LQR BASED DESIGN OF AGC

FOR MULTI AREA SYSTEM

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CERTIFICATE

I, **Priyanka Gangwar**, Roll No. 2K12/PSY/18 student of M. Tech. (Power System), hereby declare that the dissertation titled "**LQR Based Design Of AGC For MultiArea System**" under the supervision of**Dr. Suman Bhowmick** of Electrical Engineering Department, Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

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Delhi, 2014 PRIYANKA GANGWAR

ABSTRACT

Control of active power and reactive power is required to keep the system in the steady state. As the system load changes continuously, the generation is adjusted automatically to restore the frequency to the nominal value. This scheme is known as the automatic generation control (AGC). To generate and deliver power in an interconnected system as economically and reliably as possible while maintaining the voltage and frequency within permissible limits, several control strategies have been in use. One of the most controllers available commercially is the proportional integral derivative (PID) controller. The PID controller is used to improve the dynamic response as well as to reduce or eliminate the steady-state error.

In this thesis modern control designs are employed that require the use of state variables to form a linear controller. One approach in modern control systems accomplished by the use of state feedback also known as pole placement design. The pole placement design allows all roots of the system characteristic equation to be placed in desired locations. The other approach to the design of regulator systems is the optimal control problem, where a specified mathematical performance criterion is minimized. An optimal controller for linear systems with quadratic performance index, the so called linear quadratic regulator (LQR) has been designed for the AGC for two area and three area system and LQR is also designed for the two area system in deregulated environment. Multiple case studies are used to illustrate the effectiveness of the proposed load frequency control strategy.

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

AGC	Automatic Generation Control
LFC	Load Frequency Control
SG	Speed Governor
R	Speed regulation due to SG
K_g , t_g	Gain and Time constant of SG
K_t , t_t	Gain and Time constant of turbine
ΔP_m	Generating power increase due to SG
ΔP_d	Load change
f	frequency
$\Delta\delta$	Torque angle change
H	Inertia constant
T_{12}	Tie-line synchronizing coefficient between area 1 and 2
K_P	Power system equivalent gain
T_P	Power system equivalent time constant
ACE	Area Control Error
apf	Area participation factor
DPM	Participation Matrix for DISCO
cpf	Contract participation factor
A	System Matrix
B	Control input matrix
C	Output matrix
X	Vector of State variables
Y	Output vector
K	Control gain
u	Control input vector
J	Performance index
Q	State variable weighting matrix

CHAPTER 1

INTRODUCTION

Interconnection in large electric power system is intended to make electric energy more economical and more reliable. However, with highly interconnected power grid load frequency problem and load frequency instabilities may arises.

The economical aspect of the large scale interconnection is remarkable reduction of spinning reserve or stand by the generating capacity for maintenance or emergency use. Interconnected systems also enhance the reliability by transferring power from one area to other within the system. But in the mean time multiple interconnections between areas make the system unstable. For safe and efficient operation of interconnected power systems there are verities of control problem that need to be addressed.

In interconnected power systems among the various problems one of the problems is Load Frequency Control (LFC). LFC supplies time varying load along with maintaining scheduled frequency and tie-line power as nominal values. As we know that three-phase AC is used in transmission. Between generating units and loads, the active and reactive power both should be balanced.

This balance will provide two stable points' i.e frequency and voltage. If any misbalance will occur between these two powers than these points will change. Both frequency along with voltage should remain at nominal values during operation for satisfactory operation of an electric power system. However the demand of supply changes randomly. It will not be possible control active and reactive power balances without a controller. As result, frequency along with voltage level will change as load change will takes place. Thus a control system is required for controlling the frequency and voltage to its nominal values.

An active and reactive power both has combined effects on frequencyand voltage control but it can be decoupled. The voltage mainly affects reactive power and the frequency mainly affects active power, that's why the control problem in power systems can be decoupled into two independent problems. Active power control problem is called load frequency control.

The function of LFC is maintaining the frequency constant when load is varying. And the other function of LFC is decreasing the tie-line power error. Many generating units are interconnected and make a large scale power system. For increasing fault bearing capacity of the power system, generating units will be interconnected through tie-line. Use of the tie-line power will generate new error in system and this is called tie line error. When suddenly load change will takes place into the area, area will interchange the energy through tie-lines foranother area. Area in which load is varying should balance it without external support. Otherwise it will create an economic conflict issues among different areas. So that every area should have a its ownLFC so that they can regulate their tie-line power so that all areas can set their set points accordingly. Second problem is, if we connect several power systems than order and number of control parameters will also increase. As a result, when we do modelling of such complex high-order power systems, we have to consider some parameters approximation [2].

In summary, LFC has to perform the major function of maintaining the frequency within the limit and maintain the tie-line power exchange within the range if load changes takes place [1].

Modelling is basic part of the modern control design. It is obvious that without a proper model, we cannot be successful in controlling the behaviour of any system. Generally for modern control dynamical systems are described in state space form. To achieve desired response of a system without high control effort, optimal control is employed, where a performance index or cost function for the system is defined. We have to minimize the cost function for optimal control law. Weighted quadratic function of state variables and the control inputs is called cost function. Hence it is called Linear Quadratic Regulator (LQR).

In this thesis we shall concentrate on modern control approaches to LFC. Basically three category of control is discussed. These are the pole placement method, optimal control method and optimal control method in deregulated environment.

1.1LITERATURE REVIEW

Proportional-integral (PI) controller is using from last many years in industries. The design of PI controller for a power system that has three areas is presented in [3], where the other parameters are tuned by trial-and-error method. The designing of LFC is taken as a centralized method. In [4] and [5], this method introduced along with simplified multiple-area power system in order to implement such optimization techniques on whole model. The simplification is done accordingly on the assumption that all subsystems of whole power system are same while they are not. Second problem of centralized methods is that although if the method works well for a low-order system, it will face an exponentially increasing calculation problem with the increase of the system size.

There are many techniques which applied to the decentralized power systems. In [6–10], decentralized PI and PID controller is described. As *H2/H∞* control is known for robustness against parameter uncertainties, the controllers are utilizing for solving the decentralized LFC problems in [11–14]. There are many modern control theories that have yielded decentralized solutions of the LFC problem , such as disturbance accommodation control, optimal tracking approach, predictive control scheme and ramp following control, which can be found in [15–18].

Fuzzy logic is based on the fuzzy set theory, in which fuzzy logic variables will be between 0 and 1 instead of true or false. In [19-22] result obtained from the fuzzy logic control technique to decentralized LFC problem have been described. A fuzzy logic controller is develop directly from fuzzy model of the power system is developed in [19]. A fuzzy logic approach of tie line bias control scheme of a two-area power system is described in [20] while a same method on a combined cycle power plant including the comparison between the fuzzy logic control and conventional PID control techniques are introduced in [21]. A fuzzy based PI controller and its implementation on the Iraqi National Super Grid power system can be found in [22]. A comparison between the fuzzy based PI controller and the traditional PI controller was also presented in [22].

Among the most popular computer intelligence algorithms one is Genetic algorithm (GA). It has been verified that it is very useful for solving complex optimization problem [23] where PI-type controllers tuned through GA and linear matrix inequalities (GALMI) is described for a decentralized three-area power system. In [23], it is presented that, structure of GALMI tuned PI controller is much simple than that of the *H2/H∞* controller even though the performance of two methods are approximately same .For sudden large load change many of the given solution have been tested. In [2], author set 15% floating rate for parameters in one area and successfully controlled the system via an optimally tuned PID controller.

The design and implementation of the LQR with integral control action is presented in [24]. The integral action minimizes the steady state errors, whereas LQR only provides feedback gain matrix. Increasingly popular control technique ADRC, was proposed by J. Han and modified by Z. Gao In [25-26]. In [28-31] authors presented various ADRC based control design. In [36] ADRC-based LFC solution for the power systems with turbines of various types, such as non-reheat, reheat, and hydraulic is discussed. In [39] after deregulation LFC issues in power systems are discussed. Authors [41-42] discussed price-based operation of AGC simulator.

1.2ORGANISATION OF THE THESIS

In this thesis, optimal control is employed for centralized as well as in deregulated environment system for LFC problem. The thesis consists of five chapters.

Chapter one is an overview of general ideas about load frequency control (LFC), linear quadratic control (LQR) and related works and approaches to LFC and LQR.

Chapter two addresses the modelling of the AGC (automatic generation control) in two area system with supplementing the exciter loop for the generators to take into consideration the effect of the exciters on the response of the system.

Chapter three addresses the modelling of the AGC in deregulated environment and modelling of two area system in deregulated environment.

Chapter four addresses the mathematical modelling of Optimal controller (LQR) for two area and three area system.

Chapter five presents the different case studies taken up for analysis and the results.

CHAPTER 2

AUTOMATIC GENERATION CONTROL

In this chapter, modelling of a power generating system, In addition the modelling of two types of generating units, tie-line modelling and the modelling of parallel operation of multi areas is introduced.

2.1 LOAD FREQUENCY CONTROL (LFC)

Main work of LFC is maintaining uniform frequency by dividing the loads among the generators and control tie-line power deviation within limit. The frequency deviation and tie-line real power change are examined, which is a measure of the change in rotor angle δ, the error Δδ to be corrected. The error signal, i.e, Δf and ΔP_{tie}, are amplified, mixed and transformed into real power command ΔP_V signal, which is sent to the prime mover to increment the torque.

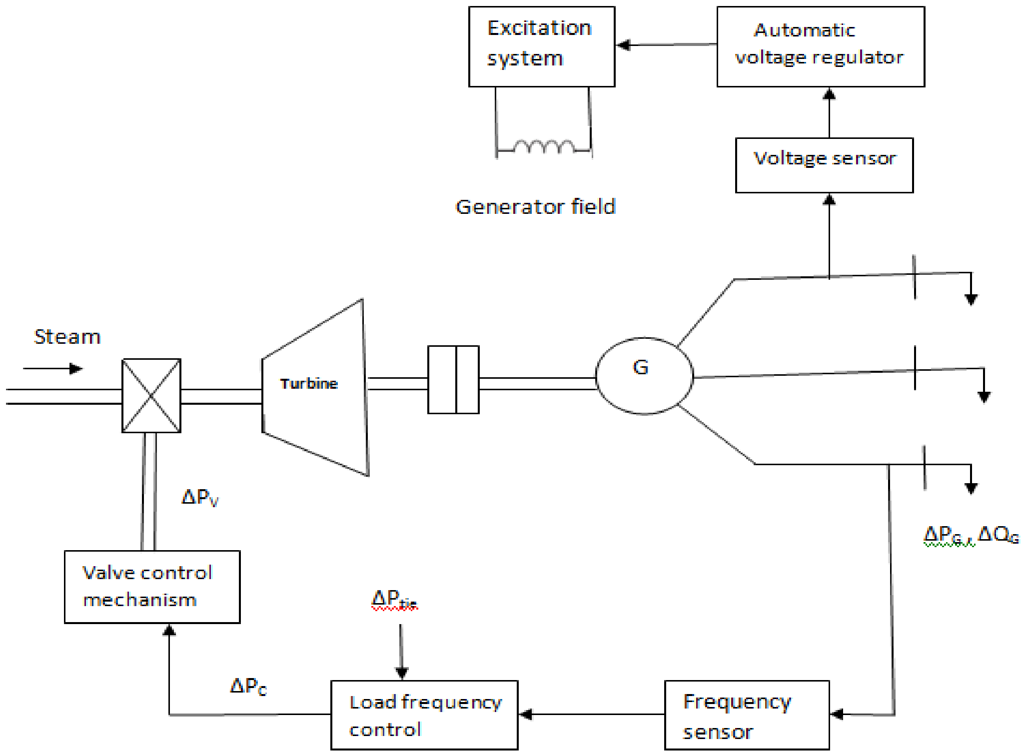

Fig 2.1 Schematic diagram of LFC and AVR of a synchronous generator

Therefore the prime mover brings change in the generator output by an amount ΔP_gwhich will change the values of Δf and ΔP_{tie} within specified limit.

2.1.1 GENERATOR MODEL

Small perturbation analysis of the swing equation of the synchronous machine gives,

$$\frac{2H}{\omega_S}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e (2.1)$$

If small deviation occurs in speed

$$\frac{d\Delta\frac{\omega}{\omega_S}}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e)(2.2)$$

Speed in p.u can be expressed as:

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e)(2.3)$$

Take Laplace transform of (2.3), we obtain

$$\Delta\omega(s) = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_e(s)] \qquad (2.4)$$

The above relation is shown in block diagram 2.2

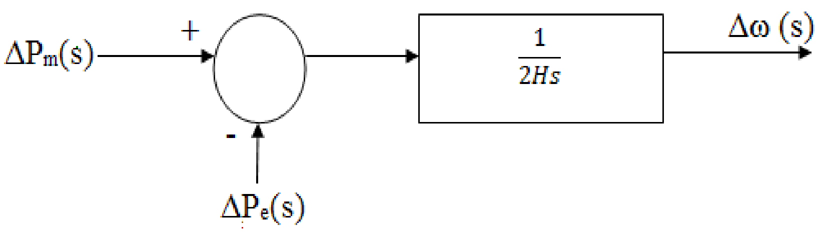

Fig 2.2 Generator block diagram

2.1.2 LOAD MODEL

A power system consist many electrical devices as a load. For resistive load, for example lighting and heating loads, the power does not depend on frequency. But the load like motors is very sensitive to changes in frequency. For all the driven devices change in frequency will depends up on the speed load characteristic of the device.
The speed load equation for a total load can be written as:

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

Where ΔP_L = The load change which is not frequency sensitive
D $\Delta\omega$ = The change in load which is frequency sensitive
D can be written as percentage change in load divide by percentage change in frequency. Now include load model in generator block diagram, resultant block diagram is shown in fig 2.3

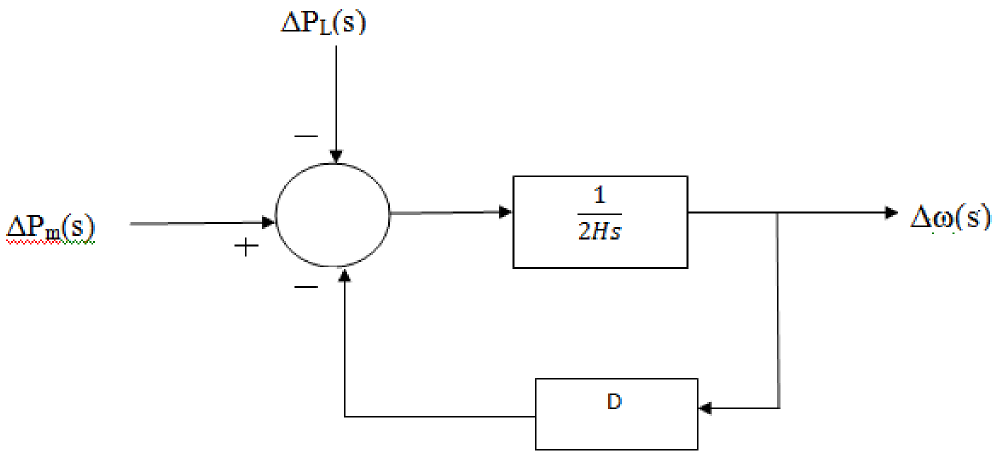

Fig 2.3 Generator and load block diagram

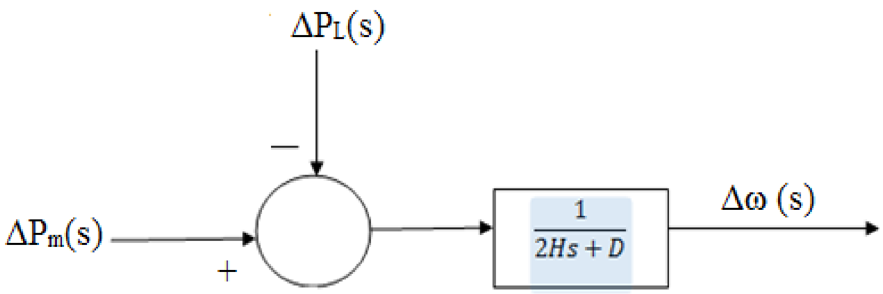

Fig 2.4 Generator and load block diagram

2.1.3 PRIME MOVER MODEL

Prime mover provides mechanical power. It may be a hydraulic turbine or can be steam turbine. Turbine model will relate the changes in the mechanical power output ΔP_m to the steam valve position ΔP_V.

Simpler prime mover model of a non reheat steam turbine can be approximated as single time constant T_T, will result the following transfer function

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1+sT_T} \quad (2.5)$$

The block diagram for a simple turbine is shown in fig 2.5

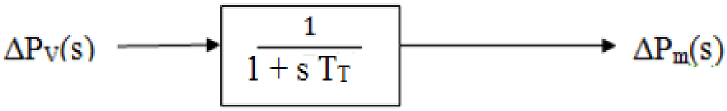

Fig 2.5 Block diagram for a simple non reheat steam turbine

The time constant T_T is in the range of 0.2 to 2 seconds.

Due to the inertia of water hydraulic turbines units are non minimum phase units. In hydraulic turbines, the water pressure response is opposite to gate position change at first and recovers after the transient response. Hence for hydraulic turbine transfer function will be

$$G_H\,(s) = \frac{\Delta P_m\,(s)}{\Delta P_v\,(s)} = \frac{-sT_W+1}{s\left(\frac{T_W}{2}\right)+1} \quad (2.6)$$

where *Tw* is starting time of water.

For stability, a transient droop compensation part in governor is added for the hydraulic turbine. The transfer function of the transient droop compensation part is

$$G_{TDC}\,(s) = \frac{sT_R+1}{sT_R\left(\frac{R_T}{R}\right)+1} \quad (2.7)$$

where T_R, R_T and R presents the reset time, temporary droop and permanent droop respectively.

2.1.4 GOVERNOR MODEL

If generator load increases suddenly, than the output of electrical power becomes greater than the mechanical input power. The deficient power is supplied through the kinetic energy,which is stored in the rotating system. So that kinetic energy starts decreasing and turbine speed starts decreases and the generator frequency start begins to drop. Turbine governor sensed the change in speed which acts to alter the turbine input valve position for changing mechanical power output and speed reaches to a new steady state value.

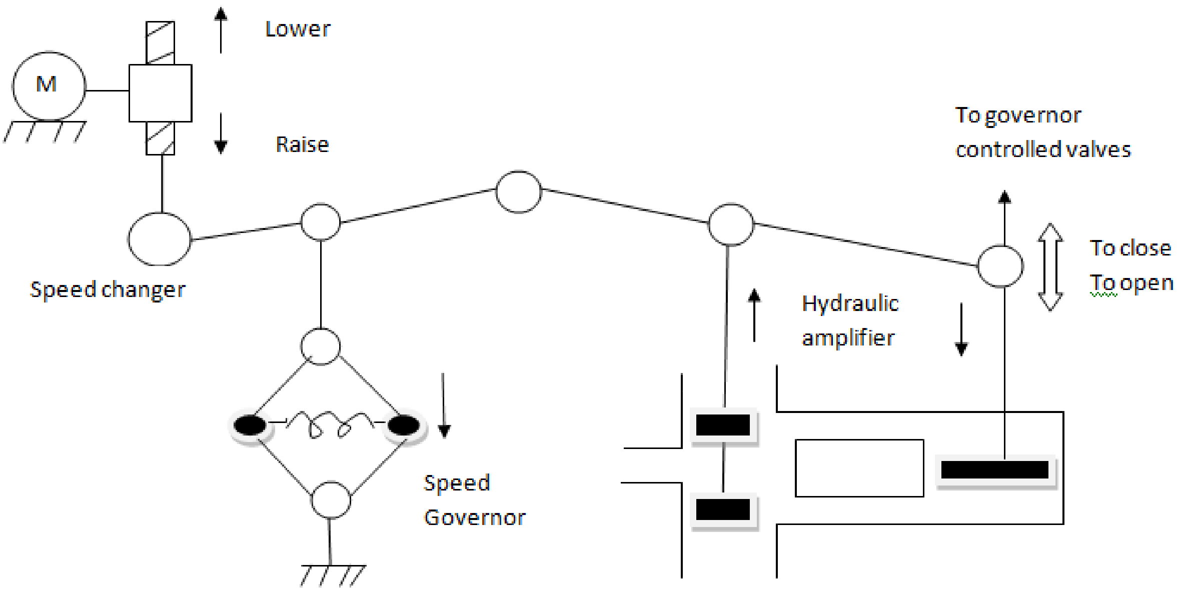

Fig 2.6 Speed governing system

The speed governor action will function like a comparator whose output ΔP_g is difference between the reference set power $\Delta P_{ref}$and power$\frac{1}{R}\Delta\omega$.

$$\Delta P_g = \Delta P_{ref} - \frac{1}{R}\Delta\omega \qquad (2.8)$$

R = Speed regulation

Or in s- domain

$$\Delta P_g(s) = \Delta P_{ref}(s) - \frac{1}{R}\Delta\omega(s) \qquad (2.9)$$

The command ΔP_g is converted into the steam valve position command ΔP_V through the hydraulic amplifier. Let us suppose a linear relationship and consider a time constant T_g,

$$\Delta P_V(s) = \frac{1}{1+sT_g}\Delta P_g(s) \qquad (2.10)$$

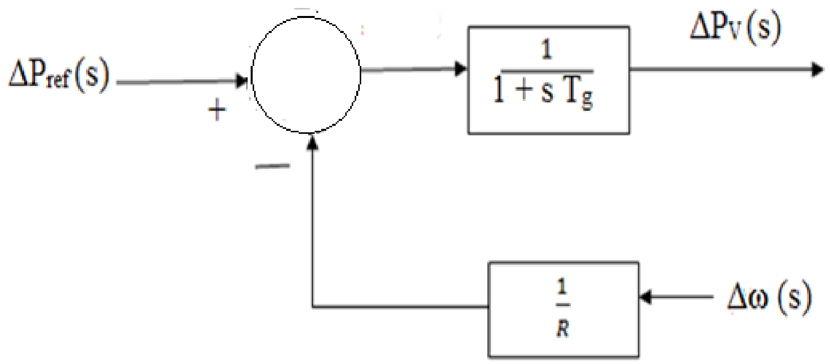

Fig 2.7 Block diagram of speed governing system for speed turbine

Equations (2.7) and (2.8)can be represented by the block diagram as shown in fig 2.7. Combining the block diagrams of figures 2.4, 2.5, 2.7 results in the complete block diagram of LFC of a power station as shown in fig 2.8

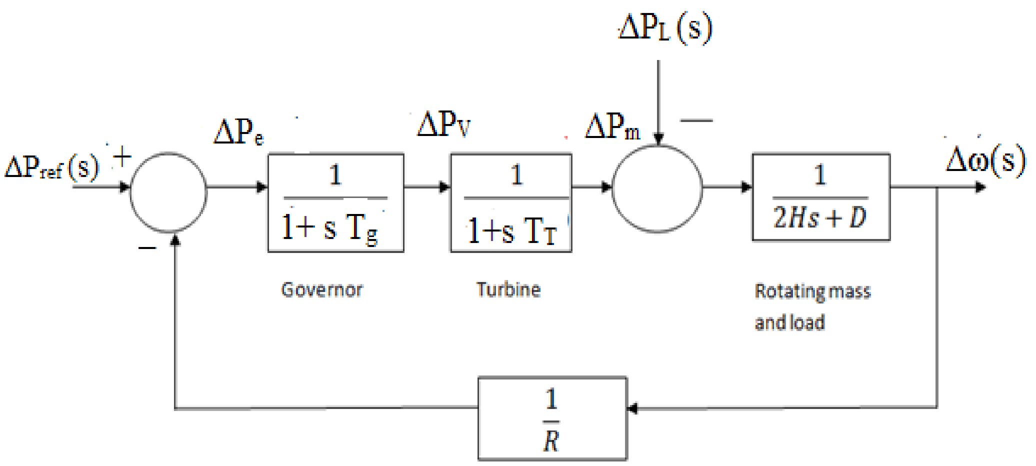

Fig 2.8 Load frequency control block diagram of an isolated power system

Redrawing the block diagram of fig 2.8 by considering the change in load $-\Delta P_L(s)$ as input and frequency deviation $\Delta\omega(s)$ as the output results in the block diagram i.e shown in fig 2.9.The open loop transfer function of block diagram in fig 2.9 is

$$K\,G(s)H(s) = \frac{1}{R}\frac{1}{(2Hs+D)(1+sT_g)(1+sT_T)} \quad (2.11)$$

and the closed loop transfer function which represents the relation between the load change ΔP_L to the frequency deviation $\Delta\omega$ is

$$T(S) = \frac{\Delta\omega(s)}{-\Delta P_L(s)} = \frac{(1+sT_g)(1+sT_T)}{(2Hs+D)(1+sT_g)(1+sT_T)+\frac{1}{R}} \quad (2.12)$$

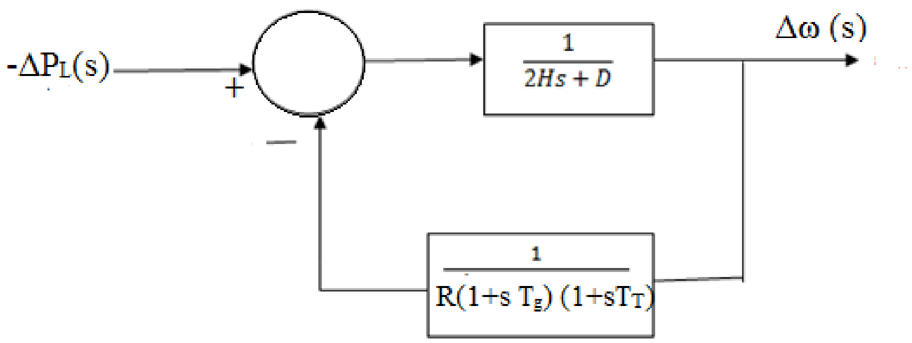

Fig 2.9 LFC block diagram with input $\Delta P_L(s)$ and output $\Delta\omega(s)$

$$\Delta\omega(s) = -\,\Delta P_L(s)\,T(s) \quad (2.13)$$

The load change is a step input , i.e, $\Delta P_L(s) = \Delta P_L / s$. Applying final value theorem, the steady state value of $\Delta\omega$ is

$$\Delta\omega_{ss} = \lim s\,\Delta\omega(s) = (-\Delta P_L)\frac{1}{D+\frac{1}{R}} \quad (2.14)$$

For no frequency sensitive load D = 0, frequency deviation in steady state can be determined by the speed regulation of governor, and is

$$\Delta\omega_{ss} = (-\Delta P_L)\,R \quad (2.15)$$

2.2 MODELLING OF AUTOMATIC GENERATION CONTROL

If the load is increased abruptly then turbine speed starts to decrease before governor can adjust the input of the steam to the new load. As the change in speed decreases the error signal will become smaller and the position of the governor will get closer to the point required to maintain the constant speed. One way to recover the speed or frequency to its given value is to add an integrator on the way. The integrator will monitor the error over a period and will reduce the offset. For bringing back frequency to nominal position when load changes occur, generation should be changed accordingly. This type of scheme is called AGC (automatic generation control). In the interconnected power system consists of several pools, the role of the AGC is to divide the load among the different systems, stations and generators so that maximum economy and fairly uniform frequency can be achieved.

2.2.1 AGC FOR SINGLE AREA SYSTEM

When we consider only primary LFC loop, load change will result in steady state frequency deviation, it depends on speed regulation of the governor. Tomaking frequency deviation to zero we must arrange a reset action by adding an integral control action to act on the load reference setting for changing the speed set point. The integral control action will increase the type of system by one, which will make the change in frequency to zero. The gain of integral control action can be readjusted for achieving desired transient response.

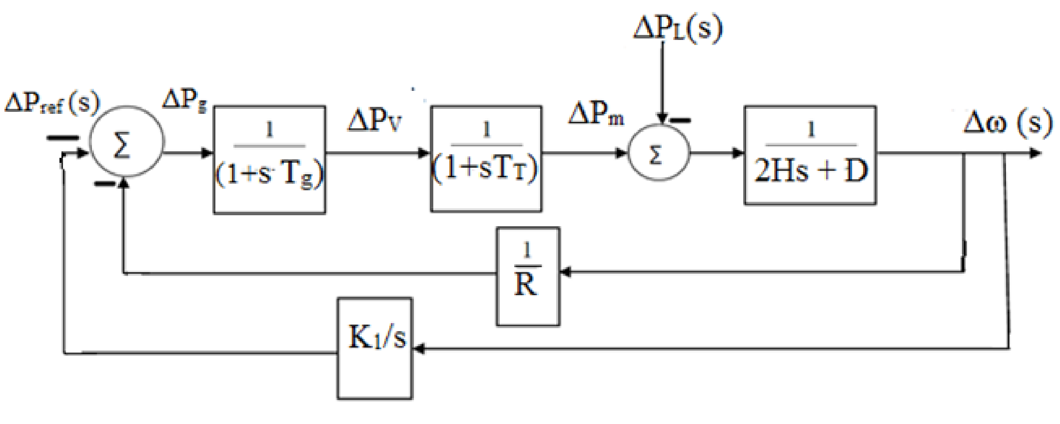

Fig 2.10 AGC for an isolated power system

The transfer function of a closed loop system is given below:

$$\frac{\Delta\omega(s)}{-\Delta P_L(s)} = \frac{s(1+sT_g)(1+sT_t)}{s(2Hs+D)(1+sT_g)(1+sT_T)+K+\frac{s}{R}} \quad (2.16)$$

2.2.2 AGC FOR TWO AREA SYSTEM

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

$$P_{12} = \frac{|E_1||E_2|}{X_{12}} Sin\delta_{12} \quad (2.17)$$

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

If a small change occur in tie-line flow:

$$\Delta P_{12} = \left.\frac{dp_{12}}{d\delta_{12}}\right|_{\delta_{12}} \quad (2.18)$$

$$= P_s \Delta\delta_{12}$$

P_s is slope of the power angle curve at initial operating angle $\delta_{120} = \delta_{10}-\delta_{20}$. Hence we have

$$P_s = \frac{dP_{12}}{d\delta_{12}}$$

$$= \frac{E_1 E_2}{X_{12}} cos\delta_{120} \quad (2.19)$$

Then the tie line power deviation becomes

$$\Delta P_{12} = P_S (\Delta\delta_1 - \Delta\delta_2) \quad (2.20)$$

The tie-line power will appear as increment in the load for one area and decrement in the load for another area, it depends upon the direction of the flow. The direction of flow is governed by the difference in phase angle; if $\Delta\delta_1 > \Delta\delta_2$, the power will flow from area1 to area2. A block diagram when LFC containing only primary loop for two area system is shown in fig 2.11

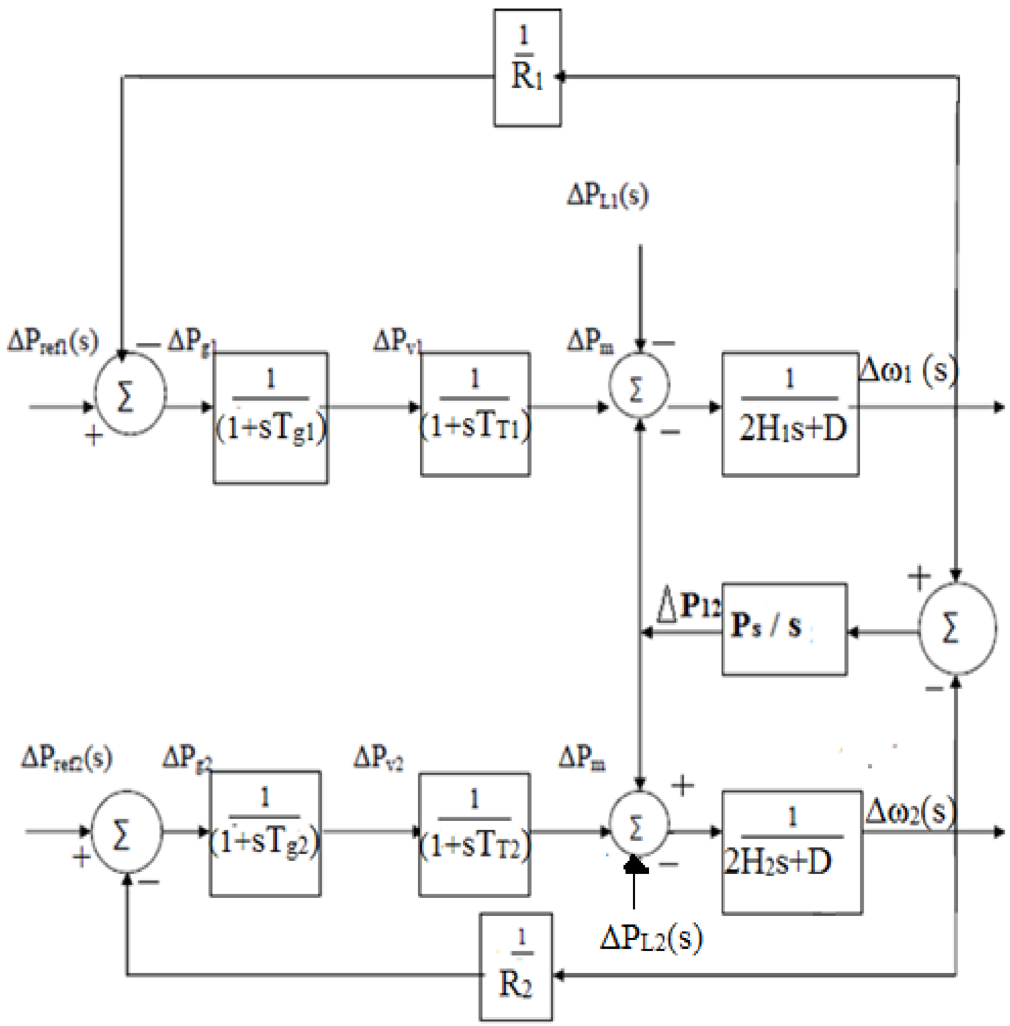

Fig 2.11 Two area system with only primary LFC loop

2.2.3 STATE SPACE MODEL OF TWO AREA POWER SYSTEM

Consider a two area system as shown in fig 2.12

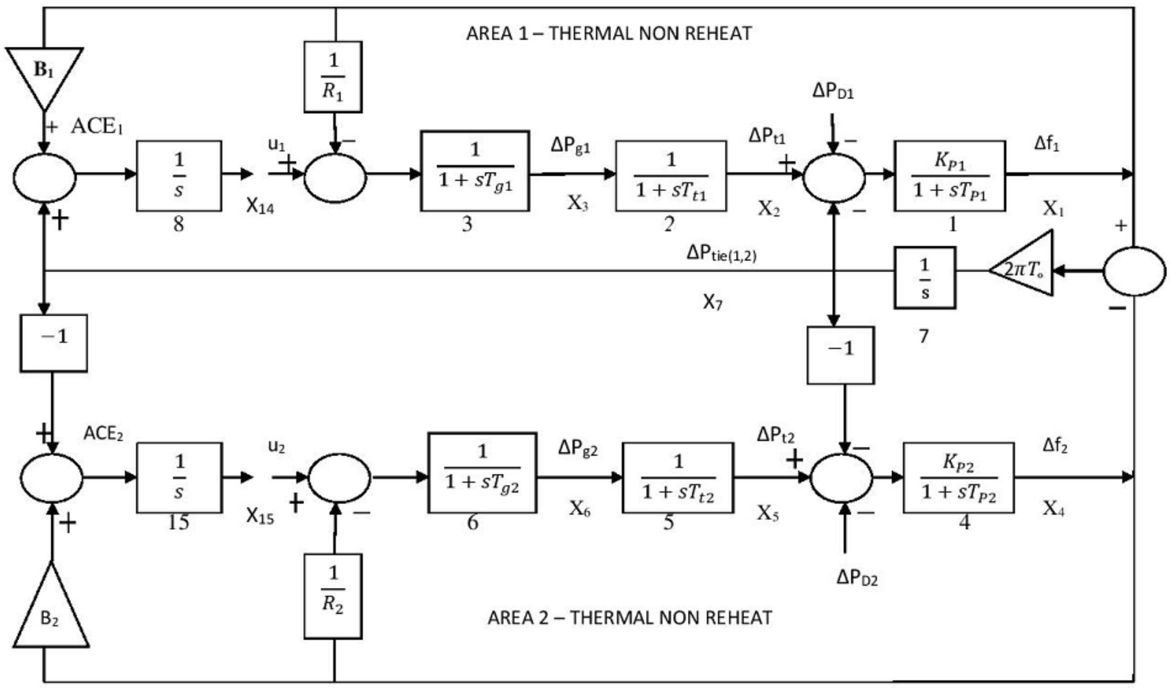

Fig 2.12 Two Area system

State variables:
$X_1 = \Delta f_1$
$X_2 = \Delta P_{t1}$
$X_3 = \Delta P_{g1}$
$X_4 = \Delta f_2$
$X_5 = \Delta P_{t2}$
$X_6 = \Delta P_{g2}$
$X_7 = \Delta P_{tie1-2}$
$X_8 = \int ACE_1\, dt$
$X_9 = \int ACE_2\, dt$
Control inputs: u_1 and u_2
Disturbance inputs: $d_1 = \Delta P_{D1}$ and $d_2 = \Delta P_{D2}$
State equations:
From the transfer function blocks labelled from 1 to 9 (fig 2.12)
$\dot{X}_1 = \frac{1}{T_{P1}} X_1 + \frac{K_{P1}}{T_{P1}} X_2 - \frac{K_{P1}}{T_{P1}} X_7 - \frac{K_{P1}}{T_{P1}} d_1$(2.21)
$\dot{X}_2 = -\frac{1}{T_{t1}} X_2 + \frac{K_{P1}}{T_{t1}} X_3$(2.22)

$\dot{X}_3 = \frac{-1}{R_1 T_{g1}} X_1 - \frac{1}{T_{g1}} X_3 - \frac{1}{T_{g1}} u_1$ (2.23)

$\dot{X}_4 = -\frac{1}{T_{p2}} X_4 + \frac{K_{P2}}{T_{p2}} X_5 + \frac{K_{P2}}{T_{p2}} X_7 - \frac{K_{P2}}{T_{p2}} d_2$ (2.24)

$\dot{X}_5 = -\frac{1}{T_{t2}} X_5 + \frac{1}{T_{t2}} X_6$ (2.25)

$\dot{X}_6 = \frac{-1}{R_2 T_{g2}} X_4 - \frac{1}{T_{g2}} X_6 + \frac{1}{T_{g2}} u_2$ (2.26)

$\dot{X}_7 = 2\pi T^0 X_1 - 2\pi T^0 X_4$ (2.27)

$\dot{X}_8 = B_1 X_1 + X_7$ (2.28)

$\dot{X}_9 = B_2 X_4 - X_7$ (2.29)

The matrices **A, B** are

$$
\mathbf{A} = \begin{bmatrix}
\frac{-1}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & \frac{-K_{P1}}{T_{P1}} & 0 & 0 \\
0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{-1}{R_1 T_{g1}} & 0 & \frac{-1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-1}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & \frac{K_{P2}}{T_{P2}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{-1}{T_{t2}} & \frac{-1}{T_{t2}} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-1}{R_2 T_{g2}} & 0 & \frac{-1}{T_{g2}} & 0 & 0 & 0 \\
2\pi T^{\circ} & 0 & 0 & 2\pi T^{\circ} & 0 & 0 & 0 & 0 & 0 \\
B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & B_2 & 0 & 0 & -1 & 0 & 0
\end{bmatrix}
$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{T_{g1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{g2}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$\mathbf{X} = [X_1\ X_2\ X_3\ X_4\ X_5\ X_6\ X_7\ X_8\ X_9]^T$

$\mathbf{u} = [u_1\ u_2]^T$

2.2.4 TIE-LINE BIAS CONTROL

For normal working conditions control strategies are:

- Keep frequency around at rated value
- It maintain the flow of tie-line power within limit
- Each area have to adjust the changes which is occurring in its own area

Every area has to reduce ACE to zero, conventional LFC is based upon it. For each area ACE is summation of frequency deviation and tie-line power error.

$$ACE_i = \sum_{j=1}^{n} \Delta P_{ij} + K_i\ \Delta\omega \quad (2.30)$$

During a disturbance in the neighbouring areas, the amount of interaction is determined by area bias factor K_i. ACEs for a two area system are

$ACE_1 = \Delta P_{12} + B_1 \Delta\omega_1$

$ACE_2 = \Delta P_{21} + B_2\ \Delta\omega_2$ (2.31)

Where $B_i = \frac{1}{R_i} + D_i$

For changing the reference power set point, ACEs are used as actuating signal and in steady state condition ΔP_{12} and $\Delta\omega$will become zero.

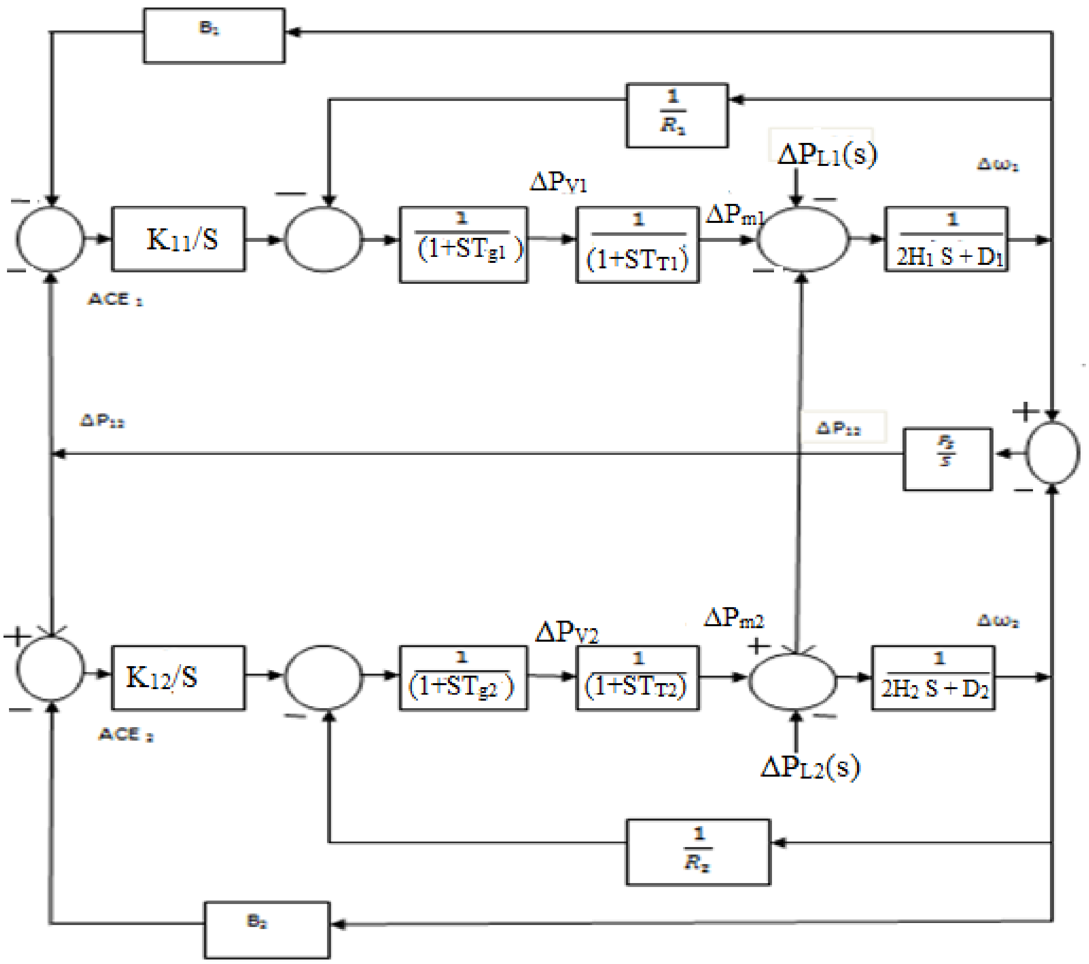

Fig 2.13 AGC block diagram for a two area system

2.3 AGC FOR THREE AREA SYSTEM

For three area system, a scheme with LFC and delayed control signal is shown in Fig 2.14. ACE signals are inputs to the controller, which is summation of frequency variations in control area and tie-line power deviation:

$$ACE_i(t) = K_{Bi} * \Delta f_i(t) + \Delta P_{tie}(t) \qquad (2.32)$$

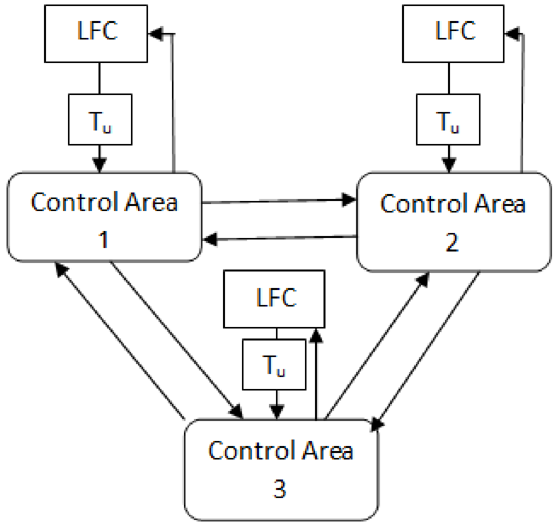

Fig 2.14 Interconnection of Three Areas

The simplified continuous model of one control area, shown in fig.2.15

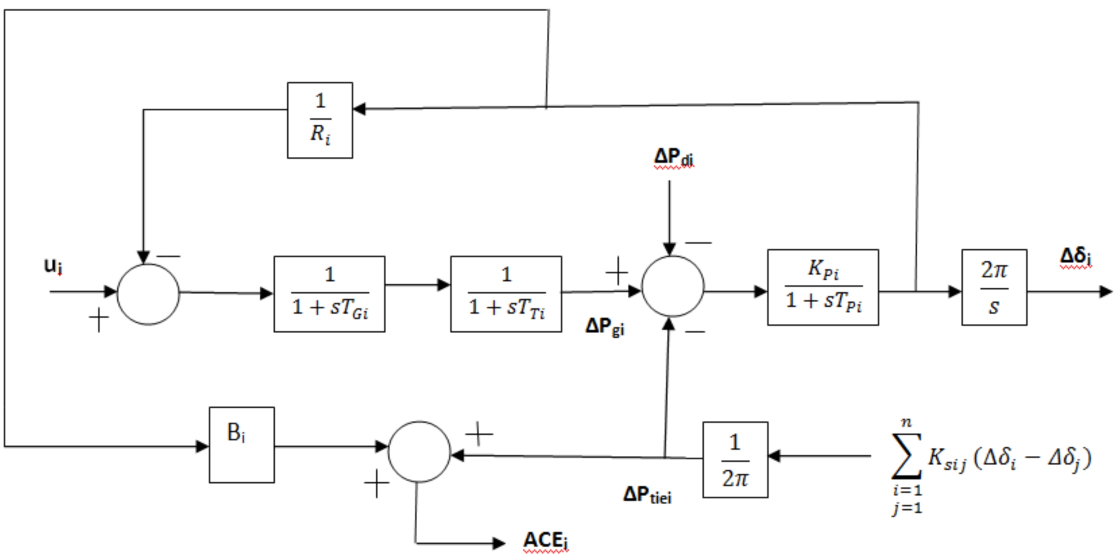

Fig 2.15 The block diagram of ith area

Let's suppose that control signals and disturbance are constant. It can be seen that from Fig.2.15, in Area i in steady state change in frequency depends upon the input disturbance and controller output signal, as is given in the equation below:

$\Delta f_{ss} = \frac{u_i - \Delta P_{di} - \Delta P_{tiei}}{\frac{1}{K_{pi}} + \frac{1}{R_i}}$(2.33)

Where i=1,2,3…..

In the steady state, frequency deviation of all the interconnected areas will be same; it is a property of power system [38]

$\Delta f_{1ss} = \Delta f_{2ss} = \Delta f_{3ss}$

In the interconnected multi area power system the addition of power flow among the areas is equal to zero, this is another property of power system.

$$\Delta P_{tie1} + \Delta P_{tie2} + \Delta P_{tie3} = 0 \quad (2.34)$$

Assume that in area i controller's output is not zero, while in all the other areas controller's output and the load disturbances are equal to zero , than tie line power for area1 can be written as:

$\Delta P_{tie1} = \frac{R_1(R_2 + R_3)}{R_1R_2 + R_1R_3 + R_2R_3} u_1$(2.35)

Assume that in area i load disturbance is other than the zero, the dependency of ΔP_{tie} on ΔP_{di} can be calculated. Tie-line power for area1 can be written as:

$\Delta P_{tie1} = \frac{R_1(R_2 + R_3)}{R_1R_2 + R_1R_3 + R_2R_3} \Delta P_{d1}$(2.36)

Block diagram for three interconnected areas is shown in fig 2.16

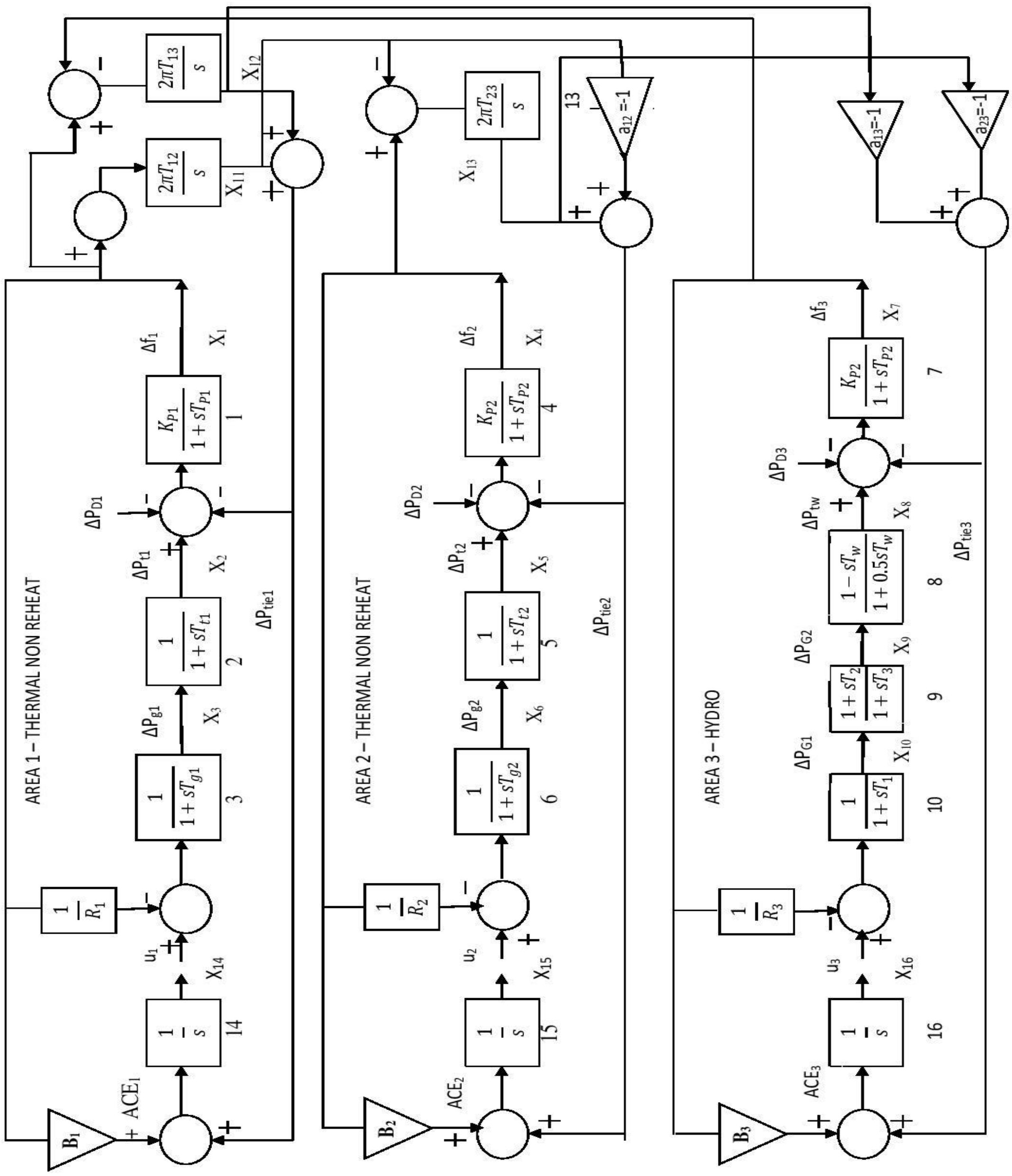

Fig 2.16 AGC for a three area system

2.4 STATE SPACE MODEL OF THREE AREA SYSTEM

Consider a interconnected three area system shown in fig 2.16. From the blocks labelled from 1 to 16

State Variables:

$X_1 = \Delta f_1$

$X_2 = \Delta P_{t1}$

$X_3 = \Delta P_{g1}$

$X_4 = \Delta f_2$

$X_5 = \Delta P_{t2}$

$X_6 = \Delta P_{g2}$

$X_7 = \Delta f_3$

$X_8 = \Delta P_{tw}$

$X_9 = \Delta P_{G2}$

$X_{10} = \Delta P_{G1}$

$X_{11} = \Delta P_{tie1-2}$

$X_{12} = \Delta P_{tie1-3}$

$X_{13} = \Delta P_{tie2-3}$

$X_{14} = \int ACE_1\, dt$

$X_{15} = \int ACE_2\, dt$

$X_{16} = \int ACE_2\, dt$

Control inputs: u_1 , u_2 and u_3

State equations:

$\dot{X}_1 = -\frac{1}{T_{P1}}X_1 + \frac{K_{P1}}{T_{P1}}X_2 - \frac{K_{P1}}{T_{P1}}X_{11} - \frac{K_{P1}}{T_{P1}}X_{12} - \frac{K_{P1}}{T_{P1}}d_1$(2.37)

$\dot{X}_2 = -\frac{1}{T_{t1}}X_2 + \frac{1}{T_{t1}}X_3$(2.38)

$\dot{X}_3 = \frac{-1}{R_1 T_{g1}}X_1 - \frac{1}{T_{g1}}X_3 + \frac{1}{T_{g1}}u_1$(2.39)

$\dot{X}_4 = -\frac{1}{T_{P2}}X_4 + \frac{K_{P2}}{T_{P1}}X_2 - \frac{K_{P1}}{T_{P1}}X_{11} - \frac{K_{P1}}{T_{P1}}X_{12} - \frac{K_{P1}}{T_{P1}}d_1$(2.40)

$\dot{X}_5 = -\frac{1}{T_{t2}}X_5 + \frac{1}{T_{t2}}X_6$(2.41)

$\dot{X}_6 = \frac{-1}{R_2\, T_{g2}}X_4 - \frac{1}{T_{g2}}X_6 + \frac{1}{T_{g2}}u_2$(2.42)

$\dot{X}_7 = -\frac{1}{T_{P3}}X_7 + \frac{K_{P3}}{T_{P3}}X_8 + \frac{K_{P3}}{T_{P3}}X_{12} + \frac{K_{P3}}{T_{P3}}X_{13} - \frac{K_{P3}}{T_{P3}}d_3$(2.43)

$\dot{X}_8 = \frac{2T_2}{R_3 T_1 T_3}X_7 - \frac{2}{T_w}X_8 + (\frac{2}{T_w} + \frac{2}{T_3})X_9 + (\frac{2T_2}{T_1 T_3} - \frac{2}{T_3})X_{10} - \frac{2T_2}{T_1 T_3}u_3$(2.44)

$\dot{X}_9 = \frac{-T_2}{R_3 T_1 T_3}X_7 - \frac{1}{T_3}X_9 + (\frac{-T_2}{T_1 T_3} + \frac{1}{T_3})X_{10} + \frac{T_2}{T_1 T_3}u_3$(2.45)

$\dot{X}_{10} = \frac{-1}{R_3\, T_1}X_7 - \frac{1}{T_1}X_{10} + \frac{1}{T_1}u_3$(2.46)

$\dot{X}_{11} = 2\pi\, T_{12}\, X_1 - 2\pi\, T_{12}\, X_4$(2.47)

$\dot{X}_{12} = 2\pi\, T_{13}\, X_1 - 2\pi\, T_{13}\, X_7$(2.48)

$\dot{X}_{13} = 2\pi\, T_{23}\, X_4 - 2\pi\, T_{23}\, X_7$(2.49)

$\dot{X}_{14} = B_1 X_1 + X_{11} + X_{12}$ (2.50)

$\dot{X}_{15} = B_2 X_4 - X_{11} + X_{13}$ (2.51)

$\dot{X}_{16} = B_3 X_7 - X_{12} - X_{13}$ (2.52)

The matrix **A** and **B** are:

$$
\mathbf{A}=\begin{bmatrix}
\frac{-1}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{K_{P1}}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 \\
0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{-1}{R_1 T_{g1}} & 0 & \frac{-1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-1}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & 0 & 0 & 0 & 0 & \frac{K_{P2}}{T_{P2}} & 0 & \frac{-K_{P2}}{T_{P2}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{-1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-1}{R_2 T_{g2}} & 0 & \frac{-1}{T_{g2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{P3}} & \frac{K_{P3}}{T_{P3}} & 0 & 0 & 0 & \frac{K_{P3}}{T_{P3}} & \frac{K_{P3}}{T_{P3}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{2T_2}{R_3 T_1 T_3} & \frac{-2}{T_w} & \frac{2}{T_w}+\frac{2}{T_3} & \frac{2T_2}{T_1 T_3}-\frac{2}{T_3} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{-T_2}{R_3 T_1 T_3} & 0 & \frac{-1}{T_3} & \frac{1}{T_3}-\frac{T_2}{T_1 T_3} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{R_3 T_1} & 0 & 0 & \frac{-1}{T_1} & 0 & 0 & 0 & 0 & 0 & 0 \\
2\pi T_{12} & 0 & 0 & -2\pi T_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2\pi T_{13} & 0 & 0 & 0 & 0 & 0 & -2\pi T_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 2\pi T_{23} & 0 & 0 & -2\pi T_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
B_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & B_2 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & B_3 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0
\end{bmatrix}
$$

$$
\mathbf{B} = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
\frac{1}{T_{g1}} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & \frac{1}{T_{g2}} & 0 \\
0 & 0 & 0 \\
0 & 0 & \frac{-2T_2}{T_1 T_3} \\
0 & 0 & \frac{T_2}{T_1 T_3} \\
0 & 0 & \frac{1}{T_1} \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
$$

State vector (**X**) = $[X_1\ X_2\ X_3\ X_4\ X_5\ X_6\ X_7\ X_8\ X_9\ X_{10}\ X_{11}\ X_{12}\ X_{13}\ X_{14}\ X_{15}\ X_{16}]^T$

Control vector (**u**) = $[u_1\ u_2\ u_3]^T$

CHAPTER 3

AGC IN DEREGULATED ENVIRONMENT

3.1 INTRODUCTION

Planning and operation of engineering aspects has been modified in a restructured power system in the recent years despite the fact that main ideas are remain same. For improving the efficiency of the power system operation some big changes in the structure of electric power service have been introduced by decentralizing the industry and open it for private competition. A single body is not responsible for generation, transmission and distribution; rather than system is divided into three individual bodies, *viz.*, GENCO (Generation Companies), TRANSCOs (Transmission Companies) and DISCOs (Distribution Companies).

In the deregulated environment there are many GENCOs and DISCOs and a distribution company can deal with any generating company. A distribution company can deal to the other area generation company. Such type of contracts or deals is called bilateral transactions. ISO (Independent system operator) is an impartial body which have to clear all the deals between the GENCOs and DISCOs. ISO has many extra services in which one is AGC.

3.1.1 TRADITIONAL VS. RESTRUCTURED SCENARIO

Vertically integrated utilities (VIUs) controls generation-transmission-distribution systems and at the regulated rates power supplies to the customer. Vertically integrated utility structure is shown in fig. 3.1 in which large box denotes VIU. Mostly VIUs are connected at the transmission voltage. So that tie-lines power can be purchased and sold out among the VIUs and furthermore, this type of interconnection increases reliability of the system [39].

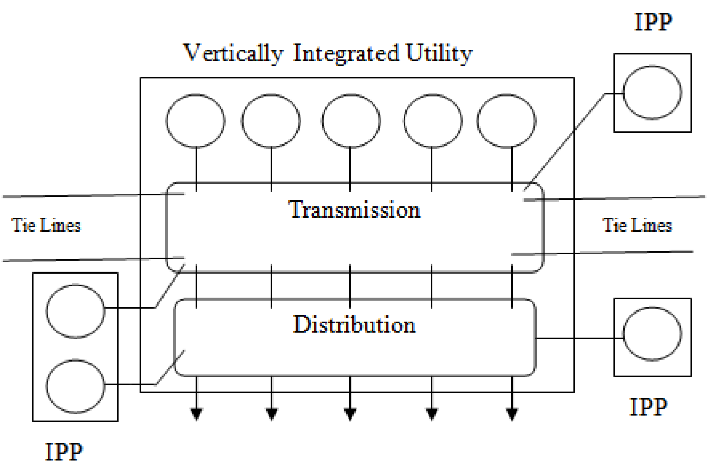

Fig 3.1 Vertically Integrated Utility Structure.

All the square box represents IPP (independent power producers) which sells the power to VIU's. In the deregulation environment firstly we have to separate generation from transmission on the same basis as the IPP's in figure 3.2 , In a open market generating companies will compete with each other to sell their produced electricity .

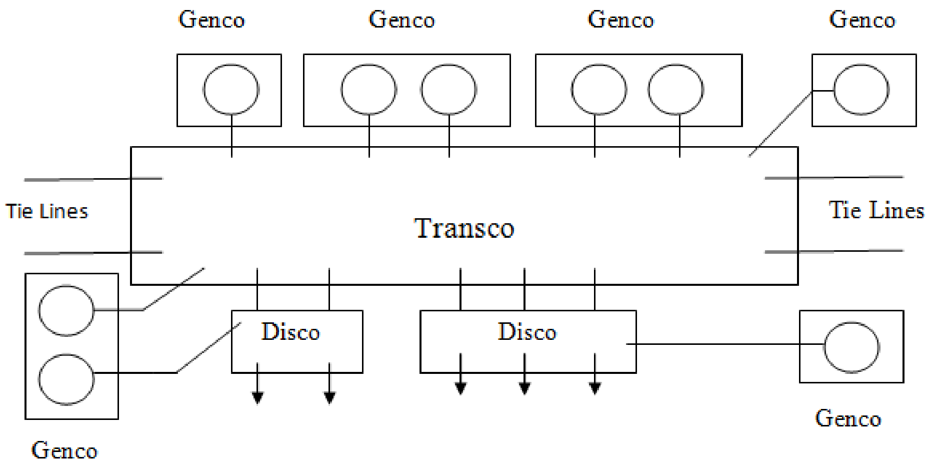

Fig 3.2 Deregulated Utility Structure

3.1.2 SIGNIFICANCE OF AUTOMATIC GENERATION CONTROL IN DEREGULATED ENVIRONMENT

In deregulated environment the significance of AGC is triple;
(i) For achieving zero change in frequency.
(ii) To match the tie-line power flow within limit by distributing the generation between areas.
(iii) To make the balance between generation and load and tie-line power transfer.
Control is highly decentralized in the deregulated environment. A separate control system is required for every load matching transaction, still to restore the frequency and tie-line power to its nominal value this process act simultaneously. ISOs (independent system operator) like market operators, supervisors and new organizations are responsible to balance the generation and load for reducing frequency deviations and load for reducing frequency deviations and controlling tie-line power flow, which will help to extend bilateral contracts in various areas. AGC should note every moment variations in load so that control area performance criterion can meet.

3.1.3 TECHNICAL ISSUES

In the deregulated environment, the operation of power system can create some serious technical problems. Sometimes on the basis of market demand and price based operation simple frequency control will become challenging. Regulatory policies allows the competition among the generating companies and creating market conditions in power sector, it is mandatory for increasing distribution and production efficiency of electrical energy, for reducing price and higher quality.

3.1.4 REQUIREMENTS OF DEREGULATION

Deregulation is necessary because:
(1)For fine operations, planning and market design engineers.
(2) There is diversity in supply and fuel.
(3) Satisfactory transmission infrastructure.
(4) Effective demand side responsiveness and management.
(5) Provide right incentives and good price signals.

3.1.5 BENEFITS OF DEREGULATION

Deregulation advantages are given below:
(i) Efficient unit will survive others will be perish.
(ii) Because of competition and innovation electricity will become cheaper.
(iii) It will improve generating and planning efficiency and economy also.
(iv) Regeneration of the power engineering profession means this will increased jobs and challenging opportunities.

3.2 GENERAL CONFIGURATION OF AUTOMATIC GENERATION CONTROL IN A DEREGULATED ENVIRONMENT

AGC in a deregulated environment is shown in Figure 3.3. By a secure network generating companies sent the bid regulating reserves to the AGC. On the basis of pre-specified time and price these bids are sorted.

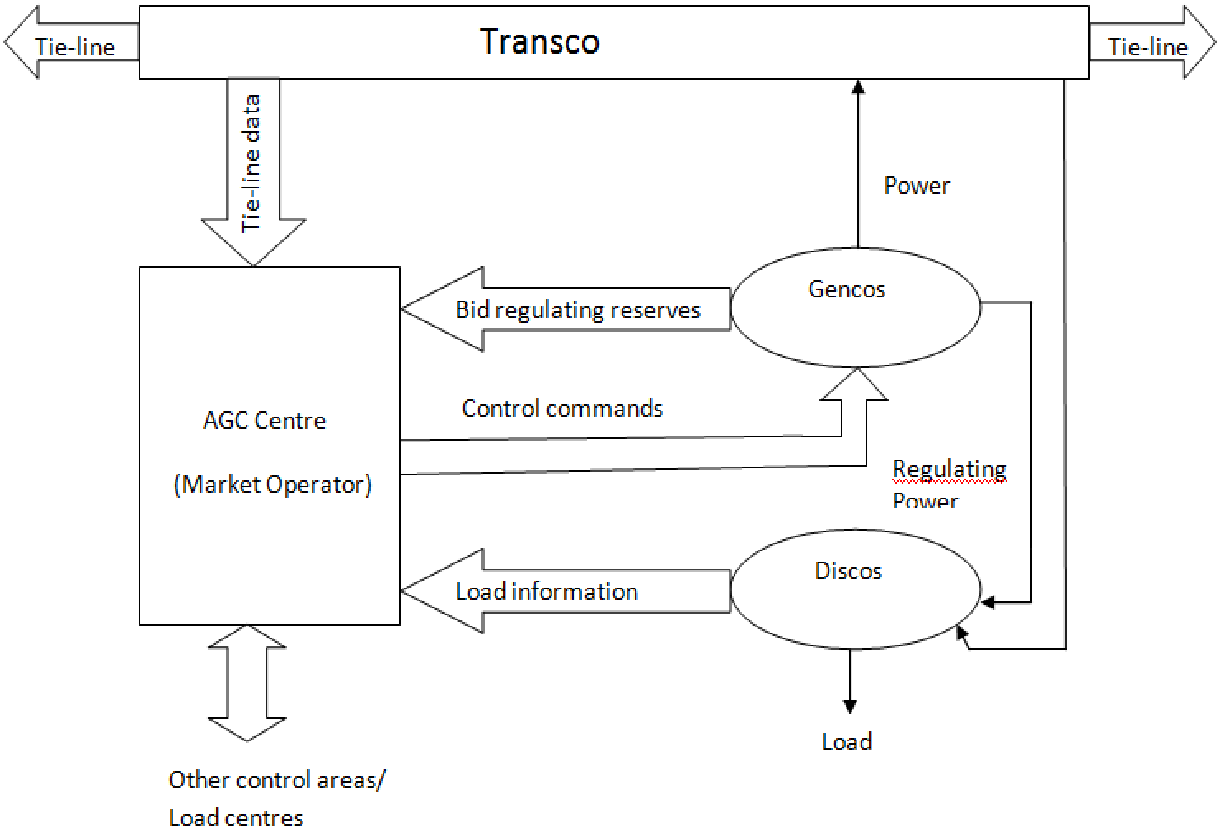

Fig 3.3 AGC configuration in deregulated environment

Then, the load demanded from distributing companies, tie-lines data from transmission companies and area frequency are used for sending control commands for tracking the load changes in the area. On the basis of received crowding information from transmission companies and available capacity screening which is collected from generating companies, bids are examined and shorted.

3.3 PARTICIPATION MATRIX FOR DISCO

Amount of the participation of a generator in automatic generation control is called participation factor. When a sudden load disturbance will occur in a area, a suitable control signal is produced and distributed in proportion to their participation factor, so that generation can follow the load. The addition of participation factors of a control area is equal to one.

In a competing atmosphere, participation factors of AGC are time dependent variables and should be calculated vigorously based on prices of bid, costs, problems in congestion, availability and other related issues by an independent organization.

In the restructured scenario, generating companies can sell their power to the different distributing companies at competing prices. So, for deal distribution companies have the choice in various generating companies. From their own area generating companies they may have deal or not. So that many GENCOs and DISCOs combinations are possible for deal. To make contract decision simpler, concept of DPM (disco participation factor) is bought. In DPM matrix, number of rows of matrix is equal to the number of generating companies and number of column of a matrix is equal to the number of distribution companies. The part of the load deal by a DISCO from a GENCO is an entry in the matrix. So, the entry will relate the power that is given by a GENCO to a DISCO. In the matrix addition of all entries in a single column will be equal to one. The participation of a distribution company in a generating company is displayed by DPM, that's why it is called "DISCO participation matrix."

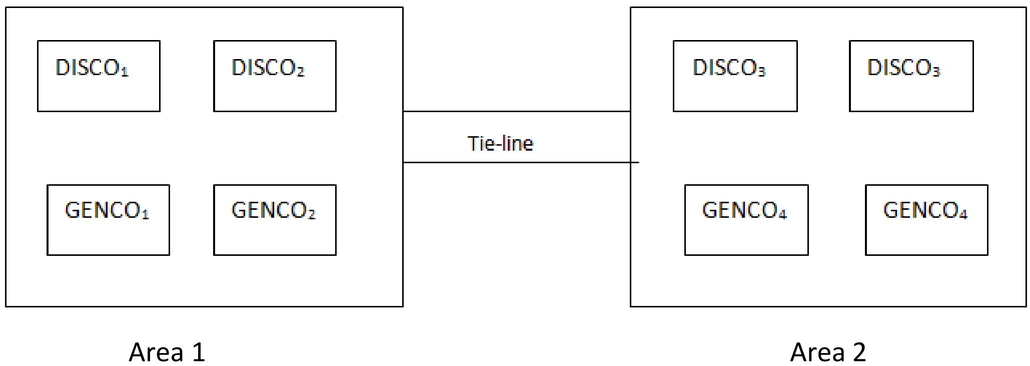

Fig 3.4 Schematic of a Two-Area System in Restructured Environment

3.4 FORMULATION OF STATE MODEL

In deregulated environment AGC for a two area system is shown in Figure 3.5. When a distribution company demands a load, it is represented as a local load in the area from which Distribution Company belongs to. This will correlate to the local loads ΔPL_1 and ΔPL_2 and in the block diagram of AGC in deregulated environment at the point of input it should be reproduced. According to the participation of several GENCOs in AGC, ACE signals are distributed in same proportion. In the traditional AGC a distribution company demands a particular generating company, but in deregulated environment ACE signal are send to many GENCOs called ACE participation factor. These demands must be reproduced in the dynamics of the system. Turbine and governor units must respond to this power demand. So load demand by a distribution company is followed by a generating company, information signals which indicating demands will flow from Distribution Company to Generating Company. In the traditional scenario information signal were absent. Contract participation factor indicates the demand and load of a distribution company. Load demanded by a DISCO followed by a GENCO, this information is carried by signal.

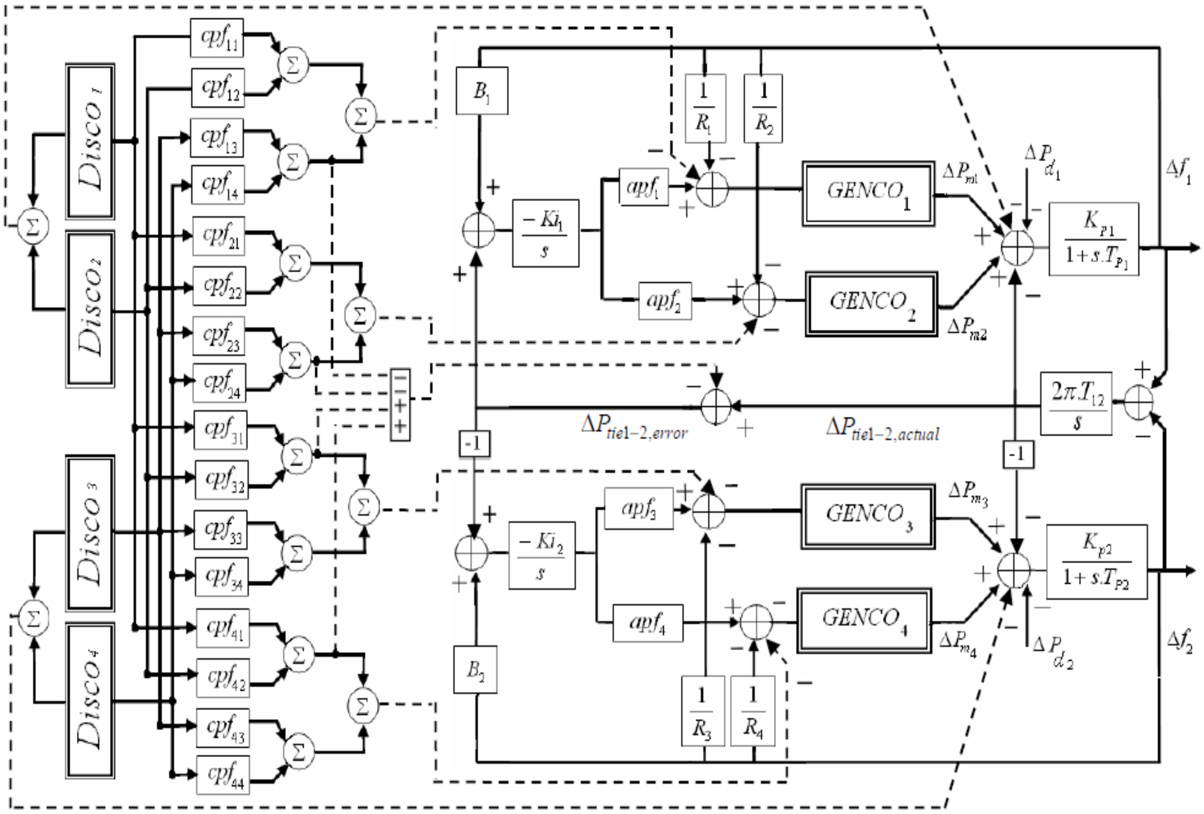

Figure 3.5: Two-Area AGC System Block Diagram in Restructured Scenario.

The scheduled power flow in steady state condition in the tie line is given below:

$\Delta P_{tie1\text{-}2,\ scheduled}$= (demand of DISCOs in area two from GENCOs in area one) - (demand of DISCOs in area one from GENCOs in area two)

For a particular time, the error in tie line power, $\Delta P_{tie1\text{-}2,error}$can be written as

$$\Delta P_{tie1\text{-}2,\ error} = \Delta P_{tie1\text{-}2,\ actual} - \Delta P_{tie1\text{-}2,scheduled} \quad (3.1)$$

$\Delta Ptie_{1\text{-}2,\ error}$ will become nil in the condition of steady state when the actual tie-line power will be equal to the scheduled tie-line power. In the traditional scenario this error signal will be used to generate the ACE signals.

$ACE_1 = B_1\Delta f_1 + \Delta P_{tie1\text{-}2,\,error}$(3.2)
$ACE_2 = B_1\Delta f_2 + \Delta P_{tie2\text{-}1,\,error}$(3.3)
Where
$\Delta P_{tie1\text{-}2,\,error} = -\frac{P_{r1}}{P_{r2}}\Delta P_{tie1\text{-}2,\,error}$
Pr1 and Pr2 are rated powers of areas one and two respectively. Therefore

$ACE_1 = B_1\Delta f_1 + \alpha_{12}\,\Delta P_{tie1\text{-}2,\,error}$ (3.4)

$$\alpha_{12} = -\frac{P_{r1}}{P_{r2}}$$

In deregulated environment the block diagram of AGC is shown in Fig. 3.5. In area 1 and 2 local loads are presented by $\Delta P_{L1,Loc}$ and $\Delta P_{L2,Loc}$, respectively.

3.5 STATE SPACE CHARACTERIZATION OF THE TWO-AREA SYSTEM IN DEREGULATED ENVIORNMENT

The proposed AGC scheme explains the behaviour of two area system. Both the areas are kept identical. State space modelling is carried out by expressing the differential equation of individual block of figure 3.5 in terms of state variables. Let us consider the state space vector as follows:

$X_1 = \Delta f_1$
$X_2 = \Delta f_2$
$X_3 = \Delta P_{GV1}$
$X_4 = \Delta P_{GV2}$
$X_5 = \Delta P_{GV3}$
$X_6 = \Delta P_{GV4}$
$X_7 = \Delta P_{M1}$
$X_8 = \Delta P_{M2}$
$X_9 = \Delta P_{M3}$
$X_{10} = \Delta P_{M4}$
$X_{11} = \int ACE_1$
$X_{12} = \int ACE_2$

$X_1 = (\Delta P_{L1,LOC} - X_3 + X_4)\,\frac{K_{P1}}{1+ST_{P1}}$
$\dot{X}_1 = \frac{1}{T_{P1}}X_1 - \frac{K_{P1}}{T_{P1}}X_3 + \frac{K_{P1}}{T_{P1}}X_4 - \Delta P_{L1,LOC}\frac{K_{P1}}{T_{P1}}$(3.5)
$X_2 = (\Delta P_{L2,LOC} - a_{12}\,X_3 + X_6)\frac{K_{P2}}{1+sT_{P2}}$
$\dot{X}_2 = \frac{1}{T_{P2}}X_1 - a_{12}\frac{K_{P2}}{T_{P2}}X_3 + \frac{K_{P2}}{T_{P2}}X_6 - \Delta P_{L1,LOC}\frac{K_{P2}}{T_{P2}}$(3.6)

$X_3 = \frac{1}{1+sT_{T1}} X_4$

$\dot{X}_3 = \frac{1}{T_{T1}} (X_4 - X_3)$ (3.7)

$X_4 = \frac{1}{1+ST_{T2}} X_5$

$\dot{X}_4 = \frac{1}{T_{T2}}(X_5 - X_4)$ (3.8)

$X_5 = \frac{1}{1+ST_{T3}} X_6$

$\dot{X}_5 = \frac{1}{T_{T3}} (X_6 - X_5)$ (3.9)

$X_6 = \frac{1}{1+ST_{T4}} X_7$

$\dot{X}_6 = \frac{1}{T_{T4}} (X_7 - X_6)$ (3.10)

$\dot{X}_7 = - \frac{X_1}{T_{G1}R_1} - \frac{X_5}{T_{G1}} + (-K_1\, apf_1) \frac{1}{T_{G1}}$(3.11)

$\dot{X}_8 = - \frac{X_1}{T_{G2}R_2} - \frac{X_6}{T_{G2}} + (-K_1\, apf_2) \frac{1}{T_{G2}}$(3.12)

$\dot{X}_9 = - \frac{X_2}{T_{G3}R_2} - \frac{X_7}{T_{G3}} + (-K_2\, apf_3) \frac{1}{T_{G3}}$(3.13)

$\dot{X}_{10} = - \frac{X_4}{T_{G4}R_2} - \frac{X_8}{T_{G4}} + (-K_1\, apf_4) \frac{1}{T_{G4}}$(3.14)

$\dot{X}_{11} = B_1 X_1 + X_{13}$ (3.15)

$\dot{X}_{12} = B_2 X_2 + a_{12} X_{13}$ (3.16)

$\dot{X}_{13} = \frac{T_{12}}{2\pi} (X_1 - X_2)$ (3.17)

The equations from (3.5) to (3.17) can be formulated in the matrix form. In figure 3.5 shown closed loop system can be described in state space form as:

$$\frac{d\boldsymbol{X}}{d\boldsymbol{t}} = \boldsymbol{A}\, \boldsymbol{X} + \boldsymbol{B}\, \boldsymbol{u}$$

where '**X**' is called state vector and **u** is called as input vector of power demands of the Disco's. From Fig 3.5 **A** and **B**are formed:

$$
\mathbf{A} = \begin{bmatrix}
\frac{-1}{T_{P1}} & 0 & \frac{K_{P1}}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_{P1}}{T_{P1}} \\
0 & \frac{-1}{T_{P2}} & 0 & 0 & \frac{K_{P2}}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{K_{P2}}{T_{P2}} \\
0 & 0 & \frac{-1}{T_{T1}} & 0 & 0 & 0 & \frac{1}{T_{T1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-1}{T_{T2}} & 0 & 0 & 0 & \frac{1}{T_{T1}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{-1}{T_{T3}} & 0 & 0 & 0 & \frac{1}{T_{T3}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{T4}} & 0 & 0 & 0 & \frac{1}{T_{T4}} & 0 & 0 & 0 \\
\frac{-1}{2\pi R_1 T_{G1}} & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{G1}} & 0 & 0 & 0 & \frac{-K_1 apf_1}{T_{G1}} & 0 & 0 \\
\frac{-1}{2\pi R_2 T_{G2}} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{G2}} & 0 & 0 & \frac{-K_1 apf_2}{T_{G2}} & 0 & 0 \\
0 & \frac{-1}{2\pi R_3 T_{G3}} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{G3}} & 0 & 0 & \frac{-K_2 apf_3}{T_{G3}} & 0 \\
0 & \frac{-1}{2\pi R_4 T_{G4}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{G4}} & 0 & \frac{-K_2 apf_4}{T_{G4}} & 0 \\
\frac{B_1}{2\pi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & \frac{B_2}{2\pi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
\frac{T_{12}}{2\pi} & \frac{-T_{12}}{2\pi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

$$
\mathbf{B} = \begin{bmatrix}
\frac{-K_{P1}}{T_{P1}} & \frac{-K_{P1}}{T_{P1}} & 0 & 0 \\
0 & 0 & \frac{-K_{P2}}{T_{P1}} & \frac{-K_{P2}}{T_{P1}} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\frac{cpf_{11}}{T_{G1}} & \frac{cpf_{12}}{T_{G1}} & \frac{cpf_{13}}{T_{G1}} & \frac{cpf_{14}}{T_{G1}} \\
\frac{cpf_{21}}{T_{G2}} & \frac{cpf_{22}}{T_{G2}} & \frac{cpf_{23}}{T_{G2}} & \frac{cpf_{24}}{T_{G2}} \\
\frac{cpf_{31}}{T_{G3}} & \frac{cpf_{32}}{T_{G3}} & \frac{cpf_{33}}{T_{G3}} & \frac{cpf_{34}}{T_{G3}} \\
\frac{cpf_{41}}{T_{G4}} & \frac{cpf_{42}}{T_{G4}} & \frac{cpf_{43}}{T_{G4}} & \frac{cpf_{44}}{T_{G4}} \\
(cpf_{31} + cpf_{41}) & (cpf_{32} + cpf_{42}) & -(cpf_{13} + cpf_{23}) & -(cpf_{14} + cpf_{24}) \\
-(cpf_{31} + cpf_{41}) & -(cpf_{32} + cpf_{42}) & (cpf_{13} + cpf_{23}) & (cpf_{14} + cpf_{24}) \\
0 & 0 & 0 & 0
\end{bmatrix}
$$

$\mathbf{u} = [\Delta PL1\ \Delta PL2\ \Delta PL3\ \Delta PL4]^T$

$$\mathbf{X} = [\Delta f_1\ \Delta f_2\ \Delta P_{GV1}\ \Delta P_{GV2}\ \Delta P_{GV3}\ \Delta P_{GV4}\ \Delta P_{M1}\ \Delta P_{M2}\ \Delta P_{M3}\ \Delta P_{M4} \int ACE1 \int ACE2\ \Delta P_{tie1-2}]^T$$

CHAPTER 4

OPTIMAL CONTROL OF AGC

4.1 OPTIMAL CONTROL

It is a method applied in the control system design that is performed by minimizing the performance index of the system variables. Here we consider the design of the optimal controllers for the linear systems with quadratic performance index, which is also specify as LQR (linear quadratic regulator). Optimal regulator design objective is find the control law **u^*(x,t),** which minimizes the performance index and transfer the system from initial state to final state. The performance index is widely used is the quadratic performance index and is based on the minimal energy criterion.

Suppose the plant as given below:

$\mathbf{X}(t)=\mathbf{A}x(t) + \mathbf{B}u(t)$

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

$\mathbf{u}(t)= -\mathbf{K}(t)*\mathbf{x}(t)$

It will reduce the value of **J** called quadratic performance index is given below:

$$\mathbf{J} = \int_{t_0}^{t_f}(\boldsymbol{x}'\mathbf{Q}\boldsymbol{x} + \boldsymbol{u}'\,\boldsymbol{R}\boldsymbol{u})dt \qquad (4.1)$$

Where **Q** and **R** are positive semi definite matrix and real symmetric matrix respectively. If all the principal minors of **Q** are not positive than **Q** is a positive definite matrix. We can choose the elements of **Q** and**R,** this allows the relative weighting of individual control input and state variables.

We will use Lagrange multipliers method using an n vector of the unconstrained equation for getting the solution of this equation:

$$[x, \lambda, u, t]= [x'\,\mathbf{Q}x + \mathbf{u}'\,\mathbf{R}\mathbf{u}] + \lambda'\,[\mathbf{A}x + \mathbf{B}u - \dot{\mathbf{x}}] \qquad (4.2)$$

For find out the optimal values, the partial derivative will equal to zero.

$$\frac{\partial L}{\partial \lambda} = \mathbf{AX}^* + \mathbf{Bu}^* - \dot{\mathbf{X}}^* = 0 \quad \Longrightarrow \dot{\mathbf{X}}^* = \mathbf{AX}^* + \mathbf{Bu}^* \quad (4.3)$$

$$\frac{\partial L}{\partial u} = \mathbf{2Ru}^* + \mathbf{B}\lambda' = 0 \quad \Longrightarrow \mathbf{u}^* = - -\frac{1}{2}\mathbf{R}^{-1}\,\boldsymbol{\lambda}'\,\mathbf{B} \quad (4.4)$$

$$\frac{\partial L}{\partial x} = \mathbf{2x}'^{*}\mathbf{Q} + \boldsymbol{\lambda}' - \boldsymbol{\lambda}'\mathbf{A} = 0 \quad \Longrightarrow \lambda' = -\mathbf{2Qx}^* - \mathbf{A}'\,\boldsymbol{\lambda} \quad (4.5)$$

Assume that there is a time varying positive definite and symmetric matrix **p(t)** satisfying the condition given below:

$$\lambda = 2\,\mathbf{p}(t)\,\mathbf{x}^* \quad (4.6)$$

Substituting 4.6 into 4.4, we get

$$\mathbf{u}^*(t) = -\,\mathbf{R}^{-1}\,\mathbf{B}'\,\mathbf{p}(t)\,\mathbf{x}^* \quad (4.7)$$

Find the derivative of 4.6 than we can write

$$\lambda = 2(\dot{\mathbf{p}}\,\mathbf{x}^* + \mathbf{p}\,\dot{\mathbf{x}}^*) \qquad (4.8)$$

Finally we equate 4.5 and 4.8

$$\dot{\mathbf{p}}(t) = -\,\mathbf{p}(t)\,\mathbf{A} - \mathbf{A}'\,\mathbf{p}(t) - \mathbf{Q} + \mathbf{p}(t)\,\mathbf{BR}^{-1}\mathbf{B}'\,\mathbf{p}(t) \qquad (4.9)$$

The equation (4.9) is known as the Riccati equation.

Compensators are mainly used to satisfy all the desired conditions in a system. But in most of the cases the system needs to full fill some more conditions that are difficult to attain in case of a compensated system. As an alternative to this we mainly use Optimal Control system. The trial and error method for the compensated design system makes it cumbersome for the designers to attain the specifications. This trial and error procedure works well for the system with a single input and a single output. But for a MIMO (multi input multi output) system the trial and error method is replaced from Optimal Control design method where the trial and error uncertainties are removed in parameter optimization. Optimal control design has a single performance index specially the integral square performance index. The minimization of the performance index is done using the Lyapunov stability theorem in order to yield better system performance for a fixed system configuration. The values of **Q** and **R** have to select carefully and if the responses are inappropriate then the some other values of **Q** and **R** can be placed. **K** is automatically generated and then we can find closed loop response.

4.2 PROBLEM STATEMENT

From an N-interconnected system an uncertain power system is originating with each sample of an uncertain system having the equations as given below:

$$\mathbf{X}(t)= [\mathbf{A}_{ii} + \Delta\, \mathbf{A}_{ii}(t)]\, \mathbf{X}_i(t) + \Sigma\, [\mathbf{A}_{ij} + \Delta\, \mathbf{A}_{ij}(t)]\mathbf{X}_j(t) + \Sigma\, [\mathbf{B}_{ij} + \Delta\, \mathbf{B}_{ij}(t)]\mathbf{u}_j(t) + \Sigma\, [\mathbf{\Gamma}_{ij} + \Delta\mathbf{\Gamma}_{ij}(t)]D_j(t) \quad (4.10)$$

$$\mathbf{Y}(t)= \mathbf{C}_{ii}\mathbf{X}_i(t) + \Sigma\, \mathbf{C}_{ij}\mathbf{X}_j(t) \quad (4.11)$$

It is pretended that the **A,B,C,Γ** matrices are of suitable dimensions and are completely controllable and observable.

Equations 4.10 and 4.11 can also be written as:

$$\mathbf{X}(t)= [\mathbf{A} + \Delta\, \mathbf{A}(t)]\, X(t) + [\mathbf{B} + \Delta\, \mathbf{B}(t)]u(t) + [\mathbf{\Gamma} + \Delta\, \mathbf{\Gamma}(t)]D(t) \quad (4.12)$$

$$Y(t)= CX(t) \quad (4.13)$$

The main purpose of interest is to determine the control function **U(t)= -KX(t)** where **K** is a constant gain matrix. Here in this case the **u(t)** achieved the objective, So determining the control matrix is same as find the matrix **K** i.e called constant gain matrix.

In the LQR design the stability robustness is not more exposed to the uncertainties of parametric variations. LQR based design does not provide guarantee of stability of perturbed system.

Suppose an uncertain linear system,

$$\dot{X}(t)= [\mathbf{A} + \Delta\, \mathbf{A}(t)]\, X(t) + [\mathbf{B} + \Delta\, \mathbf{B}(t)]\mathbf{u}(t) \quad (4.14)$$

Where **A**(n×n) and **B**(n×m) are the nominal parameter matrices and **ΔA**(t) and **B**(t) are continuous matrices that describe the ranges of the uncertainty in the parameters.

Assume that A and B matrices are completely observable and controllable, the condition described in 4.14 should be matched if there exists **G(r(t))** and **H(s(t))** matrix functions which is continuous time functions such that:

$$\Delta\, \mathbf{A}(t)= \mathbf{A}G(r(t)) \quad (4.15)$$

$$\Delta\, \mathbf{B}(t)= \mathbf{A}H(s(t)) \quad (4.16)$$

The matrices **H** and **G** are continuous functions of s(t) and r(t) respectively and continuous time-varying matrices. These are uncertain parameters that are supposed to be bounded by the conditions:

$$\mathbf{H}^T (s(t)) * \mathbf{H}(s(t)) <= I \quad (4.17)$$

$$\mathbf{G}^T (r(t)) * \mathbf{G}(r(t)) <= I \quad (4.18)$$

The main aim to define a input in the form of **u(t) = – K X(t)** in which **K** belongs to $\mathbf{R}^{m*n}$so that law can match the uncertain system defined in equation (4.14).

Let's suppose that the conditions defined in 4.15 and 4.16 are satisfied by the system 4.14. Let $\mathbf{Q}^{(n\times m)}$ be a matrix which is positive-definite symmetric matrix and there is an optimal $\psi^*>0$ in this way that all the values of ψ are greater than or equal to ψ^* and have a positive definite solution of the given equation:

$$\mathbf{A}^{\mathbf{T}}P + P\,\mathbf{A} - 2\psi^*P\,\mathbf{B}\,R^{-1}\mathbf{B}^{\mathbf{T}}\,P + \eta\,G^{T}(r(t))\,G(r(t)) + Q = [0] \qquad (4.19)$$

Suppose that the system is linear and the uncertainties are not present.

Hence $$\Delta\,\mathbf{A}(t)=0 \qquad (4.20)$$

$$\Delta\,\mathbf{B}(t)=0 \qquad (4.21)$$

Therefore the equation 4.19 can be written as

$$\mathbf{A}^{\mathbf{T}}\,P + P\mathbf{A} - 2\psi^*P\mathbf{B}R^{-1}\mathbf{B}^{\mathbf{T}}\,P + \mathbf{Q} = [0] \qquad (4.22)$$

This is called riccati equation.

4.3 DESIGN OF OPTIMAL CONTROLLER FOR TWO AREA SYSTEM

Considering the state equations from 2.28 to 2.36 and fig 2.14.In optimal control, the inputs are selected as a linear combination of feedback from all the nine system states (X_1 , X_2 , X_3............ X_9) as given below:

$u = K_{11}X_1 + K_{12}X_2 + ... + K_{19}X_9$

$u = K_{21}X_1 + K_{22}X_2 + ... + K_{29}X_9$

Where, 'K' (2×9) is the feedback gain matrix given by;

K = [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}]

Now the system state equation is:

$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{Bu}$ ……. (For a step load change of a constant magnitude, '$\mathbf{\Gamma} = 0$)

The equation of output can be written as::

$$\mathbf{y} = \mathbf{CX} + \mathbf{Du}$$

However, for a closed loop control system, the matrix D is assumed zero.

So; $\mathbf{y} = \mathbf{CX}$ where **C** (2 × 9) is the Output Matrix.

Finally, the state space model of the system under consideration takes a form as;

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{Bu} \quad \text{and}$$

$$\mathbf{y} = \mathbf{CX}$$

The control inputs are linear combinations of system states given by, $\mathbf{u} = -\mathbf{KX}$

4.3.1 DETERMINATION OF FEEDBACK GAIN MATRIX (K):

Optimal controller finds the feedback gain matrix **K** by reducing PI (performance index) when the system is transferring from initial random state $x(0) \neq 0$ to original state in infinite time i.e $x(\infty) = 0$.

Generally performance index is taken in quadratic form as given below:

$$PI = \frac{1}{2}\int_0^{\infty}(\boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{Qx} + \boldsymbol{u}^{\boldsymbol{T}}\boldsymbol{Ru})\,dt \qquad (4.23)$$

Where, '**Q**' is a real, positive semi-definite and symmetric matrix called as 'state weighting matrix' and '**R**' is a real, symmetric and positive definite matrix called as 'control weighting matrix.

The matrices **Q** and **R** are find out on the basis of following system consideration.

1) The deviations of area control errors about steady values are minimized. In this model, these excursions are;

$$ACE_1 = B_1\, \Delta f_1 + P_{tie1\text{-}2} = B_1\, X_1 + X_7 \quad \text{and} \quad (4.24)$$

$$ACE_2 = B_2\, \Delta f_2 - P_{tie1\text{-}2} = B_2\, X_4 - X_7 \quad (4.25)$$

2) The excursions of $\int ACE\, dt$ about steady values are minimized. In this model, these excursions are X_8 and X_9.
3) The excursions of control inputs u_1 and u_2 about steady values are minimized.

Under these conditions, the PI will take a form as given below:

$$PI = \frac{1}{2}\int_0^\infty [(B_1X_1 + X_7)^2 + (B_2X_4 - X_7)^2 + X_8^2 + X_9^2 + u_1^2 + u_2^2]\, dt$$

$$\text{i.e } PI = \frac{1}{2}\int_0^\infty [B_1^2 X_1^2 + 2B_1X_1X_7 + 2X_7^2 + B_2^2X_4^2 - 2B_2X_4X_7 + X_8^2 + X_9^2 + u_1^2 + u_2^2]dt$$

This gives the matrices **Q** and **R** as follows:

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

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

The matrices **A, B, Q**&**R** are known.

The optimal control is given by **u** = − **KX**

Feedback gain matrix '**K**' is given below:

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

Where, '**S**' is the unique solution of Riccati Equation, it is a symmetric, real and positive definite matrix:

$$\mathbf{A}^T\mathbf{S} + \mathbf{S}\mathbf{A} - \mathbf{S}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{S} + \mathbf{Q} = 0$$

The closed loop equation of a system is given below:

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{B}(-\mathbf{KX}) = (\mathbf{A}-\mathbf{BK})\mathbf{X} = \mathbf{A_C}\,\mathbf{X}$$

The matrix $\mathbf{A_C} = (\mathbf{A}-\mathbf{BK})$ is called closed loop system matrix.

4.4 OPTIMAL CONTROLLER DESIGN OF THREE AREA SYSTEM

Consider the state equations from 2.37 to 2.52 and fig 2.15. The control inputs are given below;

$u_1 = K_{11}\ X_1 + K_{12}\ X_2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots + K_{1\text{-}16}\ X_{16}$

$u_2 = K_{21}\ X_1 + K_{22}\ X_2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots + K_{2\text{-}16}\ X_{16}$

$u_3 = K_{31}\ X_1 + K_{32}\ X_2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots + K_{2\text{-}16}\ X_{16}$

Where,

K = [K_{11} K_{12} K_{13} K_{14} K_{15} K_{16} K_{17} K_{18} K_{19} $K_{1\text{-}11}$ $K_{1\text{-}12}$ $K_{1\text{-}13}$ $K_{1\text{-}14}$ $K_{1\text{-}15}$ $K_{1\text{-}16}$
K_{21} K_{22} K_{23} K_{24} K_{25} K_{26} K_{27} K_{28} K_{29} $K_{2\text{-}11}$ $K_{2\text{-}12}$ $K_{2\text{-}13}$ $K_{2\text{-}14}$ $K_{2\text{-}15}$ $K_{2\text{-}16}$
K_{31} K_{32} K_{33} K_{34} K_{35} K_{36} K_{37} K_{38} K_{39} $K_{3\text{-}11}$ $K_{3\text{-}12}$ $K_{3\text{-}13}$ $K_{3\text{-}14}$ $K_{3\text{-}15}$ $K_{3\text{-}16}$]

So, **u = -KX**

The system state equation is:

$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{Bu}$

The output equation is:

Y = CX

4.4.1 DETERMINATION OF FEEDBACK GAIN MATRIX FOR THREE AREAS (K):

$$\text{PI} = \frac{1}{2}\int_0^{\infty}(\boldsymbol{x^T}\,\boldsymbol{Qx} + \boldsymbol{u^T R u})\,dt$$

As we know **Q** and **R** matrices are derived under certain conditions as discussed in 4.3.1 so

$$\text{PI} = \frac{1}{2}\int_0^{\infty}[(B_1X_1 + X_{11} + X_{12})^2 + (B_2X_4 - X_{11} + X_{13})^2 + (B_3X_7 - X_{12} - X_{13})^2 + X_{14}^2 + X_{15}^2 + X_{16}^2 + u_1^2 + u_2^2]\,dt$$

$$\text{i.e PI} = \frac{1}{2}\int_0^{\infty}[B_1^2X_1^2 + 2B_1X_1X_9 + 2X_9^2 + B_2^2X_5^2 - 2B_2X_5X_9 + X_{10}^2 + X_{11}^2 + u_1^2 + u_2^2]\,\text{dt}$$

This will give **Q** and **R** matrices as:

$$
Q = \begin{bmatrix}
B_1^{\ 2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_1 & B_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & B_2^{\ 2} & 0 & 0 & 0 & 0 & 0 & 0 & -B_2 & 0 & B_2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & B_3^{\ 2} & 0 & 0 & 0 & 0 & -B_3 & -B_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
B_1 & 0 & 0 & -B_2 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 1 & -1 & 0 & 0 & 0 \\
B_1 & 0 & 0 & 0 & 0 & 0 & -B_3 & 0 & 0 & 0 & 1 & 2 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & B_2 & 0 & 0 & -B_3 & 0 & 0 & 0 & -1 & 1 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
$$

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

.

CHAPTER 5
CASE STUDY AND RESULTS

5.1 UNCOMPENSATED SINGLE AREA SYSTEM

Single area uncompensated system is considered which has the following parameters:

$T_T = 0.5$ s
$T_g = 0.2$ s
H = 5 s
D = 0.8
R = 0.05 pu
$\Delta P_L = 0.2$ pu

Uncompensated plant transfer function:

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

Simulation block diagram for a single area system without any controller is shown in fig 5.1

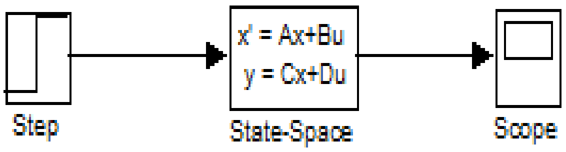

Fig 5.1 Simulation block diagram of uncompensated single area system

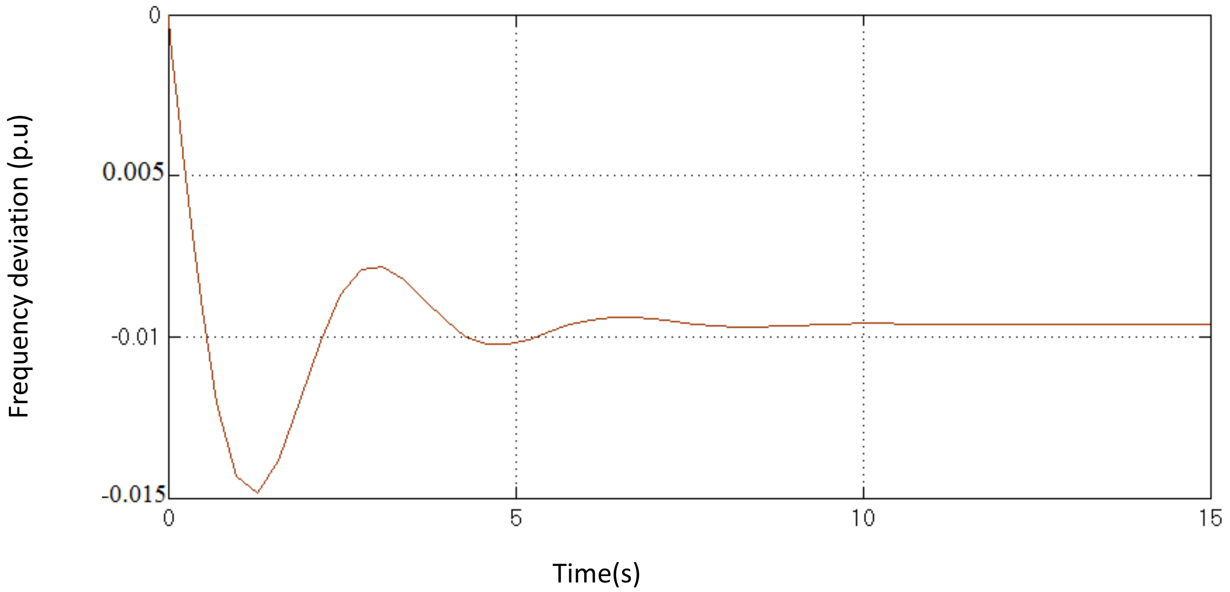

Fig 5.2 Uncompensated system frequency deviation response

5.2 SINGLE AREA SYSTEM USING POLE PLACEMENT METHOD

Same uncompensated system is considered as in 5.1 and the compensated closed loop poles are taken at -2$\pm$ j6 and -3 and compensated system closed loop transfer function is:

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

Simulation of a single area system using pole placement method is shown in fig 5.3

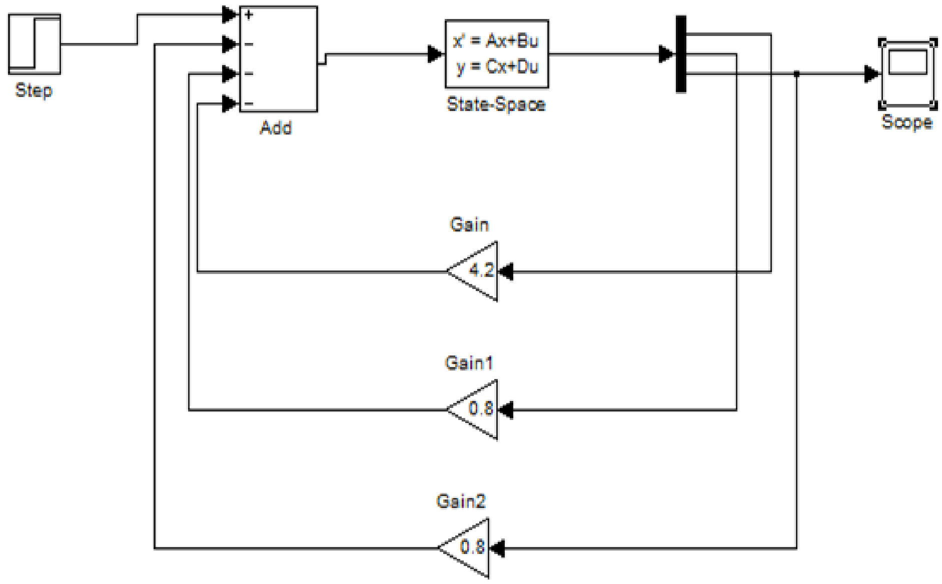

Fig 5.3 Simulation of single area system using pole placement

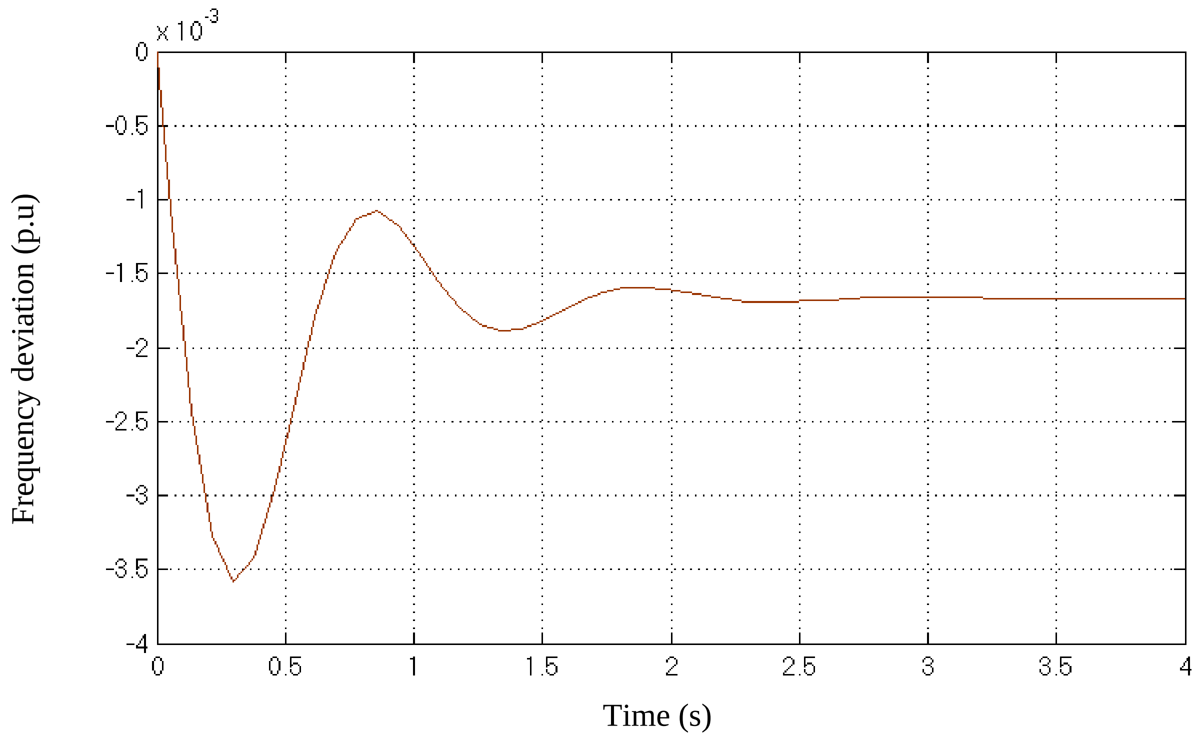

Fig 5.4 Frequency deviation response using pole placement method

5.3 AGC FOR SINGLE AREA USING PID CONTROL ACTION

A single area system is considered which has the following parameter:

	Gain	Time constant
Turbine	$K_T = 1$	$T_T = 0.5$
Governor	$K_g = 1$	$T_g = 0.2$
Amplifier	$K_A = 10$	$T_A = 0.1$
Exciter	$K_E = 1$	$T_E = 0.4$
Generator	$K_G = 0.8$	$T_G = 1.4$
Sensor	$K_R = 1$	$T_R = 0.05$
Inertia	$H = 5$	
Regulation	$R = 0.05$	

$D = 0.8$, $P_S = 1.5$, K_6(voltage coefficients) = 0.5, coupling constants $K_2 = 0.2$, $K_4 = 1.4$, $K_5 = -0.1$, $\Delta P_{L1} = 0.2$ p.u

AGC for single area system using PID controller simulation is shown in fig 5.5

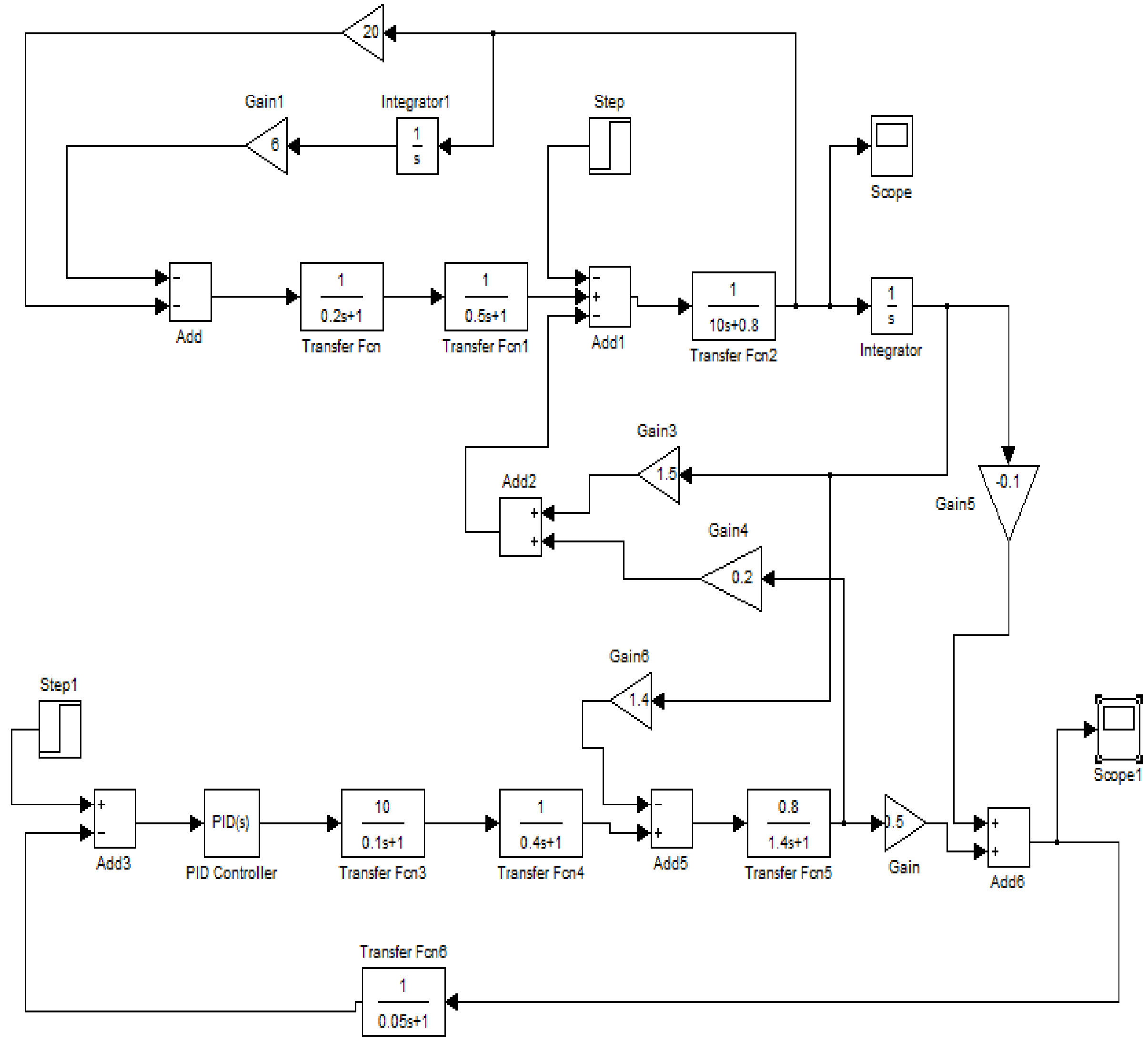

Fig 5.5 Simulation block diagram of AGC for single area using PID controller

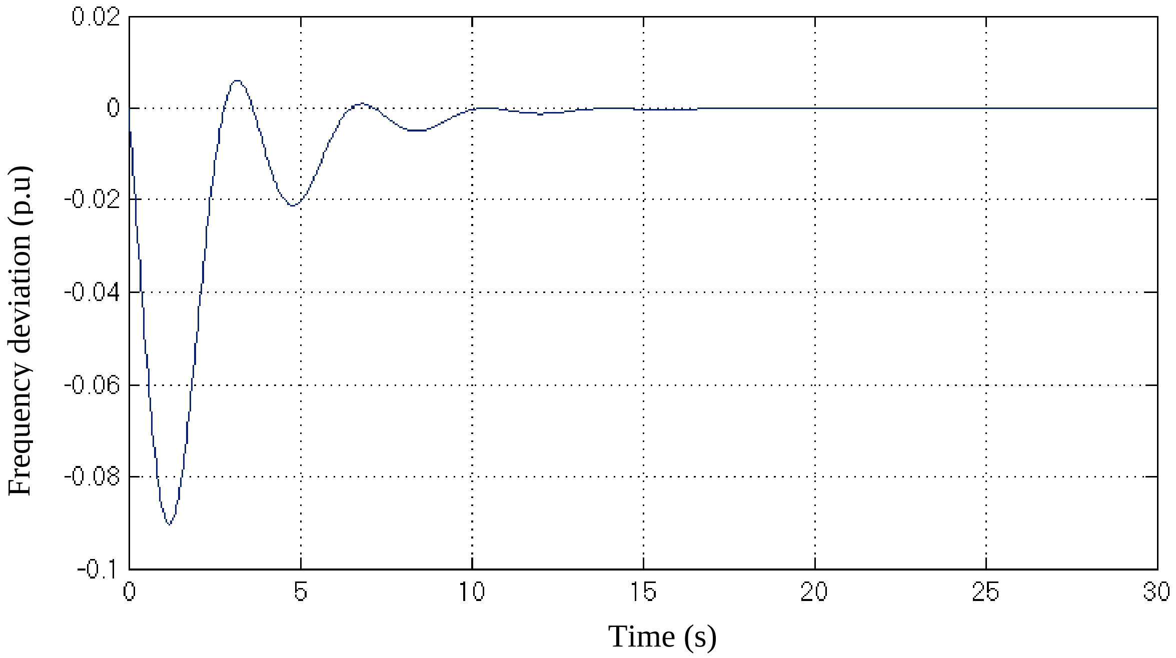

Fig 5.6 – Frequency deviation step response using PID controller

5.4 OPTIMAL CONTROLLER FOR SINGLE AREA SYSTEM

Optimal controller (LQR) is designed for single area system using MATLAB coding. Designed **A,B,C,Q** and **R** matrices are given as:

A = [-5 0 -100; 2 -2 0; 0 0.1 -0.08]
B = [0; 0; -0.1]
C = [0 0 1]
Q = [20 0 0; 0 10 0; 0 0 5]
Frequency deviation response using LQR is shown in fig 5.7

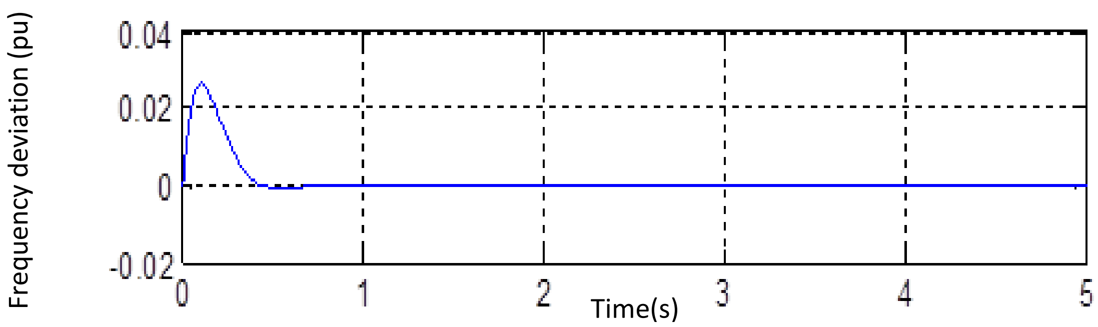

Fig 5.7 – Frequency deviation step response using LQR

5.5 AGC FOR TWO AREA SYSTEM

A two area system is considered which has the following parameters:

Area	**1**	**2**
Speed regulation	$R_1 = 0.05$	$R_2 = 0.0625$
Frequency sensitive load Coefficient	$D_1 = 0.6$	$D_2 = 0.9$
Inertia constant	$H_1 = 5$	$H_2 = 4$
Base power	1000MVA	1000MVA
Governor time constant	$T_{g1} = 0.2$ sec	$T_{g2} = 0.3$ sec
Turbine time constant	$T_{T1} = 0.5$ sec	$T_{T2} = 0.6$ sec

$P_s = 2.0$ p.u

Load change = 187.5 MW in area 1

The simulation of the two area system having only primary LFC loop is shown in fig 5.8.

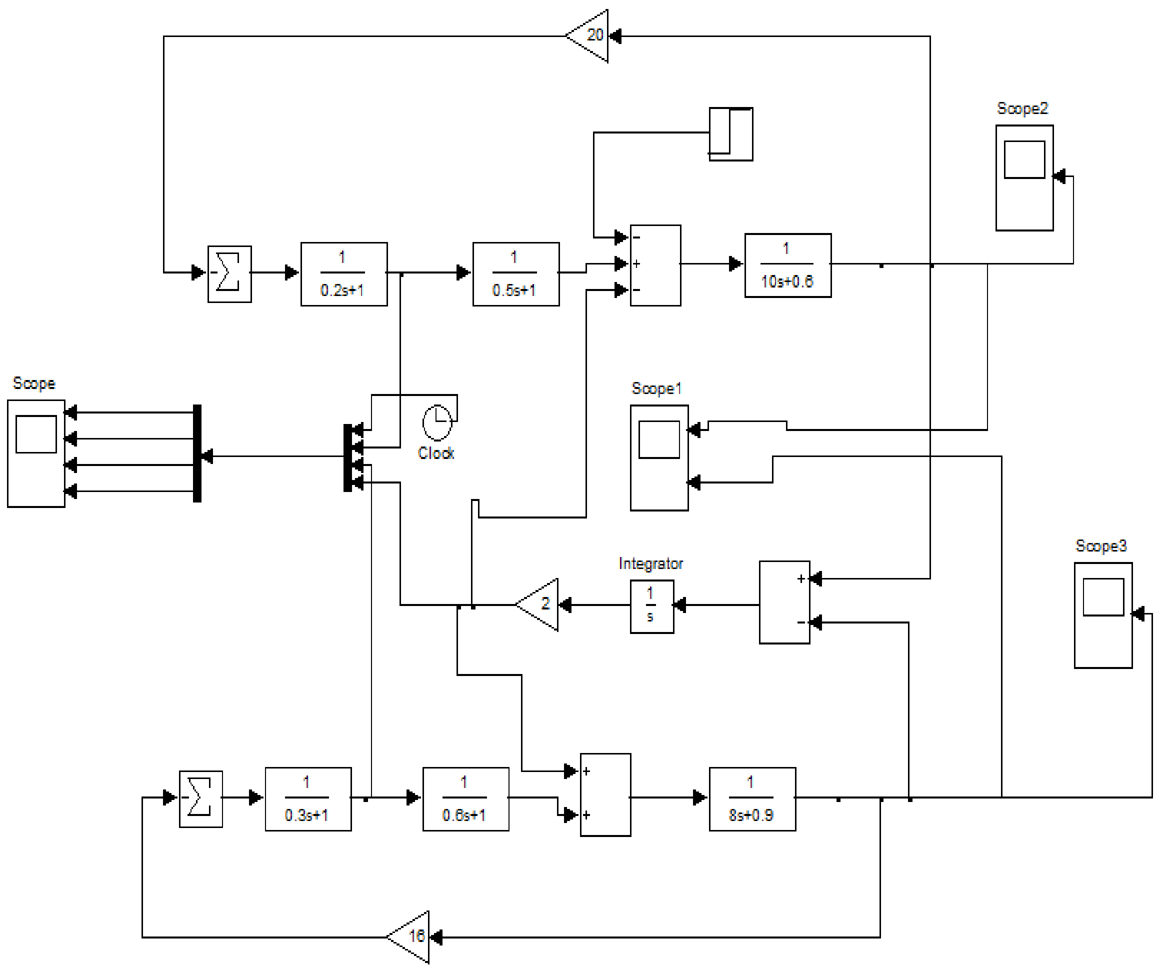

Fig 5.8 Simulation block diagram with only primary LFC loop

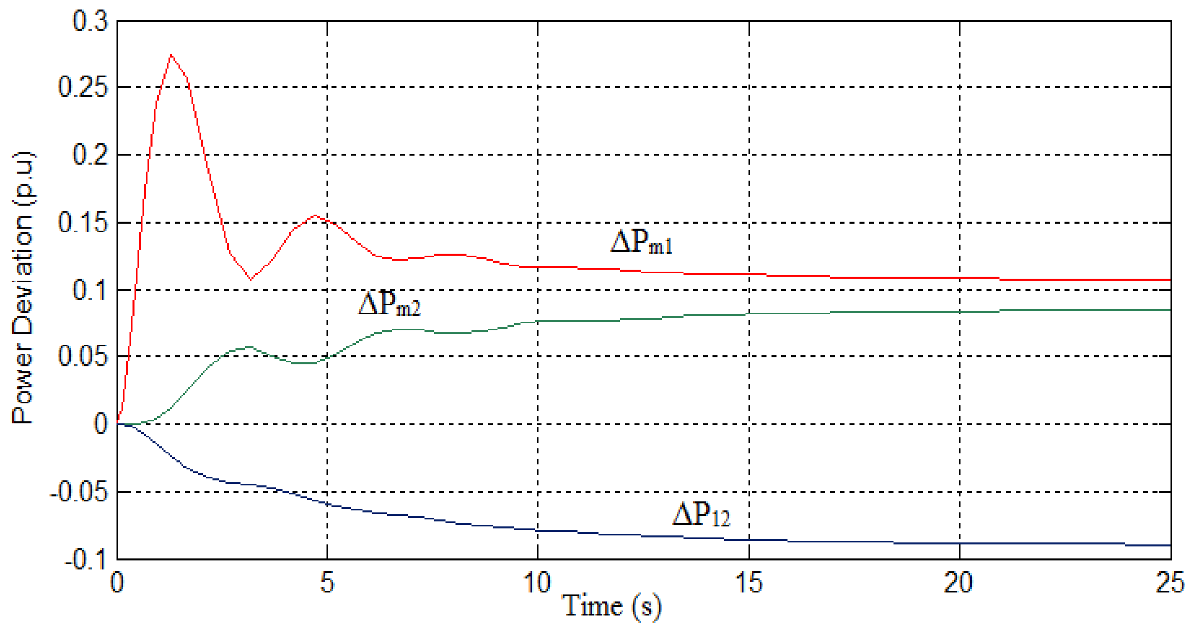

Fig 5.9 Plot of active power deviation with time corresponding to step change of load in Area1

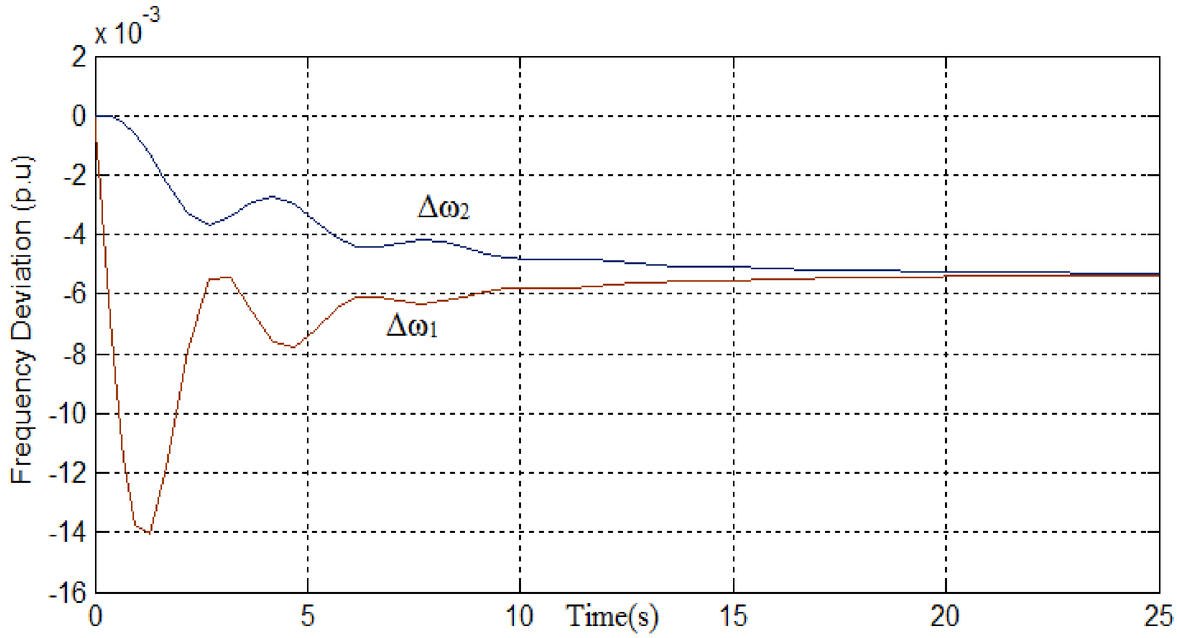

Fig 5.10 Plot of active frequency deviation with time corresponding to step change of load in Area1

5.6 AGC FOR TWO AREA USING INTEGRAL CONTROL ACTION

System considered is same as given in 5.5 and the integral control constant are adjusted for a satisfactory response. The simulation result for $K_{i1} = K_{i2} = 0.3$ is shown in fig 5.11

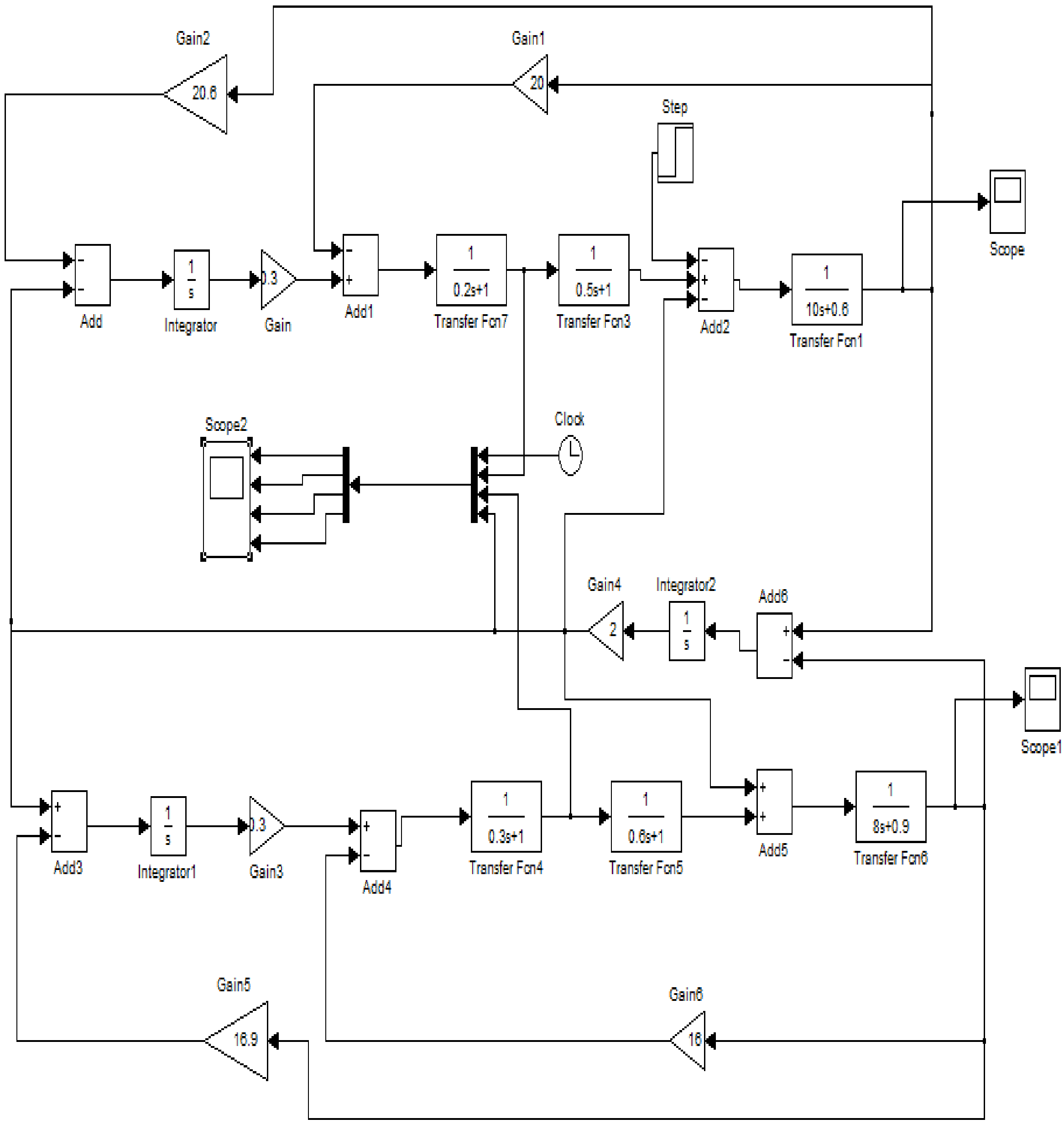

Fig 5.11 Simulation of AGC for two area system using integral control action

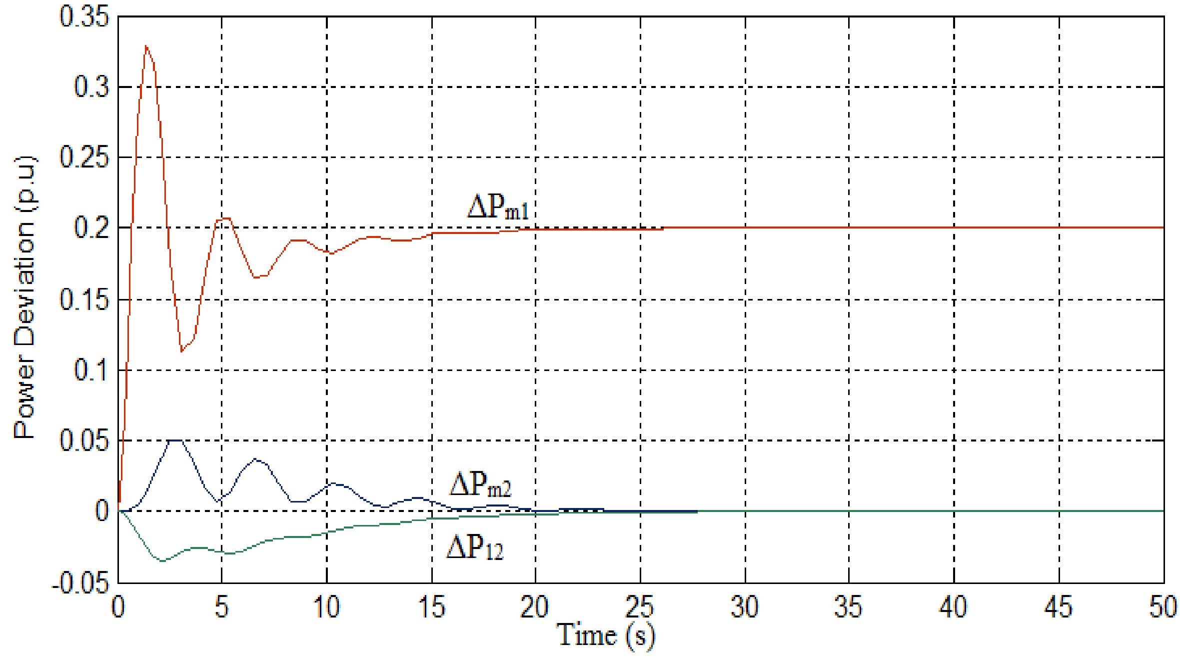

Fig 5.12 Plot of active power deviation with time for integral control action corresponding to step load change in Area1

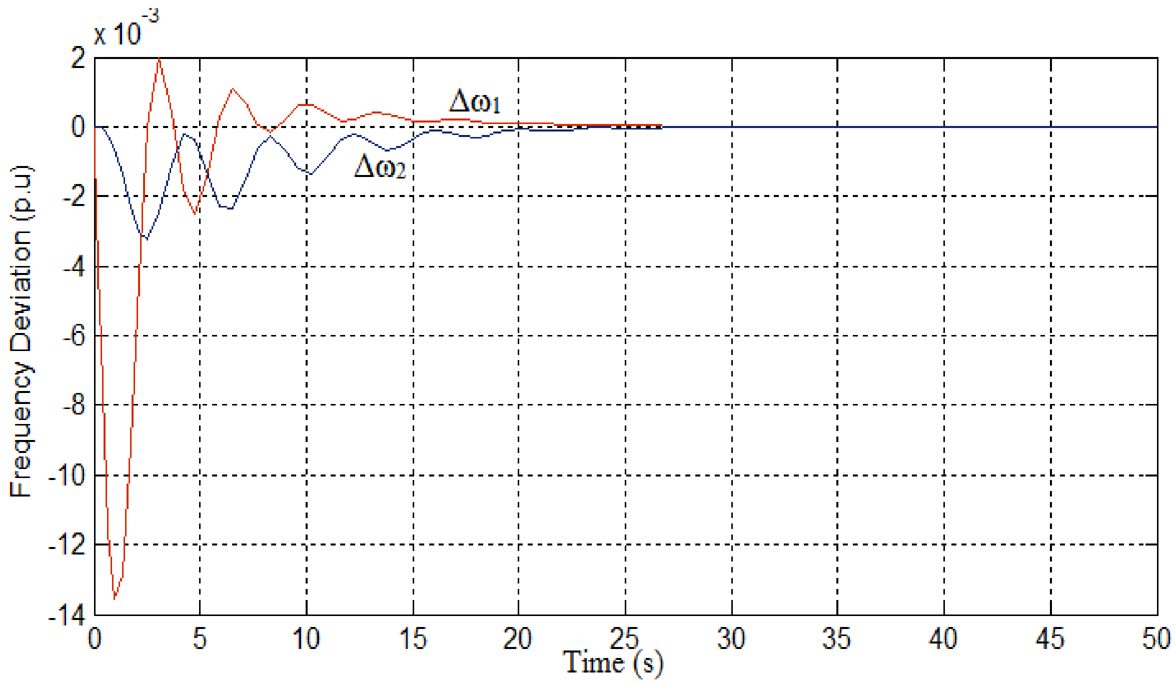

Fig 5.13 Plot of frequency deviation with time for integral control action corresponding to step load change in Area1

5.7 OPTIMAL CONTROLLER FOR TWO AREA SYSTEM

Optimal controller (LQR) is designed for two area system using MATLAB coding. Designed **A,B,C,Q** and **R** matrices are given below:

A = [0.05 6 0 -6 0 0 0; 0 -3.33 3.33 0 0 0 0 ;-5.2083 0 -12.5 0 -0.545 0 0;0.545 0 0 0 -0.05 0 0;0 0 0 6 -0.05 6 0;0 0 0 0 0 -3.33 3.33;0 0 0 0 - 5.2083 0 -12.5]
B = [0 0;0 0;0 12.5;0 0;0 0;0 0;12.5 0]
C = [0 0 0 0 0 0 1]
Q = [1 0 0 0 0 0 0;0 1 0 0 0 0 0;0 0 1 0 0 0 0;0 0 0 1 0 0 0;0 0 0 0 1 0 0;0 0 0 0 0 1 0;0 0 0 0 0 0 1]

Frequency deviation response of area1 and area2 and tie-line power response using LQR is shown in fig.

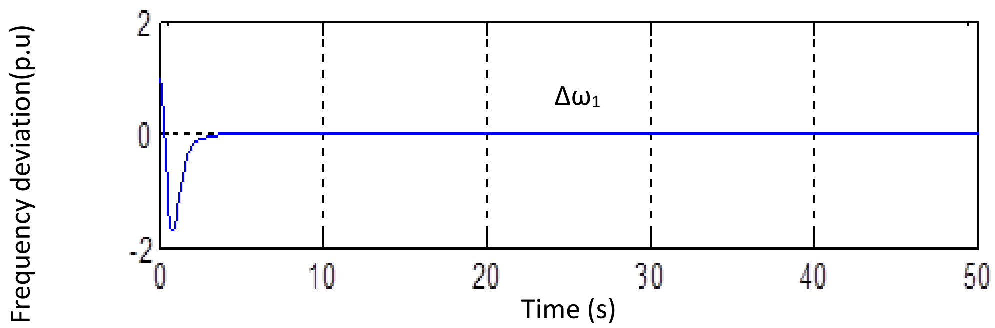

Fig 5.14 Frequency deviation response of Area 1using LQR

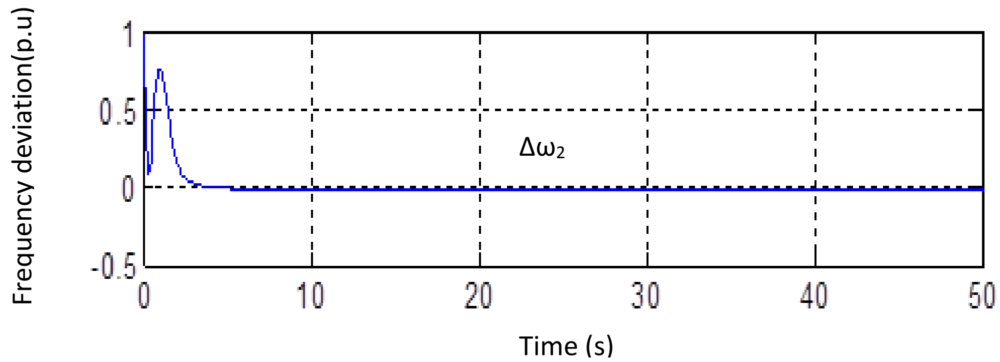

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Fig 5.15 Frequency deviation response of Area 2 using LQR

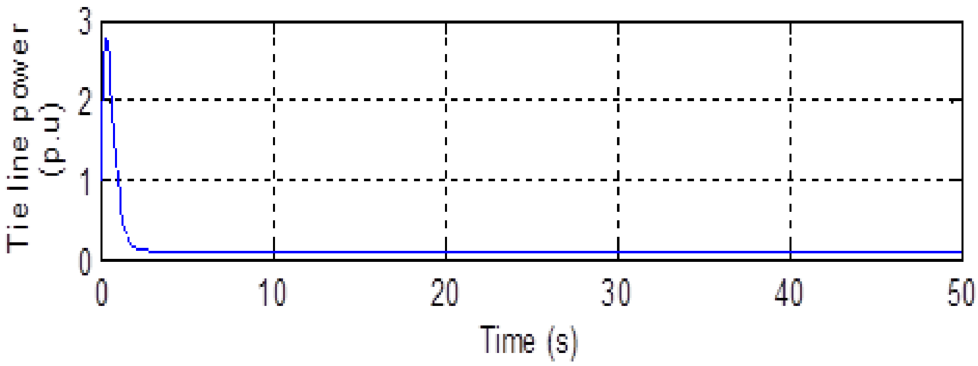

Fig 5.16 Tie-line power deviation response using LQR

5.8 OPTIMAL CONTROLLER FOR THREE AREA SYSTEM

Optimal controller (LQR) is designed for three area system using MATLAB coding. Two thermal (non reheat) and one hydro system is considered for analysis. Designed A,B,C,Q and R matrices are given below.

A = [-0.05 6 0 2 0 0 0 0 0 0 -6 -6 0 0 0 0; 0 -2.5 2.5 0 0 0 0 0 0 0 0 0 0 0 0 0; -5.2083 0 -12.5 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 -0.05 6 0 0 0 0 0 6 0 -6 0 0 0;0 0 0 0 -2.5 2.5 0 0 0 0 0 0 0 0 0 0; 0 0 0 -5.2083 0 -12.5 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 -0.05 6 0 0 0 6 6 0 0 0; 0 0 0 0 0 0 0.000877 -2 2.2 -0.19789 0 0 0 0 0 0;0 0 0 0 0 0 -0.000438 0 -0.1 0.09894 0 0 0 0 0 0; 0 0 0 0 0 0 -0.008555 0 0 -0.02053 0 0 0 0 0 0; 0.4442 0 0 -0.4442 0 0 0 0 0 0 0 0 0 0 0 0; 0.4442 0 0 0 0 0 -0.4442 0 0 0 0 0 0 0 0 0;0 0 0 0.4442 0 0 -0.4442 0 0 0 0 0 0 0 0 0; 0.425 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0; 0 0 0 0.425 0 0 0 0 0 0 -1 0 1 0 0 0; 0 0 0 0 0 0 0.425 0 0 0 0 -1 -1 0 0 0]

B = [0 0 0; 0 0 0; 12.5 0 0; 0 0 0; 0 0 0; 0 12.5 0; 0 0 0; 0 0 -0.002106; 0 0 0.001053; 0 0 0.20534; 0 0 0; 0 0 0; 0 0 0; 0 0 0; 0 0 0; 0 0 0]

C = [1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0]

Q = [0.180625 0 0 0 0 0 0 0 0 0 0.425 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 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0.180625 0 0 0 0 0 0 -0.425 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 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0.180625 0 0 0 0 -0.425 -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 0 0 0 0 0 0 0 0 0 0 0;0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0.425 0 0 -0.425 0 0 0 0 0 0 2 1 -1 0 0 0; 0.425 0 0 0 0 0 -0.425 0 0 0 1 2 1 0 0 0; 0 0 0 0.425 0 0 -0.425 0 0 0 -1 1 2 0 0 0;0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1]

Frequency deviation response of area1, area2, area 3 and tie-line power response using LQR is shown in fig.

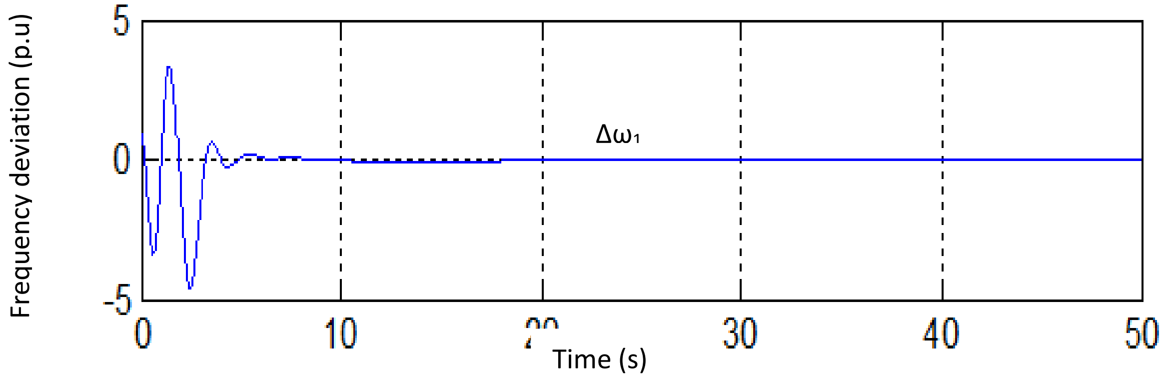

Fig 5.17 Frequency deviation step response of Area 1

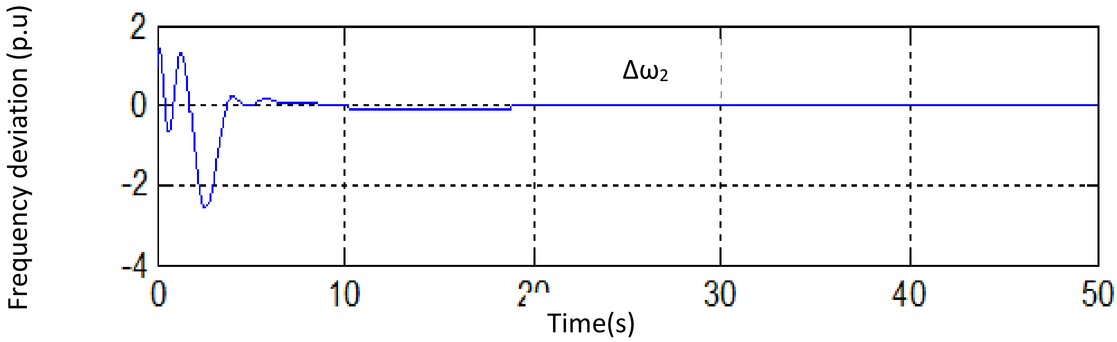

Fig 5.18 Frequency deviation step response of Area2

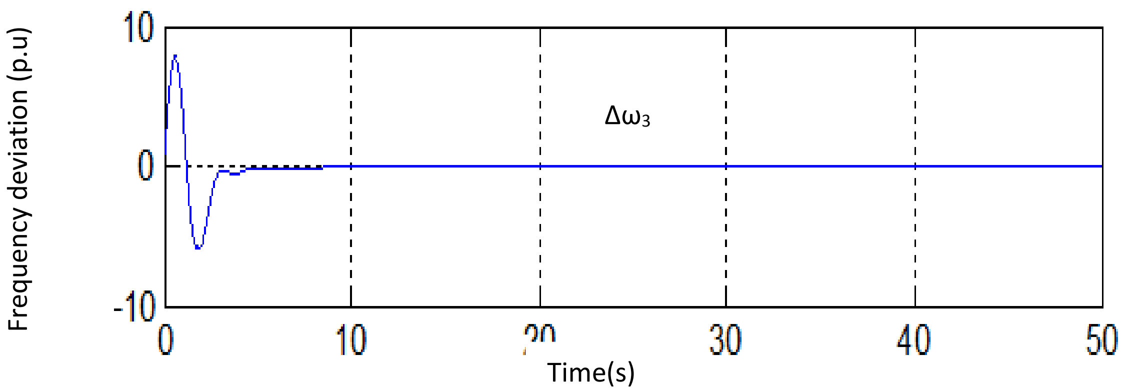

Fig 5.19 Frequency deviation step response of Area 3

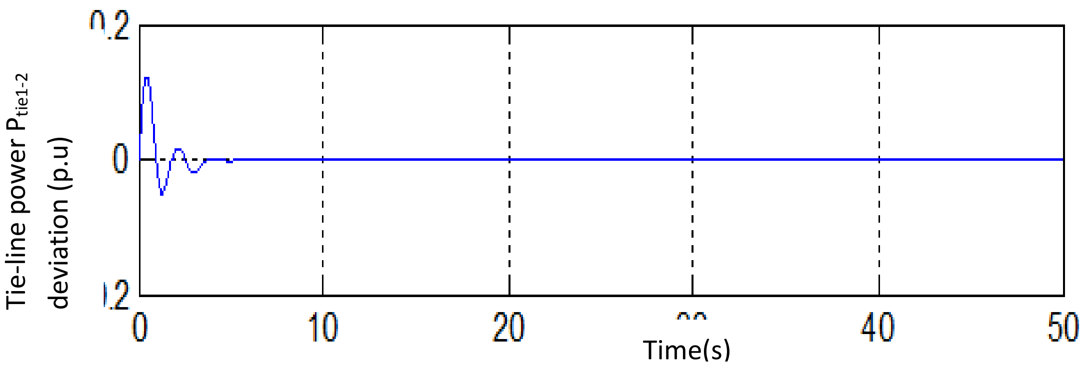

Fig 5.20 Tie-line power (P_{tie1-2}) deviation response

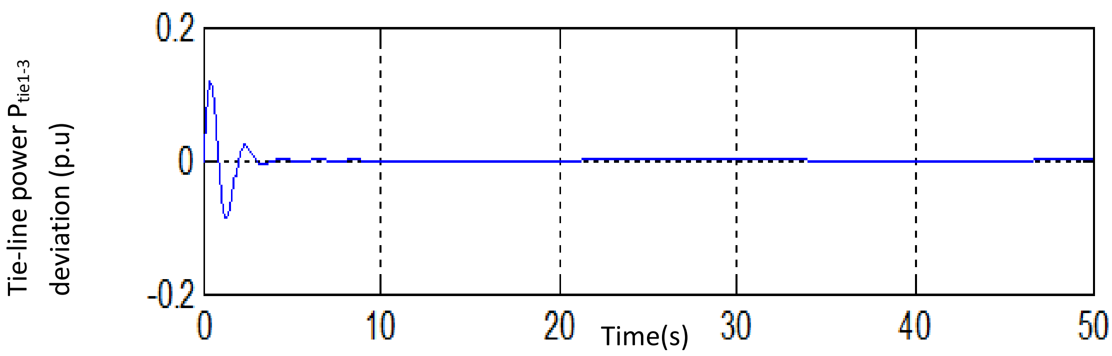

Fig 5.21Tie-line power (P_{tie1-3}) deviation response

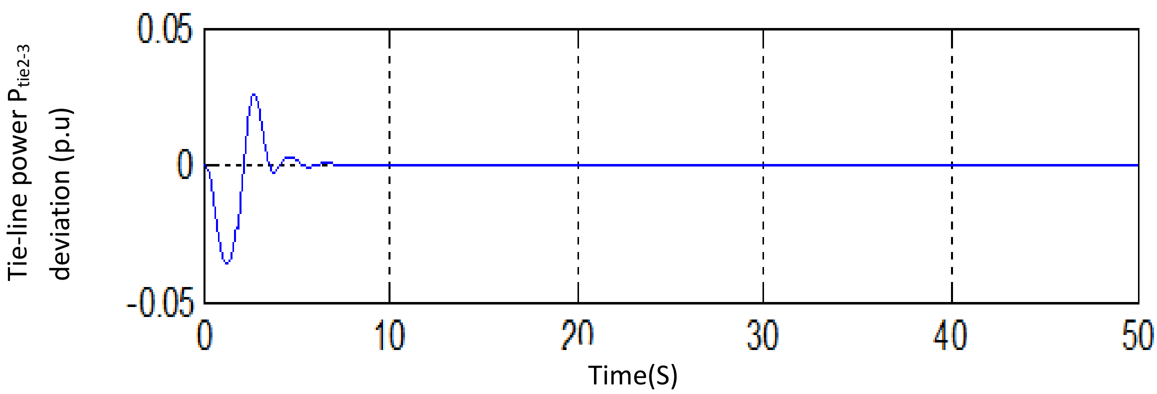

Fig 5.22 Tie-line power P_{tie2-3} deviation response

5.9 AGC WITH INTEGRAL CONTROLLER FOR TWO AREA SYSTEM IN DEREGULATED ENVIRONMENT

A two area system is considered with the following parameters:

$K_p = 41.7$

$T_p = 10.42$

$T_{t1} = T_{t3} = 0.5$ s

$T_{t2} = T_{t4} = 0.7$ s

$T_{g1} = T_{g3} = 0.4$ s

$T_{g2} = T_{g4} = 0.6$ s

$R_1 = R_3 = 2.5$ s

$R_2 = R_4 = 2.6$ s

Cpf Matrix:

0.5 0.250.2 0.3
0.2 0.250.5 0.3

0 0.250.2 0.1
0.3 0.250.1 0.3

AGC for two area system with integral control action $K_{i1} = K_{i3} = 0.084$ and $K_{i2} = K_{i4} = 0.042$ is designed. Simulation block diagram is shown in fig 5.23.

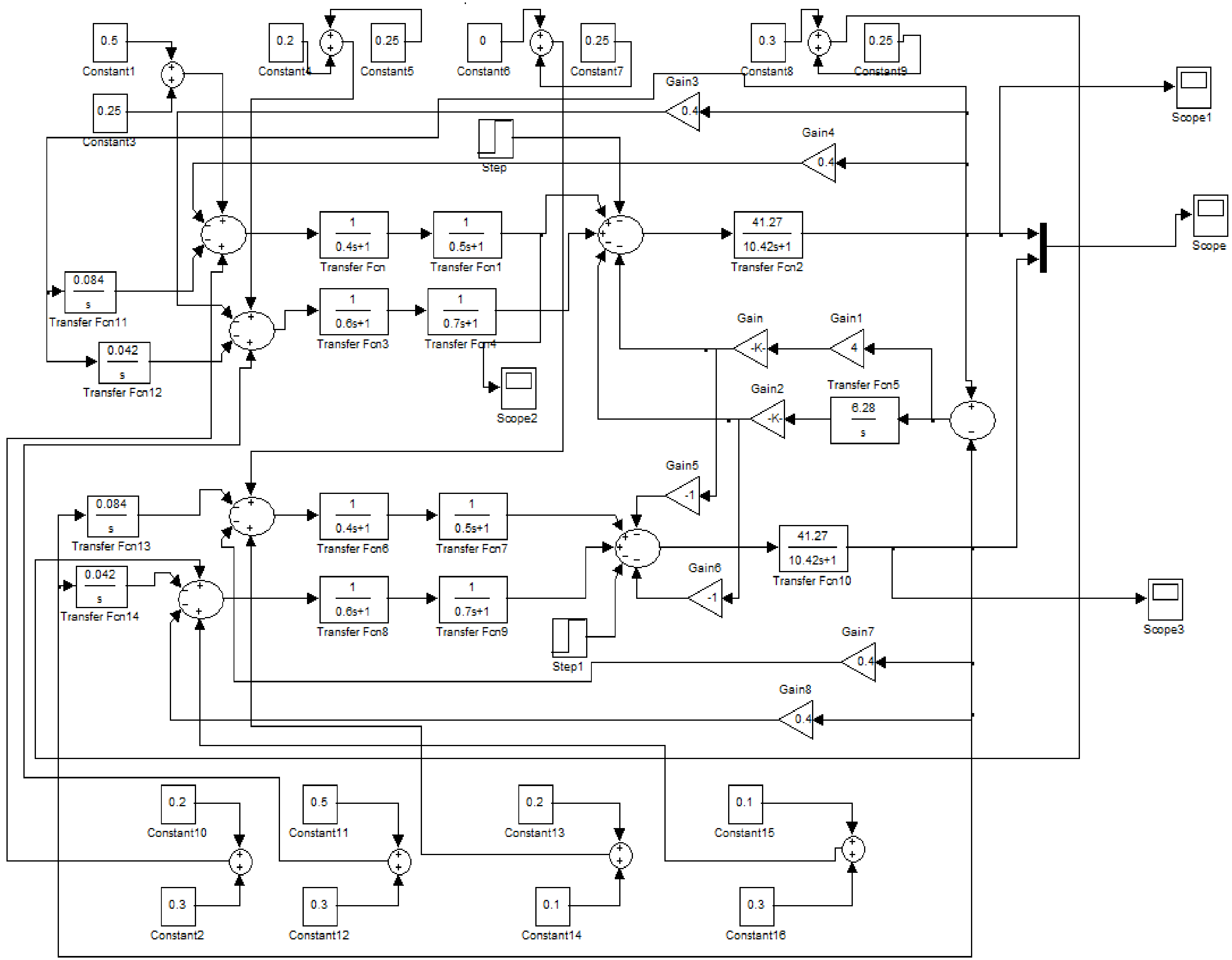

Fig 5.23 Simulation of AGC in deregulated environment for two area system

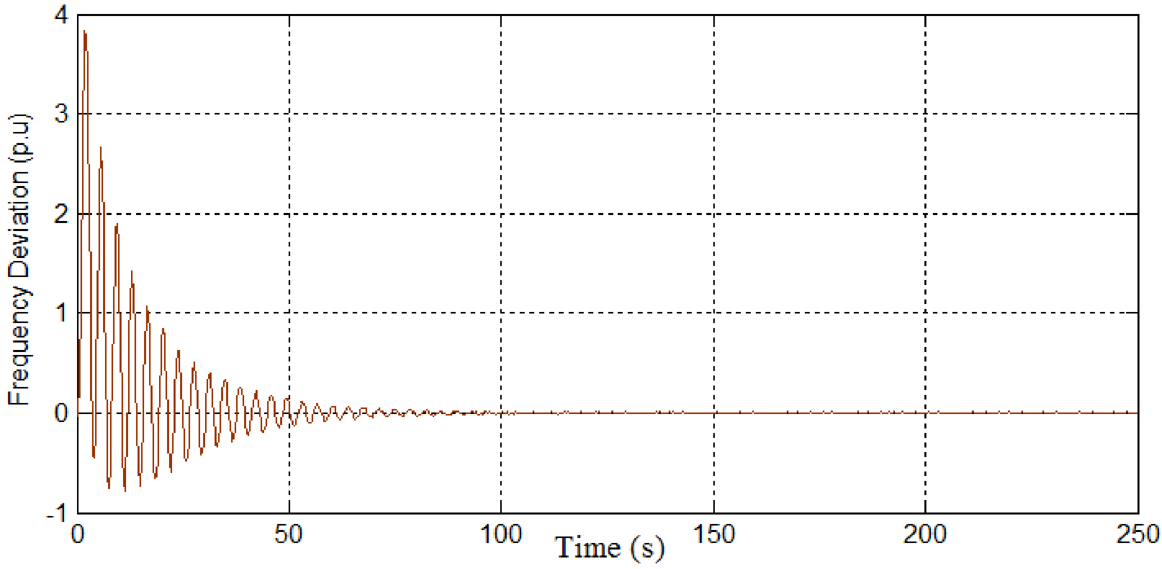

Fig 5.24 Frequency deviation response of Area1 in deregulated environment

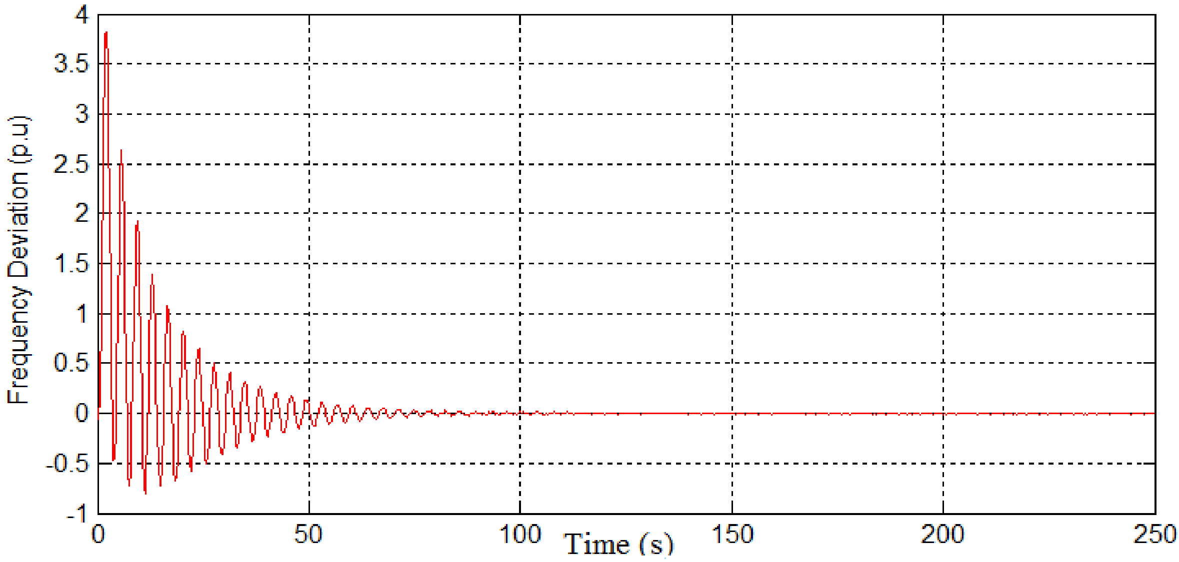

Fig 5.25 Frequency deviation response of Area2 in deregulated environment

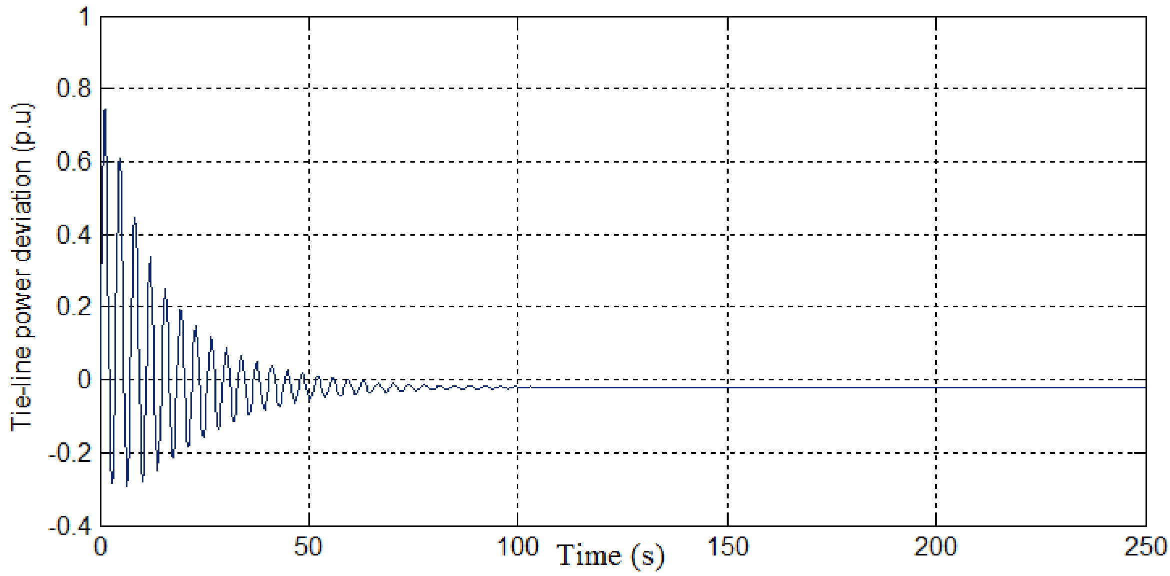

Fig 5.26 Tie-line power deviation response in deregulated environment

5.10 OPTIMAL CONTROLLER OF AGC TWO AREA SYSTEM INDEREGULATED ENVIRONMENT

Optimal controller (LQR) is designed for two area system in deregulated environment using MATLAB coding. Two thermal (non reheat) is considered for analysis. Designed **A,B,C,Q** and **R** matrices are given below:

A = [-0.0959 0 4 4 0 0 0 0 -4; 0 -0.0959 0 0 4 4 0 0 4; -0.0707 0 -1.11 0 0 0 -0.047 0 0; -0.0489 0 0 -0.769 0 0 -0.0323 0 0; 0 -0.0707 0 0 -1.11 0 0 -0.0233 0;0 -0.0489 0 0 0 -0.769 0 -0.0161 0; 0.1909 0 0 0 0 0 0 0 1; 0 0.1909 0 0 0 0 0 0 -1; 0.0867 -0.0867 0 0 0 0 0 0 0]

B = [-4 -4 0 0; 0 0 -4 -4; 0.555 0.2777 0.222 0.333; 0.1538 0.1923 0.3846 0.2307; 0 0.2777 0.222 0.111; 0.230 0.1923 0.0769 0.2307; 0.3 0.5 -0.7 0.6; -0.3 -0.5 0.7 0.6; 0 0 0 0]

C = [1 0 0 0 0 0 0 0 0; 0 1 0 0 0 0 0 0 0; 0 0 1 0 0 0 0 0 0; 0 0 0 1 0 0 0 0 0; 0 0 0 0 1 0 0 0 0; 0 0 0 0 0 1 0 0 0; 0 0 0 0 0 0 0 0 1]

Q = [5 0 0 0 0 0 0 0 0; 0 5 0 0 0 0 0 0 0; 0 0 5 0 0 0 0 0 0; 0 0 0 5 0 0 0 0 0; 0 0 0 0 5 0 0 0 0; 0 0 0 0 0 5 0 0 0; 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 5]

Frequency deviation response of area1, area2, and tie-line power response using LQR is shown in fig.

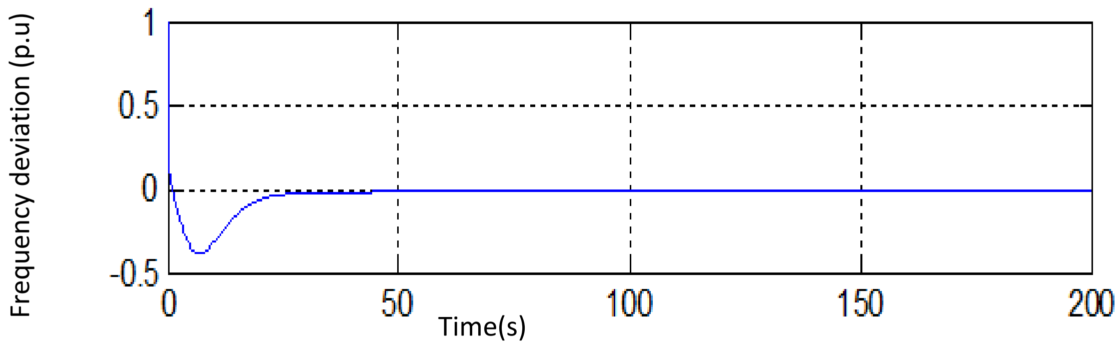

Fig 5.27 Frequency deviation step response with optimal controller for area1 in deregulated environment

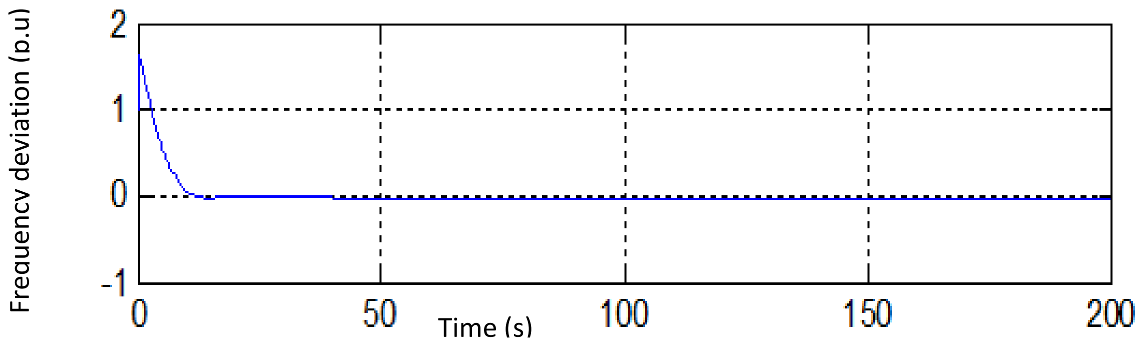

Fig 5.28 Frequency deviation step response with optimal controller of area2 in deregulated environment

Frequency de

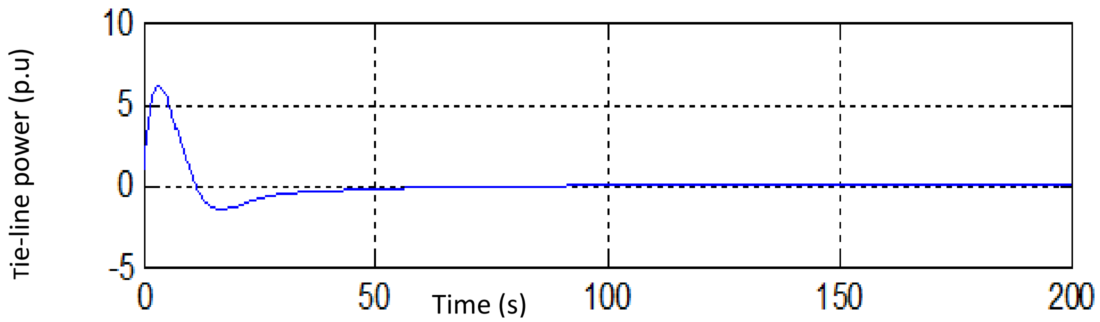

Fig 5.29 Tie-line power deviation step response with optimal controller in deregulated environment

5.11 DISCUSSIONS

- It is observed that the settling time of uncompensated single area system is approximately 15 sec and frequency deviation is not going to zero and with PID controller is approximately 10 sec and more oscillations are present. Pole placement method reduces the settling time of the system to 2.5 sec. but LQR reduces the settling time to less than 1 sec and reduces the oscillation of the system as well as and frequency deviation is brought down to zero.

- It is also observed that the settling time of two area system with integral control action is approximately 25 sec but optimal controller (LQR) reduces the settling time to only 2 to 3 seconds and frequency deviation is going to zero with minimum oscillations as compared to Integral controller.

- It is observed that optimal controller (LQR) in three area system is reducing all the frequency deviations and tie-line power deviations to zero after 5-6 sec and achieving steady state with minimum oscillations.

- It is observed that settling time of two area system with integral control action in deregulated environment is approx 80 sec but by using optimal controller in deregulated environment settling time reduces to 20 to 30 sec and oscillations are reduced. System achieving steady state very fast and all the deviations like tie-line power and frequency deviations are going to zero.

CONCLUSIONS

In this thesis, an approach for LFC based LQR based optimal control is introduced. In this approach, the state variable weighting matrix is found analytically to ensure robust and stable response of the system in varying power demand. The accomplishments are as follows:

1) **Aggregation**: By using this method we can divide a system into subsystems and find appropriate control input for each of those subsystem to get desired LQR. Overall control input and weighting matrices are the combination of the individual subsystems. This technique helps to avoid complex calculations of the complete order system.

2) **Optimal Modal Linear Quadratic Regulator:** The main purpose of this controller is improving system response in different operating conditions. This is a multi objective controller, which minimizes the cost function of the system and places the eigenvalues of the system simultaneously. While pole placement tries to restrict the transient time of the system response, optimization improves the transient response and control effort needed for the control.

3) It is a very good technique for multi input multi output system while pole placement is suitable only single input single output system.

4) It reduces oscillations, settling time and system reaches steady state in very less time and all the steady state error goes to zero.

SCOPE FOR FURTHER WORK

Linear Quadratic Regulator Control: The questions regarding LQR are in three areas:

1) The choice of quadratic cost function is selected in this work. However further research can be made for other cost functions that ensure a better response for the system.

2) Compensation of the unknown input effects for the control procedure is one other necessary objective. Otherwise it may not be possible to compensate for its effect on the system and this can cause the deteriorating of the LQR solutions. Further work can be done to address this issue.

3) The control input weighting matrix R can be changed to observe its effects on the feasibility of the LQR.

4) Artificial intelligence (AI) techniques can be used for optimization of the system response.

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