.2: Simulation diagram of LQG operating on LFC of two area power system...............26

Fig .4.1: IMC structure...27

Fig .4.2: IMC equivalent conventional feedback configuration...29

Fig .4.3: Linear model of a single area power system..29

Fig .4.4: Equivalent closed loop system for LFC of two area power system...........................33

Fig. 5.1: Change in frequency V/S time in area-1 for 0.01 step load change in area-1 36

Fig. 5.2: Change in frequency V/S time in area-2 for 0.01 step load change in area-1 36

Fig. 5.3: Change in tie line power V/S time for 0.01 step load change in area-1 36

Fig. 5.4: Change in frequency V/S time in area-1 for $\Delta P_{d1} = 0.0085$ pu ,$\Delta P_{d2} = 0.0025$ pu ...37

Fig. 5.5: Change in frequency V/S time in area-2 for $\Delta P_{d1} = 0.0085$ pu ,$\Delta P_{d2} = 0.0025$ pu ...37

Fig. 5.6: Change in Tie Line power V/S time for $\Delta P_{d1} = 0.0085$ pu ,$\Delta P_{d2} = 0.0025$ pu 37

Fig. 5.7: Changes Δf_1, Δf_2 & Δf_3 V/S time for 0.01 step load change in area-1......................38

Fig. 5.8: Changes Δf_4, $\Delta P_{tie(1,2)}$ & $\Delta P_{tie(3,1)}$ V/S time for 0.01 step load change in area-1.......38

Fig. 5.9: changes $\Delta P_{tie(3,4)}$ $\Delta P_{tie(1,4)}$ V/S time for 0.01 step load change in area-1..................38

Fig. 5.10: Change in frequency V/S time in area-1 for 0.01 step load change in area-1 39

Fig .5.11: Change in frequency V/S time in area-2 for 0.01 step load change in area-1 39

Fig .5.12: Change in tie line power V/S time for 0.01 step load change in area-1..................39

Fig.5.13: Change in frequency V/S time in area-2 for 0.01 step load change in area-1..........40

Fig.5.14: Change in frequency V/S time in area-2 for 0.01 step load change in area-1 40

Fig.5.15: Change in tie line power V/S time for 0.01 step load change in area-1 40

Fig.5.16: Change in frequency V/S time in area-1 for 0.01 step load change in area-1 41

Fig.5.17: Change in frequency V/S time in area-2 for 0.01 step load change in area-1 41

Fig.5.18: Change in tie line power V/S time for 0.01 step load change in area-1 41

CHAPTER-1

INTRODUCTION

1.1 Load Frequency Control Problem

The power systems means, it is the interconnection of more than one control areas through tie lines. The generators in a control area always vary their speed together (speed up or slow down) for maintenance of frequency and the relative power angles to the predefined values in both static and dynamic conditions. If there is any sudden load change occurs in a control area of an interconnected power system then there will be frequency deviation as well as tie line power deviation.

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 set value of frequency then it creates mismatch in power both for generation and demand. This mismatch problem is 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. In case of large power systems the equilibrium can be obtained by them at a single point when the newly added load is distracted by reducing the power consumed by the old load and power related to kinetic energy removed from the system. Definitely at a cost of frequency reduction we are getting this equilibrium .The system creates some control action to maintain this equilibrium and no governor action is required for this. The reduction in frequency under such condition is very large.

However, governor is introduced into action and generator output is increased for larger mismatch. Now here the equilibrium point is obtained when the newly added load is distracted by reducing the power consumed by the old load and the increased generation by the governor action. Thus, there is a reduction in amount of kinetic energy which is extracted from the system to a large extent, but not totally. So the frequency decline still exists for this category of equilibrium. Whereas for this case it is much smaller than the previous one mentioned above. This type of equilibrium is generally obtained within 10 to 12 seconds just after the load addition. And this governor action is called primary control.

Science 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.

In a two area interconnected power system, where the two areas are connected through tie lines, the control area are supplied by each area and the power flow is allowed by the tie lines among the areas. Whereas, the output frequencies of all the areas are affected due to a small change in load in any of the areas so as the tie line power flow are affected. So the transient situation information's of all other areas are needed by the control system of each area to restore the pre defined values of tie line powers and area frequency. Each output frequency finds the information about its own area and the tie line power deviation finds the information about the other areas. For example in a two area power system, the information can be written as $B_i\Delta f_i+\Delta P_{tie}$. B = frequency bias, f = predefined frequency And P_{tie} is the power in tie line. This is the Area Control Error (ACE) which is the input to the controller.

Thus the load frequency control of a multi area power system generally incorporates proper control system, by which the area frequencies could brought back to its predefined value or very nearer to its predefined value so as the tie line power, when the is sudden change in load occurs.

1.2 Interconnected Power Systems:

According to practical point of view, the load frequency control problem of interconnected power system is much more important than the isolated (single area) power systems. Whereas the theory and knowledge of a isolated power system is equally important for understanding the overall view of interconnected power system.

Generally now days all power systems are tied with their neighbouring areas and the Load Frequency Control Problem become a joint undertaking. Some basic operating principle of an interconnected power system is written below:

1. The loads should strive to be carried by their own control areas under normal operating conditions, except the scheduled portion of the loads of other members, as mutually agreed upon.
2. Each area must have to agree upon adopting, regulating, control strategies and equipment which are beneficial for both normal and abnormal conditions.

1.2.1 Advantages of Interconnection:

1. Effect of size: This one is one of the most important advantages for the whole interconnected power system. When a load block is added, at the initial time, the required energy is temporarily borrowed from the system kinetic energy. Generally the availability of energy is more for larger systems. So there is comparatively less static frequency drop. Whereas, for a single area power system the frequency drop may be a bit higher for same amount in load change.

2. Need of reduced reserve capacity: As the peak demands do not have any certain time, they may occur at any random time of the day in many areas, for a large power system the ratio between load peak and load average is smaller as compared to smaller systems. Therefore it is obvious that all interconnected power system areas may benefit from a decreased need of capacity reserved by the scheduled arrangement of interchanging energy.

1.3 Two Area Power System

If there is interconnection exists between two control areas through tie line than that is called a two area interconnected power system. Fig. 1.1 shows a two area power system where each area supplies to its own area and the power flow between the areas are allowed by the tie line.

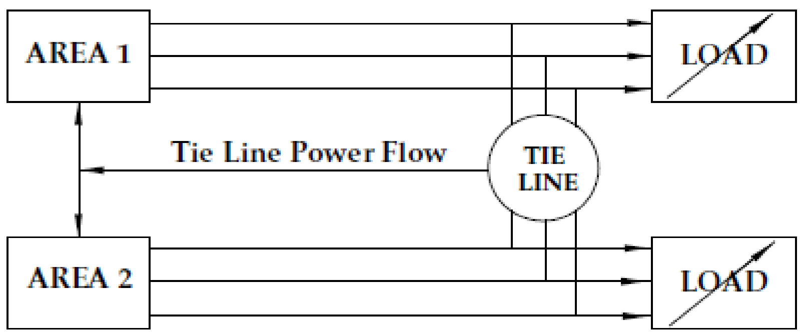

Fig. 1.1: Two area interconnected power system

In this case of two area power system an assumption is taken that the individual areas are strong and the tie line which connects the two area is weak. Here a single frequency is characterized throughout a single area; means the network area is ‘strong’ or ‘rigid’. There may be any numbers of control areas in an interconnected power system.

1.4 Major Drawbacks of Conventional Integral Controller:

The drawbacks can be summarised as

1. They are very slow in operation.
2. There is some inherent nonlinearity of different power system components, which the integral controller does not care. Governor dead band effects, generation rate constraints (GRCs) and the use of reheat type turbines in thermal systems are some of the examples of inherent nonlinearities.
3. While there is continuously load changes occur during daily cycle, this changes the operating point accordingly. It is generally known as the inherent characteristic of power system. For good results the gain of the integrator should has to be changed repeatedly according to the change in operating point. Again it should also be ensure that, the value of the gain compromises the best between fast transient recovery and low overshoot in case of dynamic response. Practically to achieve this is very difficult. So basically an integral controller is known as a fixed type of controller. It is optimal in one condition but at another operating point it is unsuitable.

Therefore, the control rule applied should be suitable with the dynamics of power system. So an advance controller would be suitable for controlling the system.

1.5 Need of Advance Control Technique:

Implementation of advanced control technique provides great help in LFC of power systems. Now days there are more complex power systems and required operation in less structured and uncertain environment. Similarly innovative and improved control is required for economic, secure and stable operation. 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, IMC has been used here for LFC of power system.

1.6 Objectives:

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.

1.7 Literature Review:

1.7.1 Overview of LFC schemes and Review of Literature:

The first attempt in case of LFC has to control the power system frequency by the help of the governor. This technique of governor control was not sufficient for the stabilization of the system. so, a extra supplementary control technique was introduced to the governor By the help of a variable proportional directly to the deviation of frequency plus its integral. This scheme contains classical approach of Load Frequency Control (LFC) of power system. Cohn has done earlier works in the important area of LFC. Concordia et al [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.

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 PES working groups [5-6]. 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 [7, 8, 9, and 10].

R. K. Green [9] discussed a new formulation of LFC principles. He has given a 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.

1.7.2 Literature on LFC Related Power System Model:

For more than last three decades researches are going on load frequency control of power system. Linearized models of multi area (including two areas) power systems are considered so far for best performance.

K. C. Divya et al [11] has presented the hydro- hydro Power system simulation model. They have taken an assumption of same frequencies of all areas, to overcome the difficulties of extending the traditional approach. The model was obtained by ignoring the difference in frequencies between the control areas.

E. C. Tacker et al [12] has discussed the LFC of interconnected power system and investigated the formulation of LFC via linear control theory. A comparison between three relatives was made to the ability for motivation of the transient response of system variables. Later, the effect of Generation Rate Constraint (GRC) was introduced in these studies, considering both discrete and continuous power system.

B. oni et al [13] described the effect of implementation of non linear tie line bias characteristic. Using UMC hybrid simulator this type of study is performed to simulate a typical type of power system voltage and frequency sensitivity, governor dead band of loads.

1.7.3 Literature Review on LFC Related to Control Techniques:

The continuing work by numerous numbers of engineers of control engineering has generated links between the closed loop transient response (in time domain) and frequency response. The research is carried over using different classical control techniques. It is revealed that it will result comparatively large transient frequency deviation and overshoots [3, 15]. Moreover, generally the settling time of frequency deviation for the system is relatively long (10 to 20 seconds) .The LFC optimal regulator design techniques using optimal control theory stimulate the engineers of control engineering to design a control system with optimal controller, in reference to given performance criterion. Fosha and Elgerd [4] were the two persons who first presented their work on optimal LFC regulator using this process. A power system of two identical areas interconnected through tie line heaving non reheat turbine is considered for investigation.

R. K. Cavin et al [16] has considered the problem of LFC for an interconnected system from the theory of optimal stochastic system point of view. A algorithm based on control strategy was developed which gives improvised performance of power system for both small and large signal modes of operation. The special attractive feature of the control scheme proposed here was that it required the recently used variables. That are deviation in frequency and scheduled inter change deviations taken as input.

1.8 Organization of Thesis:

The thesis is organized as follows:

Chapter 1 includes the brief description of Load Frequency Control problem, introduction to interconnected power system, demerits of conventional integral controller, need of advance control technique, objectives LFC and literature review.

Chapter 2 deals with the modelling of two area interconnected power system with convention integral control, state space modelling of the two area interconnected power system, derivation of state equation and state matrices etc.

Chapter 3 includes optimal controller technique applied for LFC of power system, Design of Linear Quadratic Regulator LQR, state estimation by Kalman filter, design of Linear Quadratic Gaussian (LQG) for LFC of two area power system, and the summery etc.

Chapter 4 consist introduction to tuning of PID controller for LFC of power system via IMC, IMC design for an isolated power system, equivalent PID design for LFC of power system, extension of this IMC PID design procedure for two area power system etc.

Chapter 5 contains the result and analysis, results of LQR for a two area power system, the estimated states resulted by Kalman filter, results of LQG for a two area power system and results of IMC-PID design for a two area power system.

Chapter 6 is the chapter of conclusion and scope for future work.

CHAPTER 2

MODELLING OF POWER SYSTEM FOR LFC

2.1 Introduction:

It is very necessary to obtain the suitable models of the power systems for LFC studies. In this research work a two area power system (two area thermal-thermal non reheat) model has been taken.

The model mentioned here is the integral control scheme of an interconnected power system. This chapter dealt with the state space modelling of the mentioned power system which is designed for the implementation of optimal controllers and their stability studies.

The model mentioned above is subsequently used on chapter-3 for the application of optimal controllers for LFC.

2.2 Model of a Two Area Thermal Non-Reheat Power System:

The block diagram model of two area (thermal non reheat) power system with integral controller is shown in Fig. 2.1.

The state equations of the system are produced with the help of the transfer function of the blocks named 1to 7. From the block diagram model it is clearly seen that there are two control inputs named u_1 and u_2.

The block diagram below which represents a two area power system model is heaving two control areas connected to each other through a line heaving its own dynamics (block 7) called tie line. Both the control areas of the power system are taken similar. As both the control areas contain thermal non reheat turbine.

From the figure it is clearly seen that the control areas are made-up with three block each with an integral controller block. The three blocks are namely governor block, turbine block, and the power system block which is actually the load block. Therefore total 9 blocks are present for the whole system.

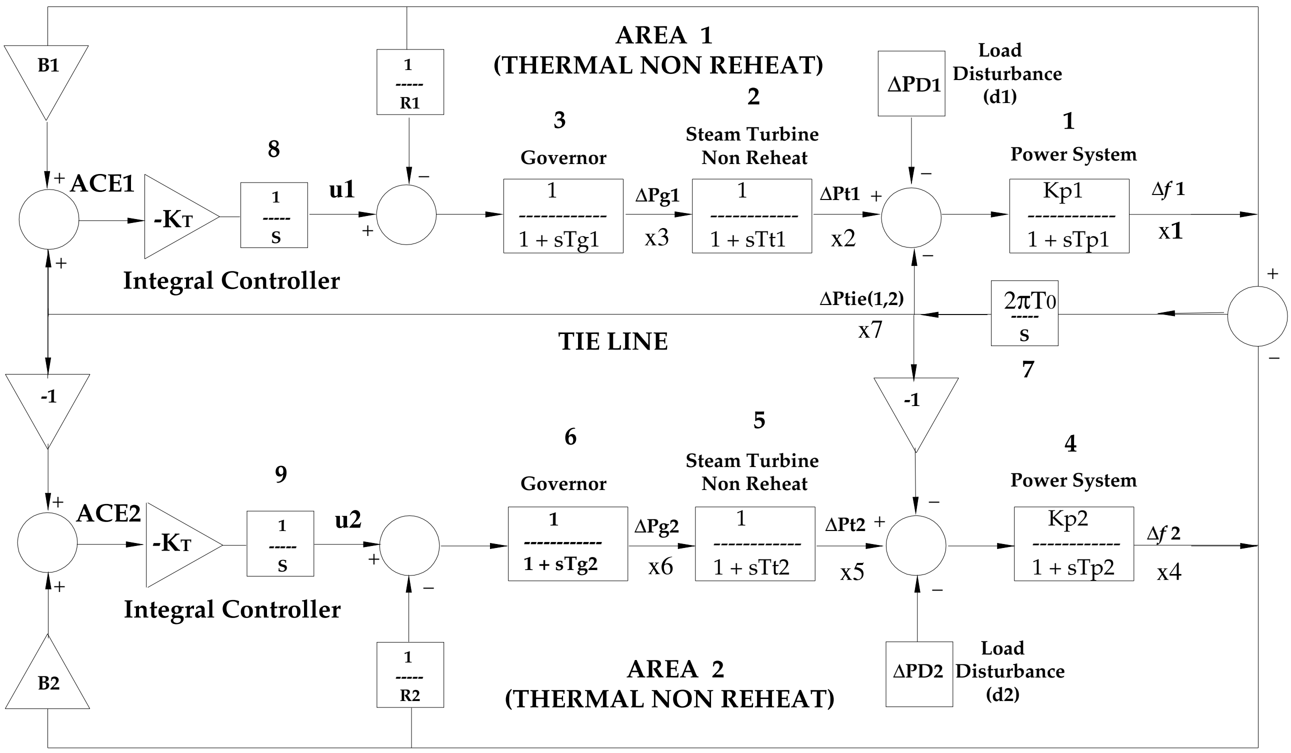

Fig. 2.1: Two area thermal (non reheat) power system with integral controller

Explaining about the block diagram, it is constructed by the combination of two control areas through tie line. Both areas consist of four blocks each and another one block (block 7) represents the tie line power. So there are total nine blocks present, which says that there is nine state equations for a two area power system (thermal non reheat) with integral controller.

The control input equations can be written as below:

For area 1 (at block 8)

$$\dot{u}_1 = -K_T(ACE_1) = -K_T(B_1 x_1 + x_7) \tag{2.1}$$

For area 2 (at block 9)

$$\dot{u}_2 = -K_T(ACE_2) = -K_T(B_2 x_4 - x_7) \tag{2.2}$$

Where ACE_1 and ACE_2 are the Area Control Errors of area-1 and area-2 respectively. K_T is the integral gain for both the areas.

2.3 State Space Representation of Two Area (Thermal Non Reheat) Power System:

For a two area (thermal non reheat) power system a state space model has been developed with all the states (9 states) being fed back as shown in Fig. 2.2

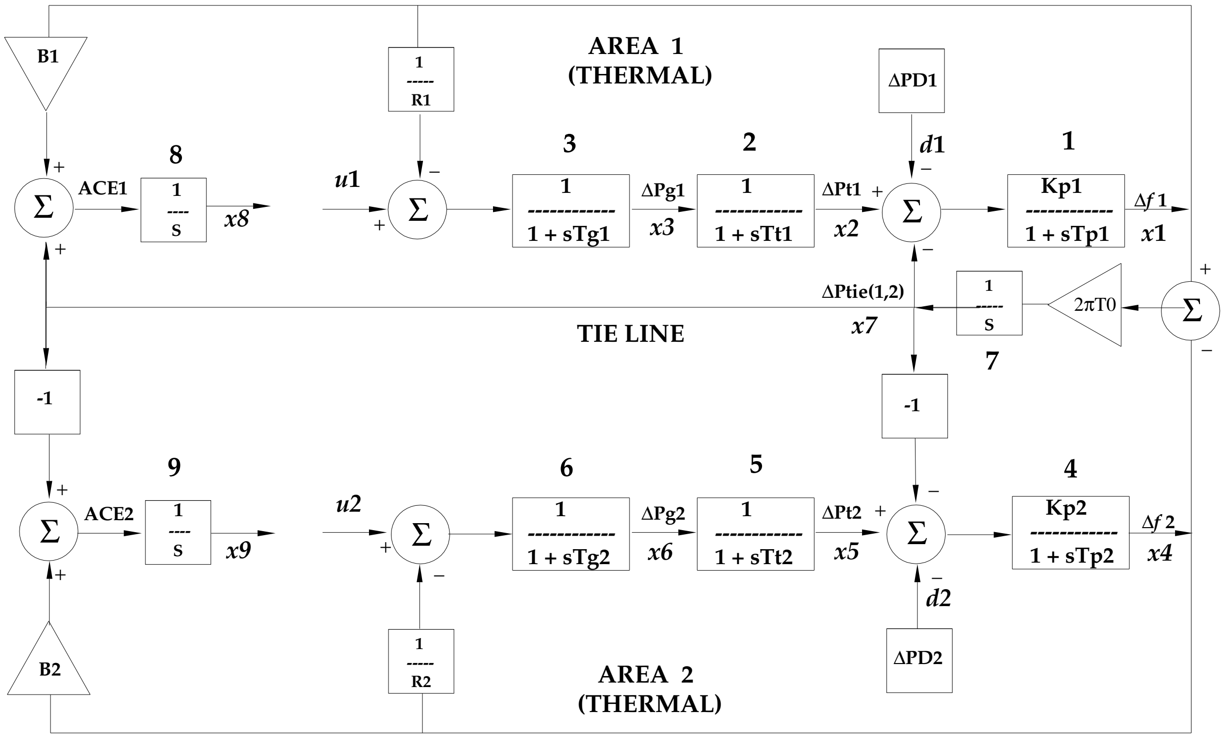

Fig. 2.2: State space model of two area power system (thermal no reheat)

State Variables:

$$x_1 = \Delta f_1 \qquad x_2 = \Delta Pt_1 \qquad x_3 = \Delta Pg_1 \qquad x_4 = \Delta f_2 \qquad x_5 = \Delta Pt_2$$

$$x_6 = \Delta Pg_2 \qquad x_7 = \Delta P_{tie(1,2)} \qquad x_8 = \int AEC_1 dt \qquad x_9 = \int AEC_2 dt$$

Control Input Variables:

u_1 and u_2.

Disturbance Input Variables:

$d_1 = \Delta P_{d1}$ and $d_2 = \Delta P_{d2}$.

State Equation Representation:

The state equations are found out from transfer function of the blocks, 1 to 9 (Fig. 2.2). There exists an equation corresponding to each block. These following are the state equations of the power system under study.

Block 1

$$x_1 + T_{p1}\dot{x}_1 = K_{p1}(x_2 - x_7 - d_1) \tag{2.3}$$

$$\text{i.e.}\quad \dot{x}_1 = -\frac{1}{T_{p1}}x_1 + \frac{K_{p1}}{T_{p1}}x_2 - \frac{K_{p1}}{T_{p1}}x_7 - \frac{K_{p1}}{T_{p1}}d_1 \tag{2.4}$$

Block 2

$$x_2 + Tt_1\dot{x}_2 = x_3 \tag{2.5}$$

$$\text{i.e.}\quad \dot{x}_2 = -\frac{1}{Tt_1}x_2 + \frac{1}{Tt_1}x_3 \tag{2.6}$$

Block 3

$$x_3 + Tg_1\dot{x}_3 = -\frac{1}{R_1}x_1 + u_1 \tag{2.7}$$

$$\text{i.e.}\quad \dot{x}_3 = -\frac{1}{R_1Tg_1}x_1 - \frac{1}{Tg_1}x_3 + \frac{1}{Tg_1}u_1 \tag{2.8}$$

Block 4

$$x_4 + T_{p2}\dot{x}_4 = K_{p2}(x_5 + x_7 - d_2) \tag{2.9}$$

$$\text{i.e.}\quad \dot{x}_4 = -\frac{1}{T_{p1}}x_4 + \frac{K_{p2}}{T_{p2}}x_5 + \frac{K_{p2}}{T_{p2}}x_7 - \frac{K_{p2}}{T_{p2}}d_2 \tag{2.10}$$

Block 5

$$x_5 + Tt_2\dot{x}_5 = x_6 \tag{2.11}$$

$$\text{i.e.}\quad \dot{x}_5 = -\frac{1}{Tt_2}x_5 + \frac{1}{Tt_2}x_6 \tag{2.12}$$

Block 6

$$x_6 + Tg_2 \dot{x}_6 = -\frac{1}{R_2} x_2 + u_2 \tag{2.13}$$

$$\text{i.e. } \dot{x}_6 = -\frac{1}{R_2 Tg_2} x_4 - \frac{1}{Tg_2} x_6 + \frac{1}{Tg_2} u_2 \tag{2.14}$$

Block 7

$$\dot{x}_7 = 2\pi T^0 x_1 - 2\pi T^0 x_4 \tag{2.15}$$

Block 8

$$\dot{x}_8 = B_1 x_1 + x_7 \tag{2.16}$$

Block 9

$$\dot{x}_9 = B_2 x_4 - x_7 \tag{2.17}$$

The vector matrix representation of the above state equations can be written as a single '**state equation'**.

$$\dot{x} = Ax + Bu + \Gamma d \tag{2.18}$$

Where, A is a square matrix of dimension 9×9 called State Matrix, B and Γ are the rectangular matrixes of order 9×2 called Control matrix and Disturbance matrix respectively.

'x' is the 9×1 State Vector, 'u' is the 2×1 Control Vector and 'd' is the 2×1 Disturbance Vector.

The vectors 'x', 'u', 'd' can be written as

$$x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \end{bmatrix}^T \qquad u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \qquad d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$$

Where x_1, ..., x_9 represents all the nine states. Each state represents a block from the block diagram.

The matrices A (9×9), B (9×2) and Γ (9×2) are:

$$A = \begin{bmatrix} \frac{-1}{T_{p1}} & \frac{K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & \frac{-K_{p1}}{T_{p1}} & 0 & 0 \\ 0 & \frac{-1}{Tt_1} & \frac{1}{Tt_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1 Tg_1} & 0 & \frac{-1}{Tg_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{T_{p2}} & \frac{K_{p2}}{T_{p2}} & 0 & \frac{K_{p2}}{T_{p2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{Tt_2} & \frac{1}{Tt_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{R_2 Tg_2} & 0 & \frac{-1}{Tg_2} & 0 & 0 & 0 \\ 2\pi T^0 & 0 & 0 & -2\pi T^0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & B_2 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{Tg_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{Tg_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad \Gamma = \begin{bmatrix} \frac{-K_{p1}}{T_{p1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{-K_{p2}}{T_{p2}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

2.4 Four-Area Power System:

As like two area power system, four area power systems are also having control areas connected with each other through tie line. Four area power systems can have maximum 6 numbers of tie lines through which power flows from one area to other area. In case of a four area power system it is not necessarily always all the areas are connected to each area. Means, there may b 6 tie lines or less than six tie lines in case of a four area power system.

In this proposed work a four area interconnected power system is taken with every area is connected to each area through tie line. So the four area power system is complete interconnected power system with four individual areas and six inter connections.

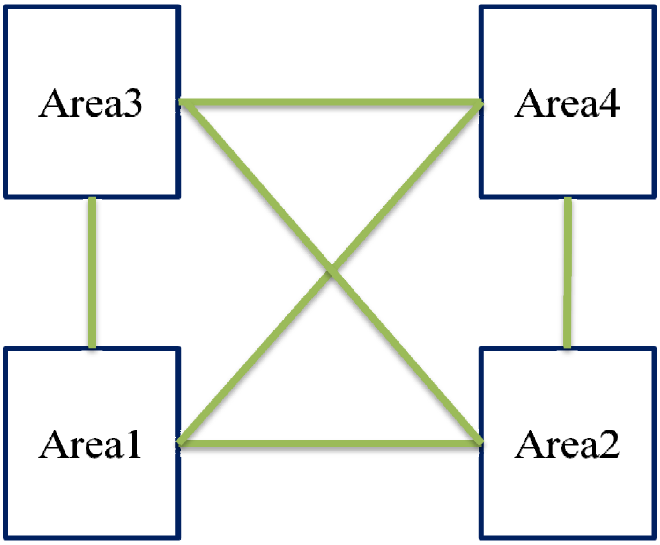

Fig. 2.3: Over view of a Four-Area Interconnected Power System

Fig. 2.3, shown here describes a four area power system which contains four control areas (shown by rectangular blocks) and six interconnections called tie line. So from this figure it is clear that each area contributes some of its power to every other area. The four areas taken here are considered as identical and all consists of thermal non reheat turbines. The deviation in frequency in all areas severely putting effect on the quality and production of frequency sensitive industries such as petro chemical industries, weaving industry, pulp and paper industry etc. So the life time of machine apparatus are reduced on the load side.

The frequency and the tie-line power flow of each area are affected by the changes in load. So here also (like in two area) the frequency and tie line power flow of each area should have to be controlled

Talking about the state space modelling of this four area power system, it is just like as the modelling of two area power system. In case of a two area power system there are two control areas and one tie line present. Each control area is made up of four blocks. So there were nine state equations found out. Here four control areas are connected with each other by six tie lines. So there can be twenty two state equations are for this power system. The modelling and state equations for a four area power system are given in reference [21].

CHAPTER-3

DESIGN OF OPTIMAL REGULATOR AND OPTIMAL COMPENSATOR

3.1 Introduction:

Now days the use conventional integral controllers is very rare in Load Frequency Control of power systems as they produce very slow dynamic response for the system. With the wide development of control system, many different controllers have been invented which are much more effective than integral controllers.

Hence to overcome the demerits of conventional integral controller some optimal controllers (Linear Quadratic Regulator, Linear Quadratic Gaussian) are introduced with integral controller which produce quite better static as well as dynamic response [21].

This chapter deals with the study and application of optimal Regulator (LQR) and optimal compensator (LQG) and demonstrates how much they are effective over the conventional controllers.

3.2 Linear Quadratic Regulator:

Linear Quadratic Regulator is an optimal controller which is a very well known controller due to its wide area use. Why it is called linear is that, it is applicable to linear systems. Quadratic means is heaving a quadratic objective function to be minimised.

Load frequency control of power system is basically a non linear system. So for the application of Linear Quadratic Regulator the system is linearized about a single operating point. A state space model is found out which is the linearized form of the non linear system, for Linear Quadratic Regulator to be applied.

3.2.1 Design of Optimal Controller (LQR):

In case of optimal control technique the inputs (control inputs) are taken as linear combination of all nine states being fed back. The nine states being feedback are x_1, x_2... x_9 and the control inputs can be written as like below:

$$u_1 = k_{11}x_1 + k_{12}x_2 + k_{13}x_3 + k_{14}x_4 + k_{15}x_5 + k_{16}x_6 + k_{17}x_7 + k_{18}x_8 + k_{19}x_9 \quad (3.1)$$

$$u_2 = k_{21}x_1 + k_{22}x_2 + k_{23}x_3 + k_{24}x_4 + k_{25}x_5 + k_{26}x_6 + k_{27}x_7 + k_{28}x_8 + k_{29}x_9 \quad (3.2)$$

Where' K' is a (2×9) matrix called Feed Back Gain matrix and is given by:

$$K = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} & k_{17} & k_{18} & k_{19} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} & k_{27} & k_{28} & k_{29} \end{bmatrix}$$

The state equation of the system is:

$$\dot{x} = Ax + Bu \quad (3.3)$$

As, step load change of constant magnitude is =0 i.e. '$\Gamma d = 0$'

The equation of output is:

$$y = Cx + Du \quad (3.4)$$

But, the matrix 'D 'is always assumed to zero for a control system with feedback.

So, the output equation is:

$y = Cx$ where 'C' is a (2×9) matrix called **Output Matrix.**

So finally, the overall system state space model under consideration can be written as follow:

$$\dot{x} = Ax + Bu \text{ and } y = Cx \quad (3.5)$$

The equation for the control input is given by :

$$u = -Kx \quad (3.6)$$

Where $u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$ and $x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \end{bmatrix}^T$

3.2.2 Determination of Feedback Gain Matrix (K):

From the definition of optimal control problem designing the control law is that to find out the feedback gain matrix 'K' such that the given Performance Index will be minimised while the system transfers from initial state $x(0) \neq 0$ to origin with in infinite time , $x(\infty)=0$.

Generally the quadratic form of PI is taken as:

$$PI = \frac{1}{2}\int_0^\infty (x^T Qx + u^T Ru)dt \tag{3.7}$$

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 are obtained according to the below system requirements.

1) The deviations of Area Control Errors about the steady state values are minimized. In this case these deviations are:

$$ACE_1 = B_1\Delta f_1 + P_{tie(1,2)} = B_1x_1 + x_7 \tag{3.8}$$

$$ACE_2 = B_2\Delta f_2 - P_{tie(1,2)} = B_2x_4 - x_7 \tag{3.9}$$

2) The deviations of $\int ACEdt$ about the steady state values are minimized. For this case these deviations are x_8 and x_9.

3) The deviations of control input**s** ($u_1$and u_2) about the steady state values are minimized.

By these considerations, the Performance Index (PI) takes a form:

$$PI = \frac{1}{2}\int_0^\infty [(B_1x_1 + x_7)^2 + (B_2x_4 - x_7)^2 + (x_8)^2 + (x_9)^2 + (u_1)^2 + (u_2)^2]dt \tag{3.10}$$

i.e.,

$$PI = \frac{1}{2}\int_0^\infty [B_1^2x_1^2 + 2B_1x_1x_7 + 2x_7^2 + B_2^2x_4^2 - 2B_2x_4x_7 + x_8^2 + x_9^2 + u_1^2 + u_2^2]dt \tag{3.11}$$

So the matrices'' and 'R' are presented as:

$$Q = \begin{bmatrix} B_1^2 & 0 & 0 & 0 & 0 & 0 & B_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & B_2^2 & 0 & 0 & -B_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & -B_2 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The matrices A, B (chapter-2), Q and R are found out.

So, the optimal control law is given by $u = -Kx$.

The feedback gain matrix 'K' is given by $K = R^{-1}B^{T}S$

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

$$A^{T}S + SA - SBR^{-1}B^{T}S + Q = 0 \tag{3.12}$$

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

$$\dot{x} = Ax + B(-Kx) = (A - BK)x = A_{c}x \tag{3.13}$$

Where $A_c = (A - BK)$ is a matrix called **closed loop system matrix.** The Eigen values of A_c will show the stability of the system with state feedback controller.

3.2.3 Analysis of System Using MATLAB:

By putting the appropriate values of parameters the matrices A, B, Q and R are calculated. Proper MATLAB code is written in MATLAB-R2010a to obtain the matrices S, K and A_c. A MATLAB command [K, S] = lqr (A, B, Q, R) is being used in this case to find out the values of the matrices 'K 'and 'S'.

The calculated matrices A, B, Q and R are shown below:

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

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

After the MATLAB program ran the calculated values S, K and A_c are obtained as follows:

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

The matrix A_c

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

The Eigen values of matrix 'A' (state matrix) are:

0, 0, -13.068, -13.052, -0.38±3.189i, -0.991±2.262i,-1.2376

All Eigen values do have negative real part rather than two Eigen values are zero. This is a marginally stable system.

The Eigen values of matrix 'A_c'(closed loop system matrix) are:

-13.0594, -13.0758, -1.034±3.4078i, -1.4791±2.5810i, -1.3521,-0.7439; -0.6887

The negative real part of all the Eigen values of 'A_c' proves that the system is stable.

So finally we concluded that after the application of state feedback controller the system became stable.

3.3 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.

Some demerits of pole placement method due to which it is not applicable for the present case:

1. Pole placement technique is could not be applied or it will not take in to account to the power spectra of process and measurement noise. It means pole placement technique is not useful when noise is introduced to the system.
2. The system taken here is a two area power system for load frequency control, which is a Multi Input and Multi Output (MIMO) system. But pole placement observer can only be applied to those systems heaving Single Input and Single output (SISO). Hence, it is not applicable for the system under study.

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:

$$e_0(t) = x(t) - x_0(t) \tag{3.14}$$

Where $e_0(t)$ 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:

$$x_0(t) = Ax_0(t) + Bu(t) + L[y(t) - Cx_0 - Du(t)] \quad (3.15)$$

Where ‘L’ is the **Kalman filter gain matrix.**

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

$$\dot{x}(t) = Ax(t) + Bu(t) + Fv(t) \quad (3.16)$$

$$y(t) = Cx(t) + Du(t) + z(t) \quad (3.17)$$

Where v(t) and z(t) are the process and measurement noise respectively

Kalman filter is generally the total opposite of optimal regulator. Kalman filter is responsible for minimization of the covariance of estimation error given by:

$$R_e(t,t) = E[e_0(t)e_0{}^T(t)] \quad (3.18)$$

Whereas, the optimal regulator is responsible for the minimization of the objective function (PI) on the basic of transient response, steady state response and control effects.

Why it is useful to minimize the covariance of estimation error is that the state vector X(t) is random in nature. The state vector $x_0(t)$, which is estimated is found out on the basis of measurement of output y(t) for a finite period of time ‘T’ such that “$T \leq t$”. Whereas the true random state vector x(t) is based on the output y(t) ,where t is infinite time.

Hence it would be the best that the kalman filter estimates not the true mean x(t) but the conditional mean $x_m(t)$ on the basis of output for finite time record .

Where $x_m(t) = E[x(t) : y(T)\, T \leq t]$ and is called the conditional mean.

There may be a little deviation in the estimated state vector $x_0(t)$ from the conditional mean $x_m(t)$ an it can be written as the estimated state vector is

$$x_0(t) = x_m(t) + \Delta x(t) \quad (3.19)$$

Where $\Delta x(t)$ could be called as the deviation from conditional mean.

The estimation error can be written as:

$$Re(t,t) = E[e_0(t)e_0^T(t) : y(T)\, T \leq t] \tag{3.20}$$

putting the value of $e_0(t) = x(t) - x_0(t)$ in the previous equation and after some mathematical evaluation we got

$$R_e(t,t) = E[x(t)x^T(t)] - x_m(t)x_m^T(t) + \Delta x(t)\Delta x^T(t) \tag{3.21}$$

From the equation above it is cleared that the best of the estimated state vector can be obtained by equating $\Delta x(t) = 0$. As a result the estimated state vector will be equal to the estimated conditional mean i.e. $x_0(t) = x_m(t)$ which would minimize the conditional covariance matrix $R_e(t,t)$ .But minimization of $R_e(t,t)$ yields optimal observer which is generally the Kalman filter.

Basically the most important factor for kalman filter is the kalman gain matrix 'L' which has the contribution of minimizing the covariance of estimation error $R_e(t,t)$ i.e. which equalizes the estimated state vector to the conditional mean vector ($x_0(t) = x_m(t)$). So derivation of L is explained below.

3.3.1 Derivation of Kalman Gain Matrix (L):

The state equation of the optimal estimation error can be written as :

$$\dot{e}_0(t) = [A - LC]e_0(t) + Fv(t) - Lz(t) \tag{3.22}$$

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

$$w(t) = Fv(t) - Lz(t) \tag{3.23}$$

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

$$\dot{e}_0(t) = A_0 e_0(t) + w(t) \tag{3.24}$$

Where A_0 = A-LC.

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

$$\frac{dR_e^0(t,t)}{dt} = AR_e^0(t,t) + R_e^0(t,t)A^T - R_e^0(t,t)C^TZ^{-1}(t)CR_e^0(t,t) + FV(t)F^T \qquad (3.25)$$

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:

$$A_G R_e^0 + R_e^0 A_G^T - R_e^0 C^T Z^{-1} C R_e^0 + FV_G F^T = 0 \qquad (3.26)$$

Where, $A_G = A - F\Psi Z^{-1}C$ and $A_G = A - F\Psi Z^{-1}C$ (3.27)

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:

$$L = R_e^0 C^T Z^{-1} \qquad (3.28)$$

3.3.2 Analysis using MATLAB

Proper MATLAB code is written in MATLAB-R2010a to obtain the matrices R_e^0, L and A_0. A MATLAB command [L, R_e^0,e]=lqe(A,F,C,F'*F,C*c') is being used in this case to find out the values of the matrices 'L 'and 'R_e^0'.

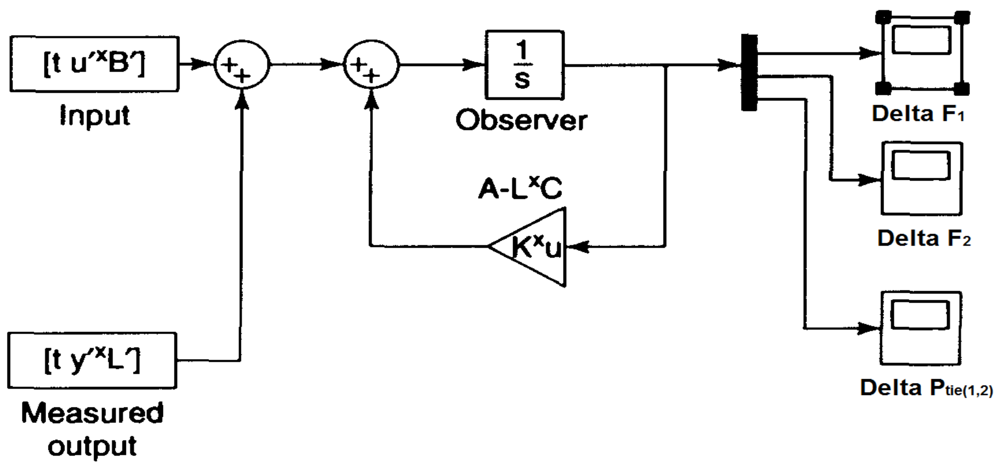

Fig.3.1: Simulation diagram of kalman filter

The above diagram is the simulink diagram of kalman filter where it is clearly seen that the the estimated states are found out based up on the measured output and present input for finite interval of time.

So finally we got to know that the kalman filter gives the best estimation of the state vectors on the basis of measured output and present input for finite period of time rather than infinite time interval.

The matrices L and A_0 are

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

$$A_0 = \begin{bmatrix} -2.9477 & 6 & 0 & 0.2973 & 0 & 0 & -5.7110 & 0 & 0 \\ -0.3659 & -2.5 & 2.5 & -0.1359 & 0 & 0 & -0.1452 & 0 & 0 \\ -4.8804 & 0 & -12.5 & -0.1247 & 0 & 0 & -0.1106 & -12.5 & 0 \\ 0.2973 & 0 & 0 & -2.9477 & 6 & 0 & 5.7110 & 0 & 0 \\ -0.1359 & 0 & 0 & -0.3659 & -2.5 & 2.5 & 0.1452 & 0 & 0 \\ -0.1247 & 0 & 0 & -4.8804 & 0 & -12.5 & 0.1106 & 0 & -12.5 \\ 0.7332 & 0 & 0 & -0.7332 & 0 & 0 & -0.5653 & 0 & 0 \\ 1.0659 & 0 & 0 & 0.0206 & 0 & 0 & 1.0218 & 0 & 0 \\ 0.0206 & 0 & 0 & 1.0659 & 0 & 0 & -1.0218 & 0 & 0 \end{bmatrix}$$

3.4 Linear Quadratic Gaussian (LQG):

In this chapter 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 a Optimal compensator which is called as Linear Quadratic Gaussian (LQG).

Hence LQR and KF are combined to form LQG which is applied to LFC of a two area power system in the presence of process and measurement noise. Why this is called LQG is that, it is basically applicable to linear plants, it is heaving a quadratic objective function and it is applied at the presence of white noise which has a Gaussian probability distribution. In abbreviation, the LQG design process can be written as follows.

1. At first an optimal regulator is designed For the linearized (State space modelled) plant of Power system assuming the availability of all the states (full-state feedback) and a quadratic objective function. The designed regulator creates a control vector on the basis of state vector (measured) x(t).
2. A Kalman filter is designed on the basis of assumption of a control input, u(t), an output already measured, y(t) and process and measurement noises considered as white Gaussian noises, v(t) and z(t), with well known spectral densities of power.
3. Both the regulator and observer, designed separately are combined together in to a compensator (optimal compensator) called Linear Quadratic Gaussian. The optimal compensator designed here generates a control input, u(t) on the basis of estimated state vector 'x_0(t)' instead of the real state vector 'x(t)'and output vector 'y(t)', that is already measured.

The designed parameters of optimal regulator are generally the state weighing matrix 'Q' and the control weighing matrix 'R'. Similarly the designed parameters of Kalman filter are the noise power spectral densities, V, Z and Ψ. Hence 'Q', 'R', 'V', 'Z' and 'Ψ' will be the designed parameters of the optimal compensator applied to the closed loop power system.

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

$$\dot{x}_0(t) = (A - BK - LC + LDK)x_0(t) + Ly(t) \tag{3.29}$$

$$u(t) = -Kx_0(t) \tag{3.30}$$

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

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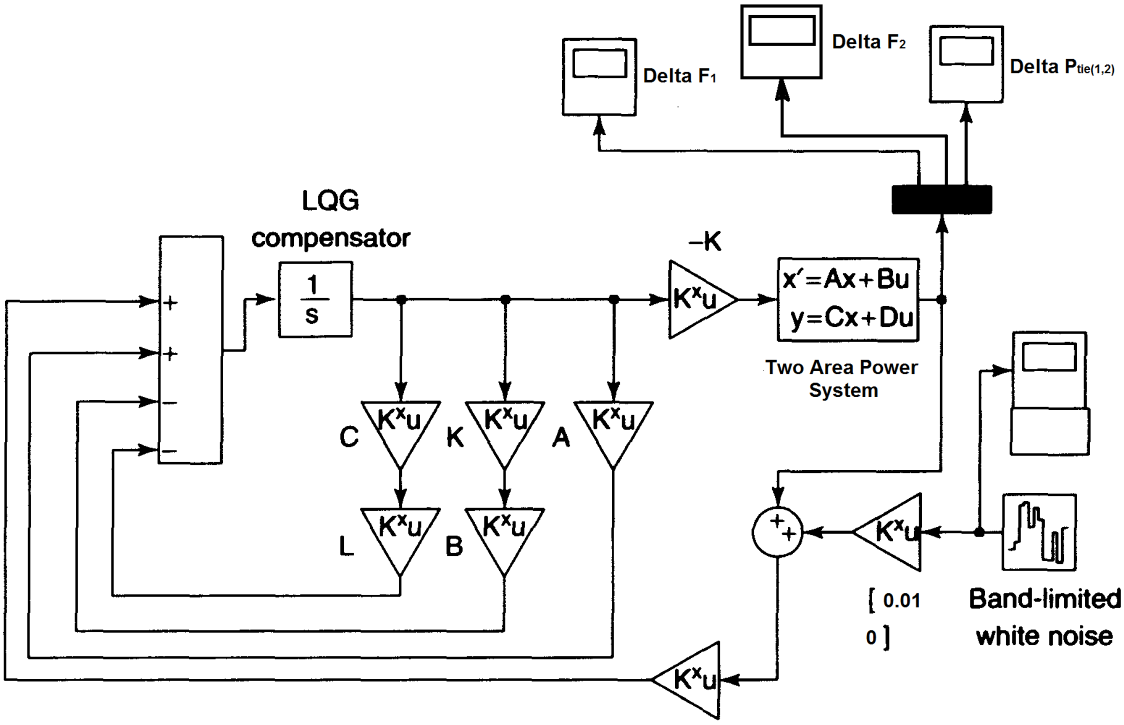

Fig. 3.2: Simulink diagram of LQG operating on LFC of two area power system

The above figure represents the simulink diagram of a linear Quadratic compensator operating on the load frequency control of a two area power system. it defines the state equation and the control law of linear quadratic regulator where the control law u=-Kx$_0$ (t) is based on the estimated state x$_0$ (t) and measured output y(t.) it will be seen that after the simulation, the LQG derives the same output as like the outputs of LQR. Means both the application of LQG and LQR are same but LQG is applicable at those places where process and measurement noise are taken in to account.

So finally we concluded that in this chapter a LQR is designed on the basis of present input and measured output. Then an optimal observer (Kalman filter) is designed which estimates the state vector at the presence of process and measurement noise considered as white Gaussian noise. And finally LQG is designed for LFC of a two area power system which creates an control input on the basis of estimated state vector and measured output for finite period of time.

CHAPTER 4

TUNING OF PID LOAD FREQUENCY CONTROLLER VIA IMC

4.1 Introduction:

Now days the complexity of power system is generally increases. so different control action or controllers like optimal controller, variable structure control, robust control ,conventional PI , PI controller, adaptive and self tuning control were used for LFC of power system. Meanwhile, PI and PID controllers were studied for LFC the simplicity of their execution. References[23] and [24] shows LFC of power system with fuzzy PI control[25] proposed load frequency controller PID tuning method for single area power system based on the tuning method in [26],and is extended for two area power system[19].

In this chapter, a different unified method is described to design and tune a PID controller for load frequency control of power system with non reheat turbine. The method is applied here on the basis of internal model control .it is also applicable to multi area power systems like to a two area power system.

4.2 IMC Design:

Here an internal model control (IMC) method is adapted for load frequency controller design. In Process control IMC is a very popular controller [22].in Fig.3.1, the IMC structure is shown where the plant to be controlled is ‘P’, and the plant model is ‘ $\tilde{P}$ ’.

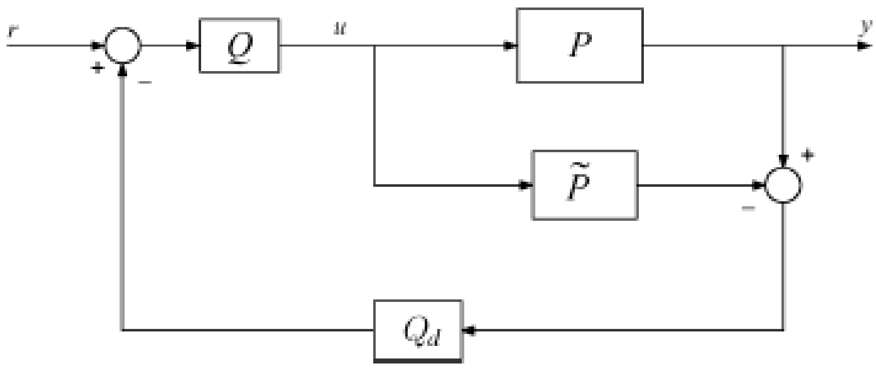

Fig.4.1: IMC structure

The procedure for IMC design goes as follows [22]:

1. Decompose the model of the plant $\tilde{P}$ in to two different parts:

$$\tilde{P}(s) = P_M(s)P_A(s) \tag{4.1}$$

Where $P_M(s)$ invertible minimum-phase is part and $P_A(s)$ is the no minimum phase part (all pass) with unity magnitude.

2. Design an IMC controller

$$Q(s) = P_M^{-1}(s)\frac{1}{(\lambda s+1)^r} \tag{4.2}$$

Where λ is the tuning parameter and the desired set point response is '$\frac{1}{(\lambda s+1)^r}$'. 'r' is the degree of $P_M(s)$

It is shown here that the IMC controller gives very good tracking performance .where as it is not satisfying the disturbance rejection performance some times. So a secondary controller Q_d is included to optimise the disturbance rejection performance.

The designed disturbance rejecting IMC controller is of the form:

$$Q_d(s) = \frac{\alpha_m s^m + \ldots + \alpha_1 s + 1}{(\lambda_d s+1)^m} \tag{4.3}$$

Where λ_d is the disturbance rejection tuning parameter, 'm' is the number of poles of $\tilde{P}(s)$. After that α_1 ... α_m should have to satisfy

$$(1-\tilde{P}(s)Q(s)Q_d(s))_{s=p_1,\ldots,p_m} = 0 \tag{4.4}$$

Where $p_1,\ldots,p_m$ are the poles of $\tilde{P}(s)$

It could be shown that the IMC structure can be equivalent to the conventional feedback structure as like in the Fig.3.2. The feedback controller K is equals to

$$K = \frac{QQ_d}{1-\tilde{P}QQ_d} \tag{4.5}$$

Here K is considered as the conventional PID controller.

Direct implementation of IMC controller needs higher order transfer function knowledge if the model $\tilde{P}$ is of higher order, which is discussed in LFC of power system. So here the IMC structure is transformed to a PID control structure.

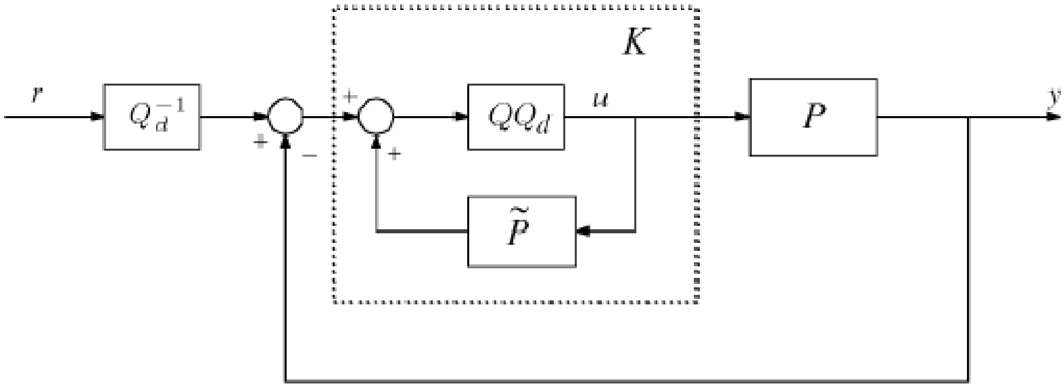

Fig.4.2: IMC equivalent conventional feedback configuration

The standard technique of tuning the PID parameters from IMC controllers is that we have to expand the controller block K shown in Fig.3.1 in to Malaren series. The first three terms coefficients of the Maclaurin series are the parameters of the PID controller. The procedure is obtained by the IMCTUNE package [27]. Here a new method is approximated for any higher order PID controller in frequency domain [26].

4.3 LFC PID Design:

First we have considered a isolated power system with a single generator supply.

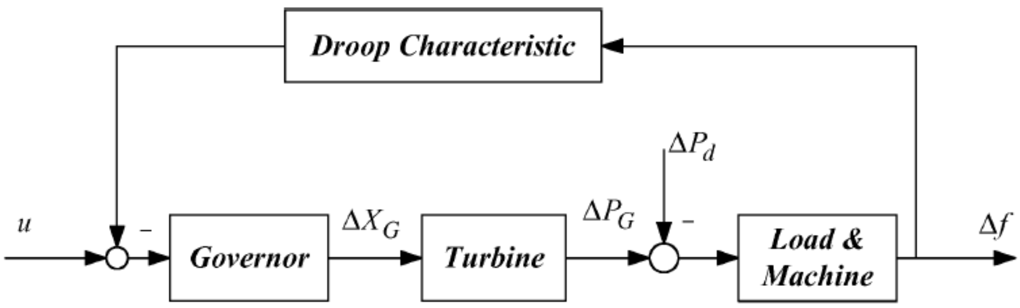

Fig. 4.3: Linear model of a single area power system

The tuning of PID controller we know is to improve the performance of the load frequency control of power system. So, here we have to design a control law $u = -K(s)\Delta f$, where K(s) has the form

$$K(s) = K_p(1 + \frac{1}{T_i s} + T_d s) \tag{4.6}$$

In general, practically PID controller is implemented to reduce the noise effect. So, K(s) can be written for this case

$$K(s) = K_p(1 + \frac{1}{T_i s} + \frac{T_d s}{Ns + 1}) \tag{4.7}$$

Where N is called as them filter constant. It is implemented in [].

$$K(s) = K_p(1 + \frac{1}{T_i s} + T_d \frac{1 - e^{-Ts}}{Ns + 1}) \tag{4.8}$$

Where ‘T’ is a very small sampling rate.

Science the load frequency control of power system considers a little change in load, it can be represented by the single area model shown in Fig.3.3 . The drop characteristic here is the reciprocal of regulation constant ‘ $1/R$ ’ which improves the damping properties. So there are two methods or alternatives for load frequency control design .i.e.

1. Design LFC of power system without drop characteristic.
2. Design LFC of power system with drop characteristic.

Here the second alternative is taken in to account for study.

4.3.1 LFC Design without drop characteristic:

1. A Non-Reheated Turbine is taken in the power system. so the plant with non-reheated turbine made of three different parts

a) A Governor with its dynamics:

$$G_g(s) = \frac{1}{T_g s + 1} \tag{4.9}$$

b) A turbine with its dynamics:

$$G_t(s) = \frac{1}{T_t s + 1} \tag{4.10}$$

c) Load and machine with their dynamics:

$$G_p(s) = \frac{K_p(s)}{T_p s + 1} \tag{4.11}$$

Now the overall open loop transfer function without any drop characteristic is:

$$\tilde{P}(s) = G_p(s)G_t(s)G_g(s) = \frac{K_p}{(T_p s+1)(T_t s+1)(T_g s+1)} \quad (4.12)$$

From the IMC-PID design method, as, model $\tilde{P}$ is a minimum phase system, the IMC controller gets the form

$$Q(s) = P^{-1}(s)\frac{1}{(\lambda s+1)^3} = \frac{(T_p s+1)(T_t s+1)(T_g s+1)}{Kp(\lambda s+1)^3} \quad (4.13)$$

To improvise the disturbance response another controller $Q_d(s)$ is used. In Fig.3.3, we noticed that the change in load demand $\Delta P_d(s)$ must have to pass through the load and machine dynamics to affect the deviation in frequency $\Delta f(s)$. So for disturbance rejection $Q_d(s)$ is chosen which cancels the pole $s = \frac{-1}{T_P}$. Let

$$Q_d(s) = \frac{\alpha_1 s+1}{\lambda_d s+1} \quad (4.14)$$

Then α_1 should have to satisfy

$$(1-\tilde{P}(s)Q(s)Q_d(s))_{s=\frac{-1}{T_P}} = \left(1-\frac{\alpha_1 s+1}{(\lambda s+1)^3(\lambda_d s+1)^3}\right)_{s=\frac{-1}{T_P}} = 0 \quad (4.15)$$

That is

$$\alpha_1 = T_p\left(1-\left(1-\frac{\lambda}{T_p}\right)^3\left(1-\frac{\lambda_d}{T_p}\right)\right) \quad (4.16)$$

By choosing appropriate values of λ and λ_d, the IMC controllers Q(s) and $Q_d(s)$ can be derived from equation () and() and then the corresponding PID could be tuned according to the method described previously.

Hence the procedure of IMC PID controller design for the LFC of a isolated power system contains the design of IMC controller first den it is expanded to tune the PID parameters.

4.3.2 LFC Design with Drop Characteristic:

For this case the plant model for LFC design is

$$P(s) = \frac{RG_g G_t G_p}{R + G_g G_t G_p} \tag{4.17}$$

Unlike the step response of $\tilde{P}(s)$ which is non-oscillatory described in the previous section, the step response of the model for LFC with drop characteristics oscillatory and unstable some times. so LFC design of power system became more complicated. In[], it is shown that for LFC purpose, the third order transfer function of the model is reduced to second order neglecting the real pole. Then PID controller is tuned based on IMC method. This approximation only works for power system with non-reheated turbine.

The reduced second order transfer function should be in the form:

$$P(s) = \frac{k\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} e^{-\tau s} \tag{4.18}$$

Where ξ is the damping ratio, ω_n is the undammed frequency and τ is the dead time.

For example, consider the second order reduced dead time model() with parameters from[]. If the IMC tuning parameters λ and are taken as 0.1 and 0.4 respectively. Then we do have

$$Q(s) = \frac{0.12s^2 + 0.33s + 1}{0.02353s^2 + 0.4706s + 2.353} \tag{4.19}$$

$$Q_d(s) = \frac{0.2292s^2 + 0.6523s + 1}{0.16s^2 + 0.8s + 1} \tag{4.20}$$

The approximated PID controller is

$$K_{PID} = 0.6669 + \frac{1.0185}{s} + 0.2235s \tag{4.21}$$

4.4 Two Area Extension:

The tuning of IMC-PID controller can be extended for load frequency control of a two area power system. The difference between LFC for single are and multi area is that in multi area case not only the area frequencies comes back to its set value but also the tie line power comes to its nominal value. In this case the Area Control Error (ACE), is used for feedback variable. Consider the model for LFC of two area power system shown in Fig.2.1.

$$\Delta P_{tie(1,2)} = \frac{T_{12}}{s}(\Delta f_1 - \Delta f_2) \quad (4.22)$$

B_1 and B_2 both are the frequency bias coefficients, and the area control errors AEC_1 and AEC_2 are defined by

$$AEC_1 = \Delta P_{tie(1,2)} + B_1 \Delta f_1 \quad (4.23)$$

$$AEC_2 = -\Delta P_{tie(1,2)} + B_2 \Delta f_2 \quad (4.24)$$

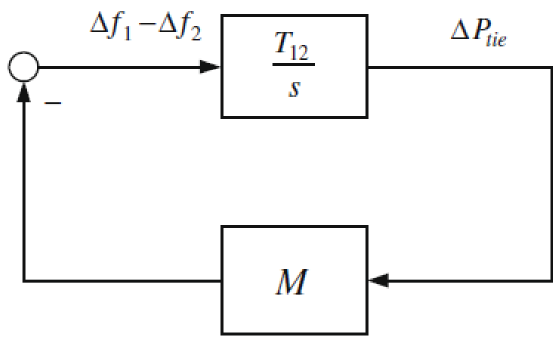

Fig.4.4. Equivalent closed loop system for LFC of two area power system

The load frequency control for each area could be tuned separately in this present case. Whereas, there is a tie line coupling between the areas, the tuning parameter of each area should be taken in to consideration.

To give the guarantee of the stability of closed loop system when tie line is connected by tuning the decentralized controller, a closed loop system is arranged in Fig.3.4. in the figure 'M' is the transfer function from $P_{tie(1,2)}$ to f_1-f_2 .At the absence of $P_{tie(1,2)}$ it is very easy to find $M(s)=M_1(s)-M_2(s)$.

Where $M_i(s)$ is the transfer function from - $P_{tie(1,2)}$ to Δf_i (i=1,2)

$$M_1(s) = \frac{G_{p1} + G_{g1}G_{t1}G_{p1}}{1 + \left(G_{g1}G_{t1}G_{p1}\right)/R_1 + G_{g1}G_{t1}G_{p1}K_1R_1} \quad (4.25)$$

$$M_2(s) = \frac{-G_{p2} - G_{g2}G_{t2}G_{p2}}{1+\left(G_{g2}G_{t2}G_{p2}\right)/R_2 + G_{g2}G_{t2}G_{p2}K_2B_2} \tag{4.26}$$

Consider the example []. Just for simplicity purpose both the areas are assumed identical. Using the tuning parameters same as used in single area case ($\lambda = 0.1, \lambda_d = 0.4$) the designed PID controllers are:

$$K_1(s) = K_2(s) = 1.5692 + \frac{2.3966}{s} + 0.5259s \tag{4.27}$$

A LFC PID tuning procedure for power system was described on the basis of two degree IMC method. The two parameters tuned determine the operation performance of the resulted PID controller. The simulation and results are shown in chapter5 which are very effective.

CHAPTER-5

RESULTS AND DISCUSSION

5.1 Introduction:

The performance of LQR, Kalman filter, LQG with full state feedback and IMC-PID controller, along with the performance of integral and optimal controller are shown in the below figures. The responses shown here are in form of dynamic responses of each area frequencies and the power of tie line, for the two area power system model. The stability for closed loop system stability for the model using different controller has already been found out in chapter 3 by determining their Eigen values.

5.2 Results and Discussion:

In this study here, first a optimal control law is generated for the power system stability, then the states are estimated by kalman filter at the presence process and measurement noises taken as white Gaussian noise. Then combining those both a optimal compensator is designed which recovers the responses of optimal regulator at the presence of noise. So, the operation of optimal compensator is equal to the operation of optimal regulator but it can work noise environment.

After that an IMC-PID controller is designed for LFC of power system and its results are compared with conventional integral Load Frequency Controller for a two area power system.

5.2.1 Results of LQR for LFC of Two Area Power System:

Fig. 5.1 to Fig. 5.3 are showing the dynamic responses of deviation in frequency for both the areas ($\Delta f_1, \Delta f_2$) and the power deviation in tie line ($\Delta P_{tie(1,2)}$) 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. Again the Fig. 5.4 to Fig. 5.7 shows the same responses of frequency deviation and tie line power deviation for load disturbances ($d_1 = 0.0085$ pu , $d_2 = 0.0025$ pu).

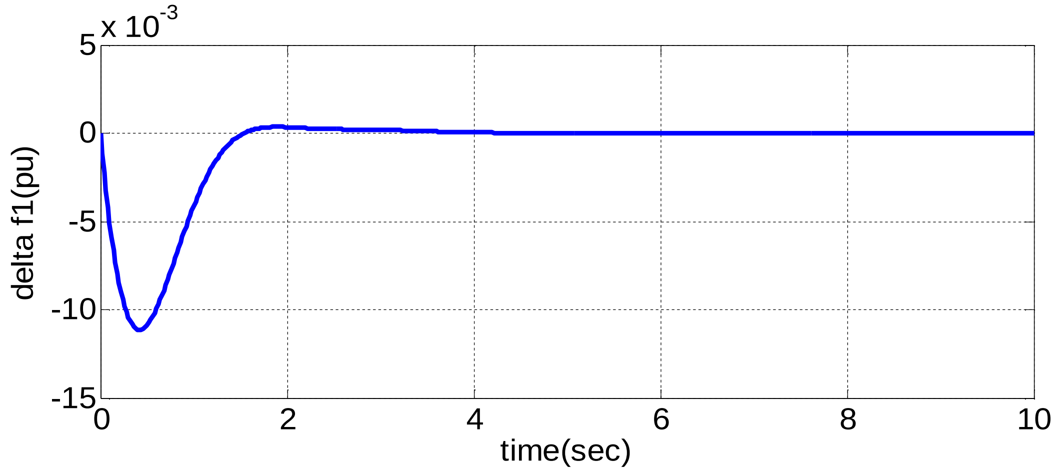

Fig.5.1: change in frequency V/S time in area-1 for 0.01 step load change in area-1

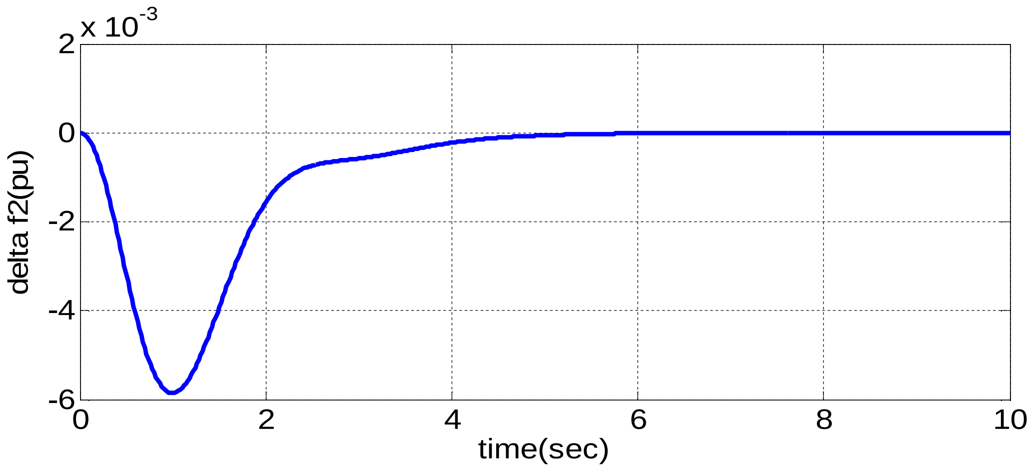

Fig.5.2: change in frequency V/S time in area-2 for 0.01 step load change in area-1

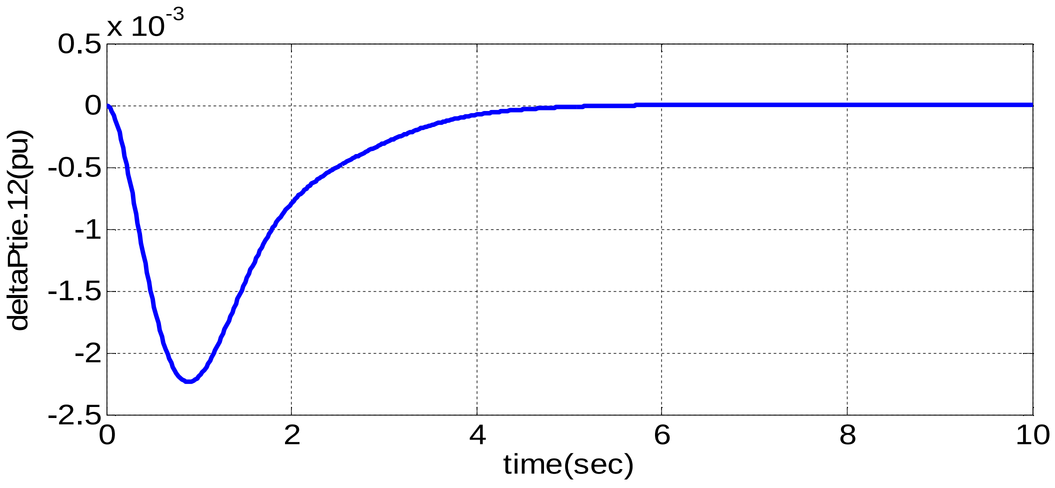

Fig.5.3: change in tie line power V/S time for 0.01 step load change in area-1

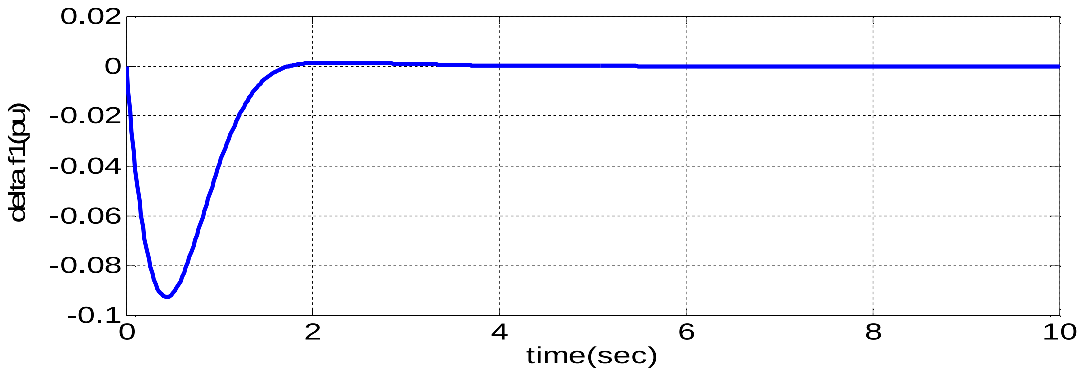

Fig.5.4: change in frequency V/S time in area-1 for ΔP_{d1} = 0.0085 pu ,ΔP_{d2} = 0.0025 pu

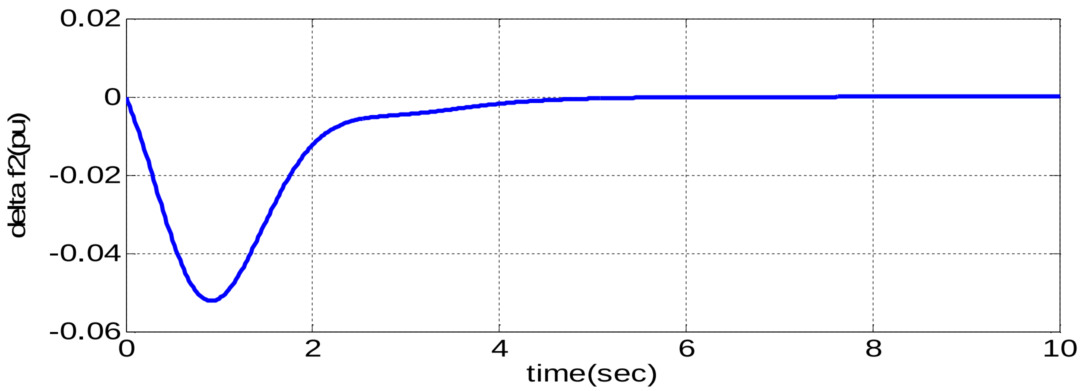

Fig.5.5: change in frequency V/S time in area-2 for ΔP_{d1} = 0.0085 pu ,ΔP_{d2} = 0.0025 pu

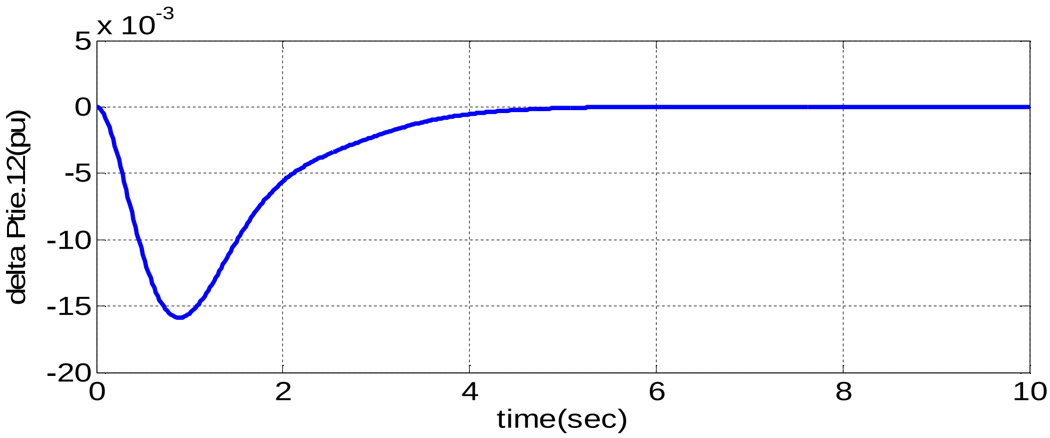

Fig.5.6: change in Tie Line power V/S time for ΔP_{d1} = 0.0085 pu ,ΔP_{d2} = 0.0025 pu

So from the over two set of figures we got to know that, for load change in any of the areas or both the areas, the Linear Quadratic Regulator is able to bring the area frequencies and tie- line power flow to their pre defined values or nominal values.

5.2.2 Results of LQR for a Four Area Power System:

Like a two area power system LQR is applied to a four area interconnected power system by finding out its state space model [21]. As four control areas are there will be ten output states (Four for area output frequencies and six for tie lines) will be found out out of which only eight outputs are shown here.

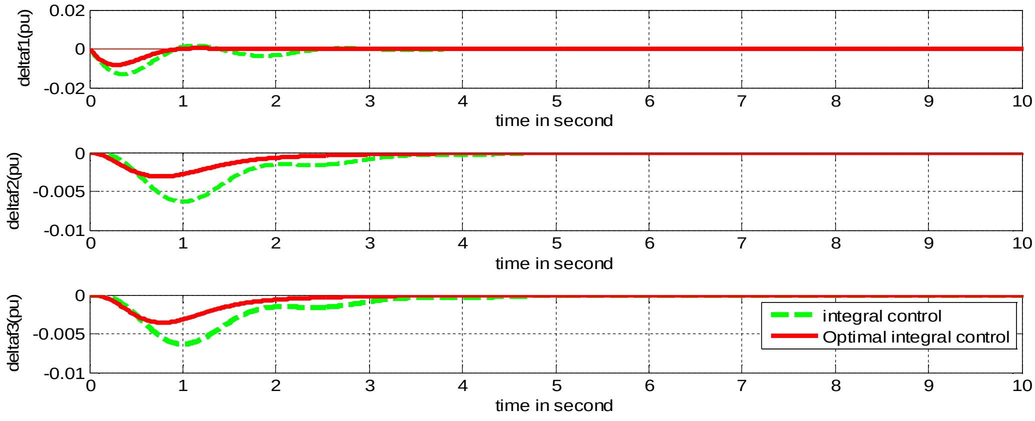

Fig. 5.7: Change in Frequencies $\Delta f_1, \Delta f_2$ & Δf_3 V/S time for 0.01 step load change in area-1

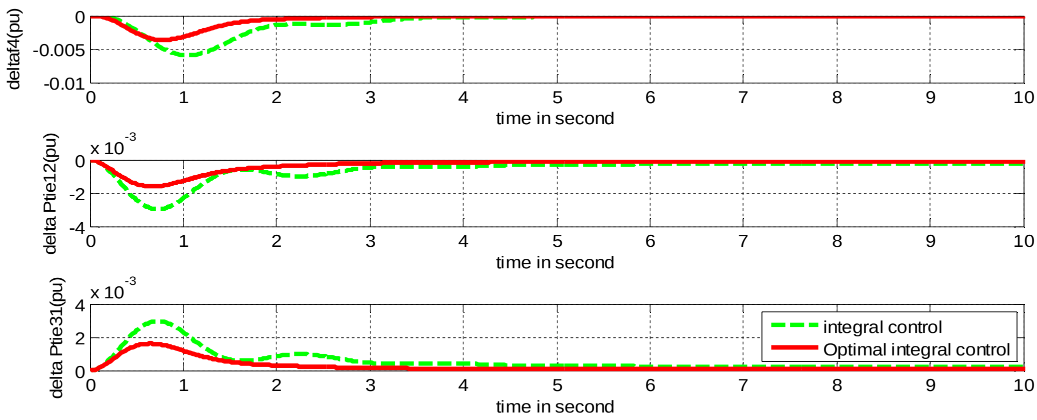

Fig. 5.8: Changes Δf_4, $\Delta P_{tie(1,2)}$ & $\Delta P_{tie(3,1)}$ V/S time for 0.01 step load change in area-1

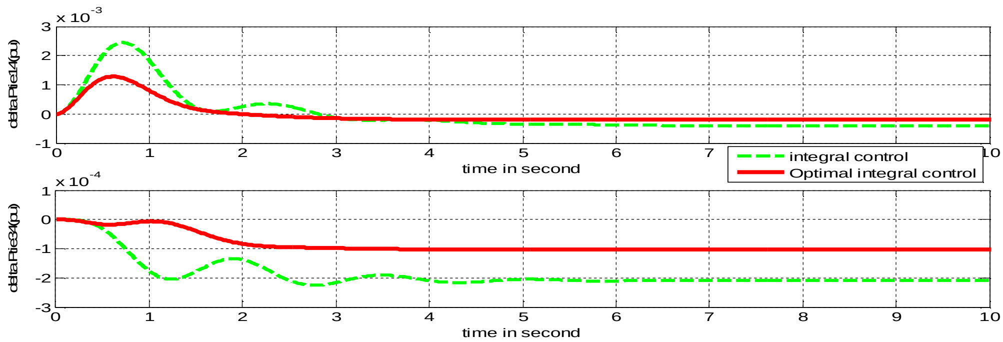

Fig. 5.9: changes $\Delta P_{tie(3,4)}$ $\Delta P_{tie(1,4)}$ V/S time for 0.01 step load change in area-1

5.2.3 Estimated States for LFC of Power System by Kalman Filter:

Fig. 5.10 to Fig. 5.12 are showing the estimated states of deviation in frequency for both the areas ($\Delta f_1, \Delta f_2$) and the power deviation in tie line ($\Delta P_{tie(1,2)}$) 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. these estimated 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.

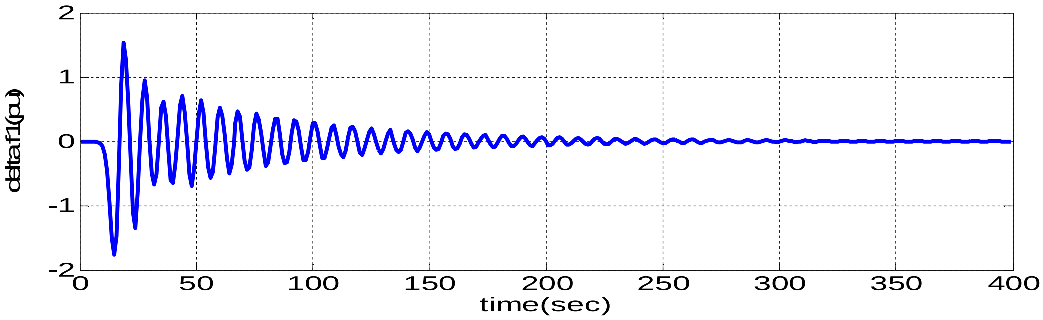

Fig.5.10: change in frequency V/S time in area-1 for 0.01 step load change in area-1

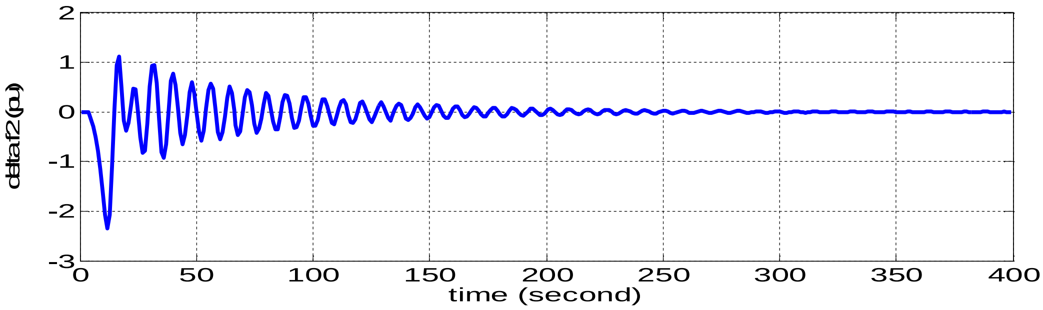

Fig.5.11: change in frequency V/S time in area-2 for 0.01 step load change in area-1

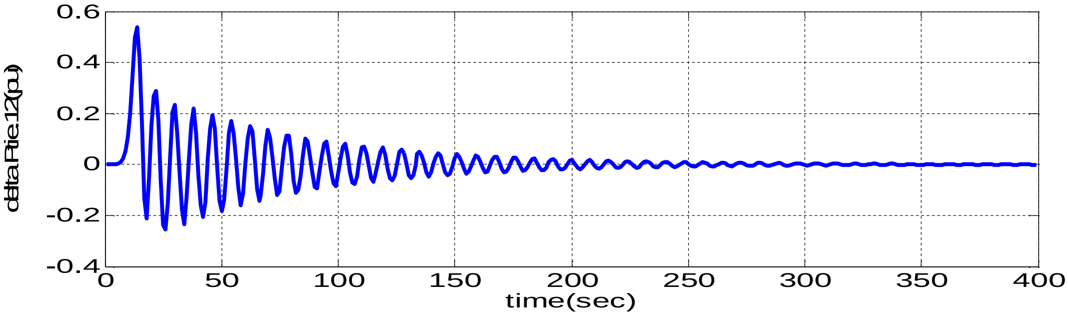

Fig.5.12: change in tie line power V/S time for 0.01 step load change in area-1

5.2.4 Results of LQG for LFC of Two Area Power System

Fig. 5.13 to Fig. 5.15 are showing the dynamic responses of deviation in frequency for both the areas ($\Delta f_1, \Delta f_2$) and the power deviation in tie line ($\Delta P_{tie(1,2)}$) for a power system heaving two control areas with thermal non-reheat turbines. The changes in load powers which are the input disturbance are taken as $d_1 = 0.01$ pu , $d_2 = 0.00$ pu. 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.

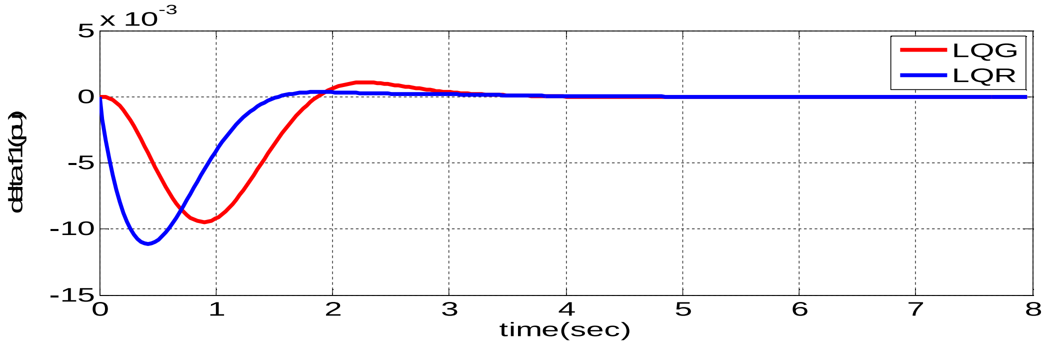

Fig.5.13: change in frequency V/S time in area-2 for 0.01 step load change in area-1

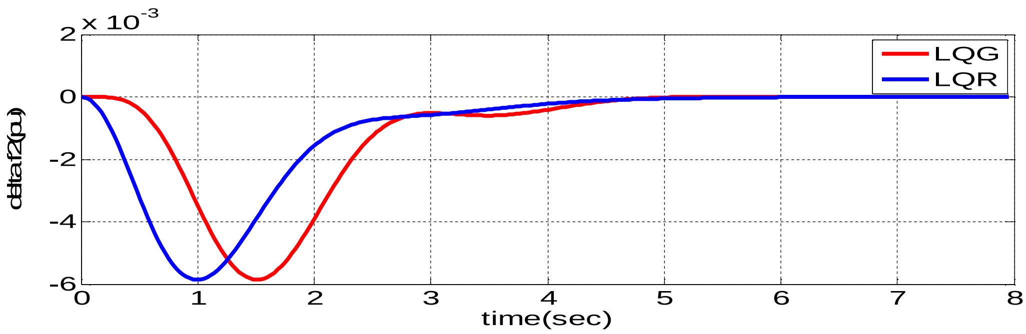

Fig.5.14: change in frequency V/S time in area-2 for 0.01 step load change in area-1

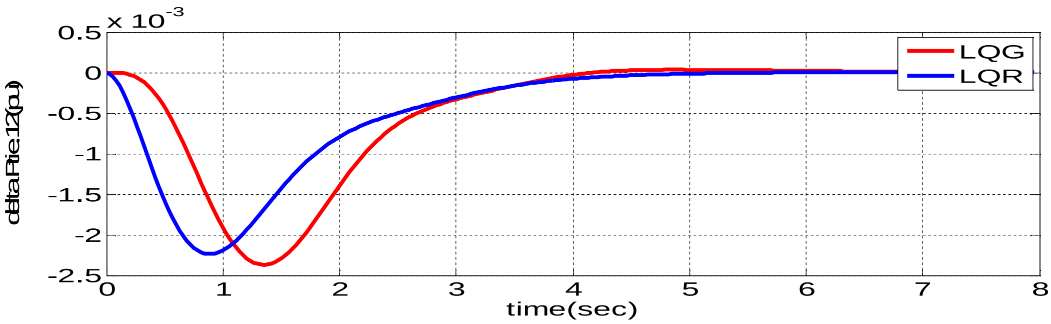

Fig.5.15: change in tie line power V/S time for 0.01 step load change in area-1

5.2.5 Results of IMC-PID Controller for LFC of Two Area Power System:

Fig. 5.16 to Fig. 5.18 are showing the dynamic responses of deviation in frequency for both the areas ($\Delta f_1, \Delta f_2$) and the power deviation in tie line ($\Delta P_{tie(1,2)}$) for a power system heaving two control areas with thermal non-reheat turbines. The figures show the performances of a PID controller for LFC of power system, tuned via Internal Model Control (IMC) . From figures we can clearly see that the responses are stable with very less overshoot and less settling time. So IMC-PID controller is a powerful controller which gives better stability for LFC of a two area power system.

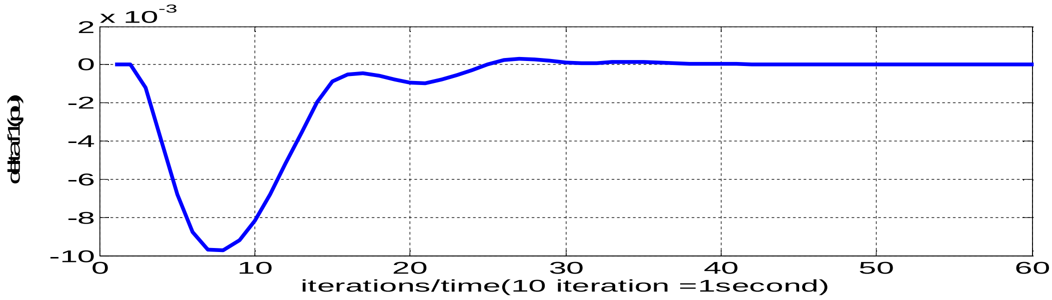

Fig.5.16: change in frequency V/S time in area-1 for 0.01 step load change in area-1

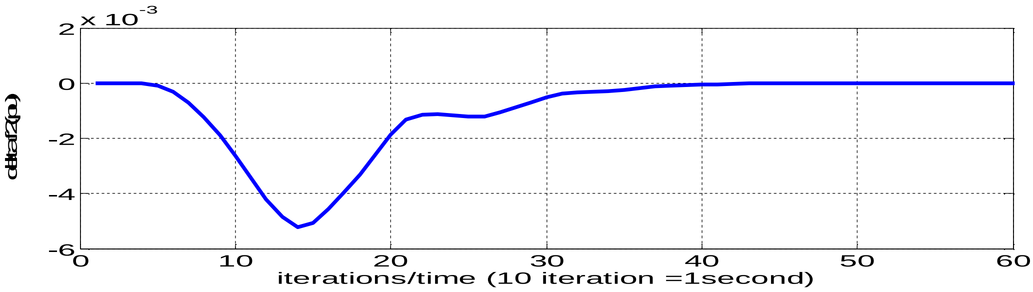

Fig.5.17: change in frequency V/S time in area-2 for 0.01 step load change in area-1

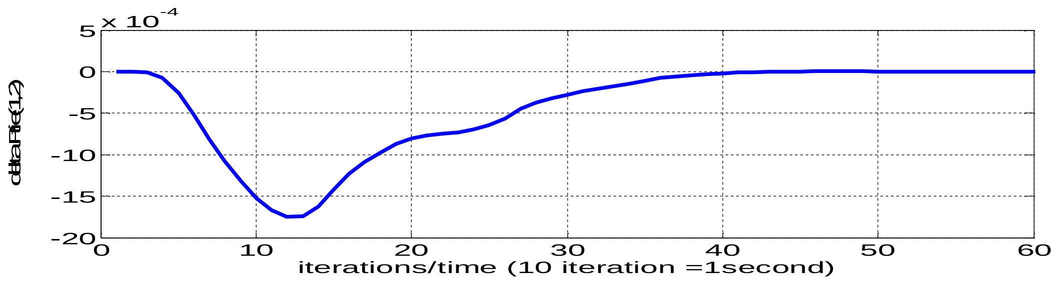

Fig.5.18: change in tie line power V/S time for 0.01 step load change in area-1

So finally from the figures we got to know that the IMC-PID controller gives better response than the Linear Quadratic Regulator for LFC of power system.

CHAPTER 6

CONCLUSIONS AND SCOPE FOR FURTHER WORK

6.1 Conclusions:

Model of a two area interconnected power system has been developed with different area characteristics for optimal and conventional control strategies. The control equations and the state equations have successfully been derived in continuous time for a two area power system. The model developed here has also been examined for the stability before and after the application of state feedback control.

Optimal control technique has a huge application over control engineering. An optimal regulator called Linear Quadratic Regulator (LQR) has been applied for Load Frequency Control (LFC) of a two area power system. A control law is generated on the basis of measured output and present states for infinite period of time. A State space model was developed by the help of state equations for the application of LQR. So by the application of state feedback controller the stability of area frequency and tie line power was obtained which is been proved as one of the effective controller in this proposed work.

It is well known to everyone, that the optimal regulator (LQR) is not sufficient for full state feedback and also is not applicable at noisy environments. So an powerful observer, which is applicable for MIMO systems called Kalman filter is designed for the Load Frequency Control of a two area power system, at the presence of process and measurement noise. This observer minimizes the covariance of estimation error. The process and measurement noises in this type of observer are considered as white Gaussian noise. In this case all the states are estimate on the basis of present input and measured output for finite period of time.

The purpose of estimation of states using an optimal observer is to design a optimal compensator called Linear Quadratic Gaussian (LQG) for load frequency control of a two area power system at the presence of white Gaussian noise. So by the combination of optimal regulator and optimal observer an optimal compensator (LQG) has already been designed for LFC. The performance of LQG for LFC of power system are obtained and compared with that of LQR.(shown in chapter 5). From the results of the optimal compensator, it is seen that it works as a optimal regulator at the presence of white Gaussian noise.

At last a PID controller is designed for LFC of the proposed power system via Internal Model Control (IMC). First an IMC controller is designed, a disturbance rejection IMC controller is designed then a model equivalent to feed back (conventional controller model) model is developed. This feedback model is compared with the conventional PID controller model and by Toyler series expansion the parameters of PID control are found out. So PID controller is designed on the basis of IMC controller and applied for LFC of a two are power system and well steblized responses are obtained.

6.2 Scope for Future Work:

1. In this present work the load disturbances d_1 and d_2, are taken as deterministic (static) in nature. So, in future the work could be extended to time varying (dynamic) load disturbances.

2. The parameters in this work has been taken constant throughout the whole operation. But there may be parameter uncertainty due to wear and tear, temperature variation, imperfection of component, aging effect, environment changes etc. So during controller design the variation of parameter may be taken in to consideration.

3. The LFC of power system can be designed by PID controller via different optimization technique.

REFERENCES

[1] C. Concordia and L.K. Kirchmayer, ‘Tie line power and frequency control of electric power systems,’ Amer. Inst. Elect. Eng. Trans., Pt. II, Vol. 72, pp. 562 572, Jun. 1953.

[2] N. Cohn, ‘Some aspects of tie-line bias control on interconnected power systems,’ Amer. Inst. Elect. Eng. Trans., Vol. 75, pp. 1415-1436, Feb. 1957.

[3] O. I. Elgerd and C. Fosha, ‘Optimum megawatt frequency control of multiarea electric energy systems,’ IEEE Trans. Power App. Syst., vol. PAS-89, no. 4, pp. 556–563, Apr. 1970.

[4] C. Fosha, O. I. Elgerd, ‘The megawatt frequency control problem: A new approach via Optimal control theory,’ IEEE Trans. Power App. Syst., vol. PAS- 89, no. 4, pp. 563 577, Apr. 1970.

[5] IEEE PES Committee Report, IEEE Trans. Power App. Syst., vol. PAS-92, Nov. 1973. ‘Dynamic models for steam and hydro-turbines in power system studies.’

[6] IEEE PES Working Group, ‘Hydraulic turbine and turbine control models for system dynamic Studies,’ IEEE Trans. Power Syst., vol. PWRS-7, no. 1, pp. 167–174, Feb. 1992.

[7] IEEE PES Committee Report, IEEE Trans. Power App. Syst., vol. PAS-98, Jan./Feb. 1979. ‘Current operating problems associated with automatic generation control.’

[8] N. Jaleeli, L. S. Vanslyck, D. N. Ewart, L. H. Fink, and A. G. Hoffmann, ‘Understand-ing automatic generation control,’ IEEE Trans. Power App.Syst. vol. PAS-7, no. 3, pp . 1106–1122, Aug. 1992.

[9] R. K. Green, ‘Transformed automatic generation control,’ IEEE Trans.Power Syst., vol. 11, no. 4, pp. 1799–1804, Nov. 1996

[10] A. M. Stankovic, G. Tadmor, and T. A. Sakharuk, ‘On robust control analysis and design for load frequency regulation,’ IEEE Trans. Power Syst., vol. 13, no. 2, pp. 449 –455, May 1998.

[11] K. C. Divya, and P.S. Nagendra Rao, ‘A simulation model for AGC studies of hydro-hydro systems’, Int. J. Electrical Power & Energy Systems, Vol 27, Jun.- Jul. 2005, pp. 335-342.

[12] E. C. Tacker, T. W. Reddoch, O. T. Pan, and T. D. Linton, ‘Automatic generation Control of electric energy systems—A simulation study,’ IEEE Trans. Syst. Man Cybern., vol. SMC-3, no. 4, pp. 403–5, Jul. 1973.

[13] B. Oni, H. Graham, and L. Walker, ‘non linear tie-line bias control of Interconnected power systems,’ IEEE Trans. Power App.Syst., vol. PAS-100 no. 5 pp. 2350–2356.

[14] T. Kennedy, S.M. Hoyt, and C. F . Abell, ‘Variable, non-linear tie line frequency bias for interconnected systems control ’, IEEE Ttrans. On Power Systems, Vol. 3, No. 3, August 1988, pp. 1244-1253.

[15] D. Das, J. Nanda, M. L. Kothari, and D. P. Kothari, ‘Automatic generation control of Hydro hermal system with new area control error considering generation rate constraint,’ Elect. Mach. Power Syst., vol. 18, no. 6, pp. 461– 471, Nov./Dec. 1990.

[16] R. K. Cavin, M. C. Budge Jr., P. Rosmunsen, ‘An Optimal Linear System Approach to Load Frequency Control’, IEEE Trans. On Power Apparatus and System, PAS-90, Nov./Dec. 1971, pp. 2472-2482.

[17] A. Rubaai and V. Udo, ‘An a daptive control scheme for LFC of multi area power systems. Part I: Identification and functional design, Part-II: Implementation and test results by simulation,’ Elect. Power Syst. Res., vol. 24, no. 3, pp. 183–197, Sep. 1992.

[18] V. R. Moorthi and R. P. Aggarawal, ‘Suboptimal and near optimal control of a load frequency control system,’ Proc. Inst. Elect. Eng., vol. 119, pp. 1653– 1660, Nov. 1972.

[19] A. Khodabakhshian and M. Edrisi, “A new robust PID load frequency controller,” Control Eng. Pract., vol. 16, no. 9, pp. 1069–1080, 2008.

[20] C. E. Fosha and O. I. Elgerd, “The megawatt -frequency control problem: A new approach via optimal control theory,” IEEE Trans. Power App. Syst., vol. PAS-89, no. 4, pp. 563–567, 1970.

[21] Yogendra Arya, Narendra Kumar, S.K. Gupta, “Load Frequency Control of a Four-Area Power System using Linear Quadratic Regulator”, IJES Vol.2 2012 PP.69-76

[22] M. Morari and E. Zafiriou, Robust Process Control. Englewood Cliffs, NJ: Prentice-Hall, 1989.

[23] J. Talaq and F. Al-Basri, “Adaptive fuzzy gain scheduling for load frequency control,” IEEE Trans. Power Syst., vol. 14, no. 1, pp. 145–150, Feb. 1999.

[24] M. F. Hossain, T. Takahashi, M. G. Rabbani, M. R. I. Sheikh, and M. Anower, “Fuzzy-proportional integral controller for an AGC in a single area power system,” in Proc. 4th Int. Conf. Electrical and Computer Engineering (ICECE), Dhaka, Bangladesh, Dec. 2006, pp. 120–123.

[25] Y. H. Moon, H. S. Ryu, J. G. Lee, and S. Kim, “Power system load frequency control using noise-tolerable PID feedback,” in Proc. IEEE Int. Symp. Industrial Electronics (ISIE), Jun. 2001, vol. 3, pp. 1714–1718.

[26] A. Khodabakhshian and N. Golbon, “Unified PID design for load frequency control,” in Proc. 2004 IEEE Int. Conf. Control Applications (CCA), Taipei, Taiwan, Sep. 2004, pp. 1627–1632.

[27] C. Brosilow and B. Joseph, Techniques of Model-Based Control. Englewood Cliffs, NJ: Prentice-Hall, 2002.