AUTOMATIC LOAD FREQUENCY CONTROL OF TWO AREA SYSTEM USING L-Q-R METHOD

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ABSTRACT:
Design of optimal controllers for linear systems with quadratic performance index known as Linear Quadratic Regulator for load frequency control system are realized in this paper. The objective of optimal regulator design is to determine the optimal control law which can transfer the system from its initial state to the final state such that given performance index (PI) is minimized. In this paper by using state space analysis a state equation for two area load frequency is obtained. The proposed optimal LQR load frequency has been compared with integral control simulink using MATLAB.
KEYWORDS: LQR (Liner Quadratic Regulator), performance index, ACE (Area Control error), State space, Integral controller.

1. INTRODUCTION

When generation or load changes; it adversely affects the frequency of entire system and for satisfactory operation of power system, the frequency should remain nearly constant and this is dependent on active power balance. As frequency is common factor throughout the system, the change in active power demand at one point is reflected throughout the system by change in frequency. Here, we have adopted the LFC i.e. Load Frequency Controller in interconnected system with two or more independently controlled areas. In multi area system the change of power in one area is met by increasing the generation in all areas associated with a change in tie-line power and reduction in frequency.[1]

In normal mode power system should operate in such a way that….

- Keep frequency at approximately nominal value.
- Maintain the tie-line flow.
- Each area should absorb its own load changes.

There are two methods to analyse any control system which can be stated as follows:

a) Transfer function model (For linear system)
b) State variable approach (For linear as well as non-linear system)

Here, we have adopted the transfer function method for analysis of two area system (Thermal-Thermal & Thermal-Hydro), By **MATLAB Simulink.**

2. MODELING OF POWER SYSTEM

BASIC LOAD FREQUENCY CONTROLLER:

The operation objective of LFC is to maintain reasonably frequency to divide the load between generators and to control the tie-line schedules.The change in frequency is sensed by frequency sensor where as tie-line power is sensed by LFC, which is measure of change in rotor angle δ.

Δf & ΔP_{tie} , are amplified, mixed and transformed into real power command signal ΔP_v which is sent to prime mover to call for an increment in torque. The prime mover brings change in generator output by an amount ΔP_g

which will change values of Δf & ΔP_{tie} within specific tolerance.

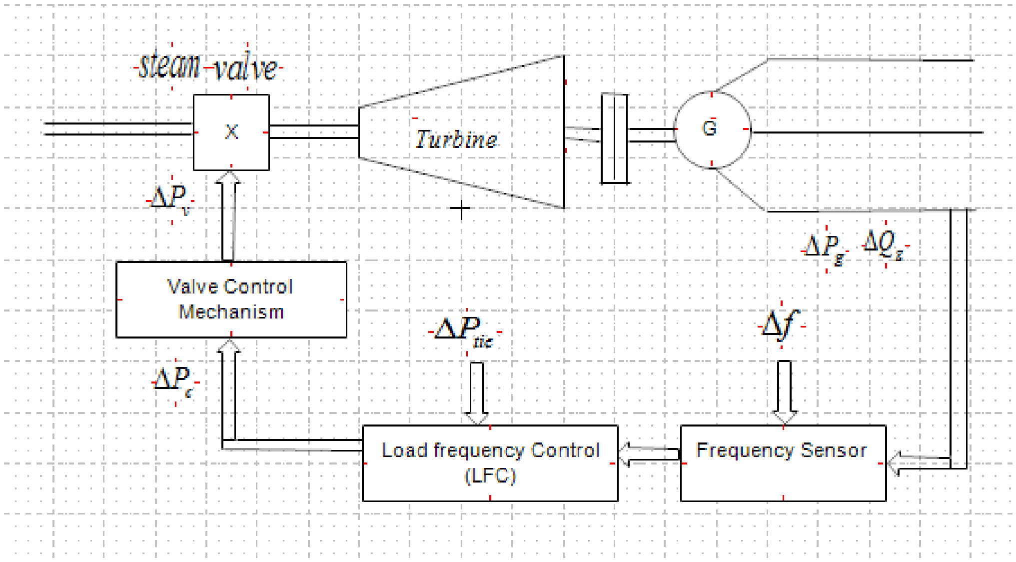


Figure 1: Basic layout of LFC

Let's consider the problem of controlling generator output of respective area to main the shedual frequency. All generators speed up and slow down together maintaining their relative power angles as they are connected together form coherent group an area constitute such a coherent group define as a control area. To understand AGC with frequency control let's consider a single area as shown in above figure.[1]

For a simplicity transfer functions are used to model each component of system shown in figure 1.

Transfer function of governor: $\frac{1}{1 + sT_g}$

Transfer function of turbine: $\frac{1}{1 + sT_t}$

Transfer function of generator: $\frac{K_p}{1 + sT_p}$

3. ROLE OF CONTROLLER:

Controller determines the value of controlled variable and compare the actual variable with desired value i.e. reference input and determines the deviation and produces control signal that will reduce the deviation to zero or minimum possible value.

In AGC of generating unit there is need to control or maintain frequency constancy, reduced oscillation & zero steady state error so following controllers are used. [10]

3.1 conventional integral (I) controller:

This controller was form many years ago to controlling such action. Its control action is shown in figure.2

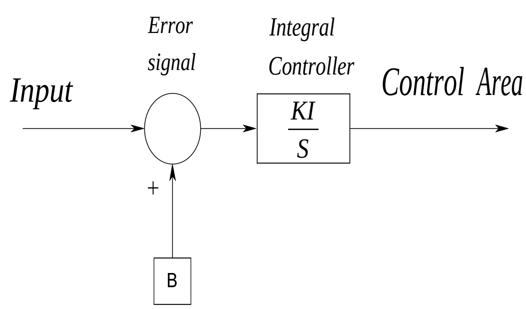


Figure 2: Integral controller scheme

Controller output = [input + frequency bias gain (B)]* $\frac{KI}{S}$

3.2 LQR (linear quadratic regulator) Controller:

Design of optimal controllers for linear systems with quadratic performance index known as **LQR**.

Objective of LQR:

To determine the optimal control law u*(x,t) which can transfer the system from its initial state to the final state such that a given performance index is minimized.

The PI is selected to give the best trade-off between performance and cost of control. The PI is widely used in optimal control design is known as quadratic performance index and is based on minimum error and minimum energy criteria.

4. STATE SPACE ANALYSIS OF TWO SYSTEMS:

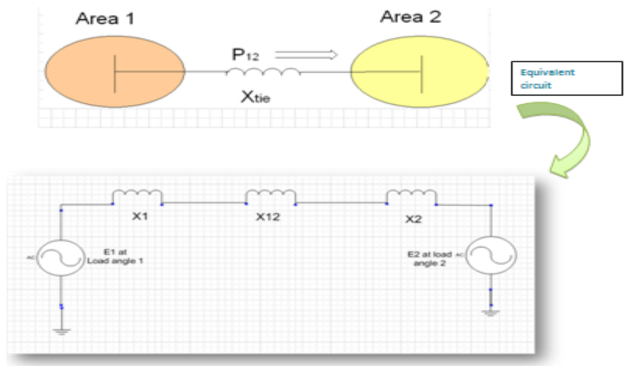


Figure 3: Equivalent circuit of two independent interconnected areas

4.1 State Space Analysis of Two Area Thermal – Thermal (Non- Reheat) Systems:

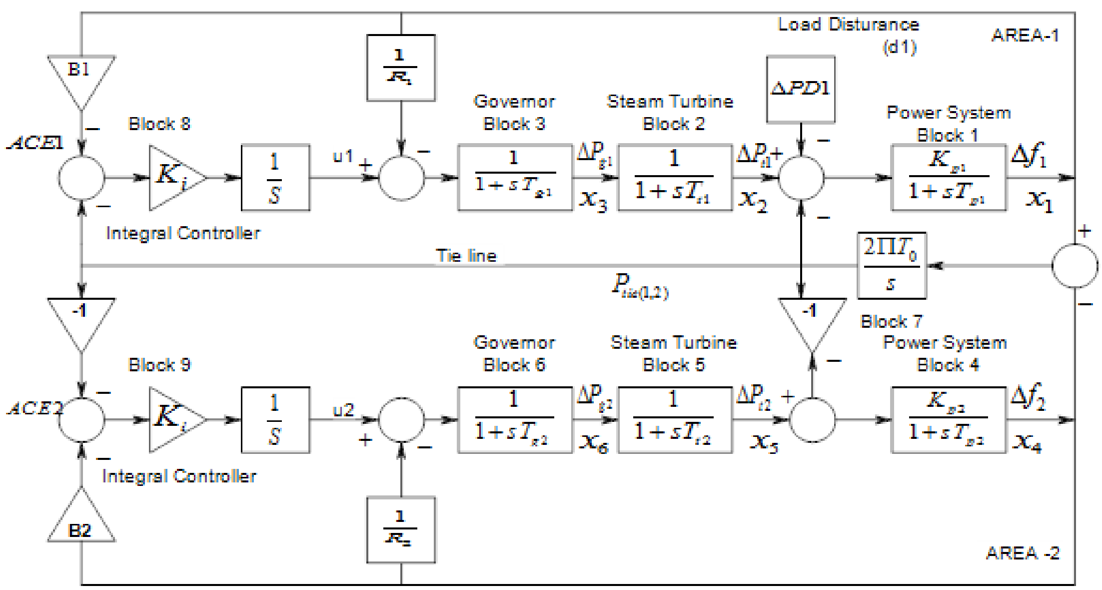


Figure 4: Modeling of two area (Thermal -Thermal) system

We have derived the state space equation for two area systems from figure 4 is as shown below;
Deferent variables have been defined as:

State variables: $x_1 = \Delta f_1 \; x_2 = \Delta Pt_1 \; x_3 = \Delta Pg_1$

$x_4 = \Delta f_2 \; x_5 = \Delta Pt_2 \; x_6 = \Delta Pg_2 \; x_7 = \Delta P_{tie12}$

$x_8 = \int ACE_1 dt \;\; x_9 = \int ACE_2 dt$

Control inputs: $u_1 \; u_2$

Disturbance inputs: $d_1 = \Delta P_{D1} \; d_2 = \Delta P_{D2}$

For block: 1

$$\dot{x}_1 = \frac{-x_1}{T_{p1}} + \frac{K_{p1}x_2}{T_{p1}} - \frac{K_{p1}x_7}{T_{p1}} - \frac{K_{p1}d_1}{T_{p1}}$$

For block: 2 $\quad \dot{x}_2 = \frac{-x_2}{T_{t1}} + \frac{x_3}{T_{t1}}$

For block: 3 $\quad \dot{x}_3 = \frac{-x_1}{T_{g1}R_1} - \frac{x_3}{T_{g1}} + \frac{u_1}{T_{g1}}$

For block: 4

$$\dot{x}_4 = \frac{-x_4}{T_{p2}} + \frac{x_5 k_{p2}}{T_{p2}} + \frac{x_7 k_{p2}}{T_{p2}} - \frac{d_2 k_{p2}}{T_{p2}}$$

For block: 5 $\quad \dot{x}_5 = \frac{x_5}{T_{t2}} + \frac{x_6}{T_{t2}}$

For block: 6 $\quad \dot{x}_6 = \frac{-x_4}{T_{g2} R_2} - \frac{x_6}{T_{g2}} + \frac{u_2}{T_{g2}}$

For block: 7 $\quad \dot{x}_7 = (x_1 - x_4) 2\pi T_0$

For block: 8 $\quad \dot{x}_8 = -x_1 B_1 - x_7$

For block: 9 $\quad \dot{x}_9 = -x_4 B_2 + x_7$

Above equations are arranged in vector matrix which ate known as STATE EQUATION:

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

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

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$$

$$A = \begin{bmatrix} \frac{-1}{T_{p1}} & \frac{K_{p1}}{T_{(\,)p1}} & 0 & 0 & 0 & 0 & \frac{-K_{p1}}{T_{p1}} & 0 & 0 \\ 0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{T_{g1} R_1} & 0 & \frac{-1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{T_{p2}} & \frac{K_{p2}}{T_{p2}} & 0 & \frac{K_{p2}}{T_{p2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{T_{g2} R_2} & 0 & \frac{-1}{T_{g2}} & 0 & 0 & 0 \\ 2\pi T_0 & 0 & 0 & -2\pi T_0 & 0 & 0 & 0 & 0 & 0 \\ -B_1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -B_2 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\Gamma = \begin{bmatrix} \frac{-K_{p1}}{T_{p1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{-K_{p2}}{T_{p2}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{T_{g1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{g2}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

4.2State Space Analysis Of Two Area Thermal (Reheat) – Hydro Systems:

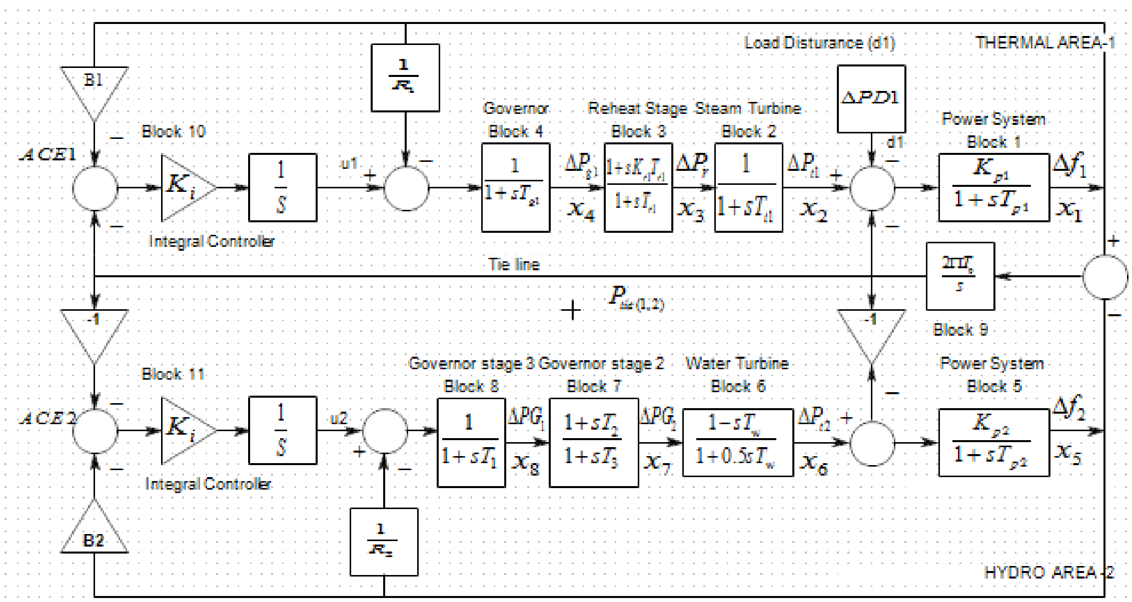


Figure 5: Modeling of two area (Thermal -Hydro) system

We have derived the state space equation for two area systems from figure no. 21 is as shown below;

Deferent variables have been defined as:

State variables: $x_1 = \Delta f_1$ $x_2 = \Delta P_{t1}$ $x_3 = \Delta P_{r1}$ $x_4 = \Delta P_{g1}$ $x_5 = \Delta f_2$

$x_6 = \Delta P_{tw}$ $x_7 = \Delta P_{G2}$ $x_8 = \Delta P_{G2}$ $x_9 = \Delta P_{tie(1,2)}$ $x_{10} = \int ACE_1 dt$

$x_{11} = \int ACE_2 dt$

Control inputs: u_1 u_2

Disturbance inputs: $d_1 = \Delta P_{D1}$ $d_2 = \Delta P_{D2}$

For block 1: $x_1 + T_{p1}\dot{x}_1 = K_{p1}(x_2 - x_9 - d_1)$

$$\therefore \dot{x}_1 = \frac{-1}{T_{p1}}x_1 + \frac{K_{p1}}{T_{p1}}x_2 - \frac{K_{p1}}{T_{p1}}x_9 - \frac{K_{p1}}{T_{p1}}d_1$$

For block 2: $x_2 + T_{t1}\dot{x}_2 = x_3$

$$\therefore \dot{x}_2 = \frac{-x_2}{T_{t1}} + \frac{x_3}{T_{t1}}$$

For block 3: $x_3 + T_{r1}\dot{x}_3 = x_4 + K_{r1}T_{r1}\dot{x}_4$

$$\therefore \dot{x}_3 = \frac{-1}{T_{r1}}x_3 + \frac{1}{T_{r1}}x_4 + K_{r1}\dot{x}_4$$

$$\therefore \dot{x}_3 = -\frac{K_{r1}}{T_{g1}R_1}x_1 - \frac{1}{T_{r1}}x_3 + \left(\frac{1}{T_{r1}} - \frac{K_{r1}}{T_{g1}}\right)x_4 + \frac{K_{r1}}{T_{g1}}u_1$$

For block 4: $x_4 + T_{g1}\dot{x}_4 = -\frac{1}{R_1}x_1 + u_1$

$$\therefore \dot{x}_4 = -\frac{1}{T_{g1}R_1}x_1 - \frac{1}{T_{g1}}x_4 + \frac{1}{T_{g1}}u_1$$

For block 5: $x_5 + T_{p2}\dot{x}_5 = K_{p2}(x_6 - x_9 - d_2)$

$$\therefore \dot{x}_5 = \frac{-1}{T_{p2}}x_5 + \frac{K_{p2}}{T_{p2}}x_6 - \frac{K_{p2}}{T_{p2}}x_9 - \frac{K_{p2}}{T_{p2}}d_2$$

For block 6: $x_6 + 0.5T_W\dot{x}_6 = x_7 - T_W\dot{x}_7$

$$\therefore \dot{x}_6 = \frac{-2}{T_w}x_6 + \frac{-2}{T_w}x_7 - 2\left[\frac{-T_2}{R_2T_1T_3}x_5 - \frac{1}{T_3} - \frac{1}{T_3}x_7 + \left(\frac{1}{T_3} - \frac{T_2}{T_1T_3}\right)x_8 + \frac{T_2}{T_1T_3}u_2\right]$$

$$\therefore \dot{x}_6 = \frac{-2}{T_w}x_6 + \frac{-2}{T_w}x_7 - 2\left[\frac{-T_2}{R_2T_1T_3}x_5 - \frac{1}{T_3} - \frac{1}{T_3}x_7 + \left(\frac{1}{T_3} - \frac{T_2}{T_1T_3}\right)x_8 + \frac{T_2}{T_1T_3}u_2\right]$$

For block 7: $x_7 + T_3\dot{x}_7 = x_8 + T_2\dot{x}_8$

$$\therefore \dot{x}_7 = \frac{-1}{T_3}x_7 + \frac{1}{T_3}x_8 + \frac{T_2}{T_3}\dot{x}_8$$

$$\therefore \dot{x}_7 = \frac{-1}{T_3}x_7 + \frac{1}{T_3}x_8 + \frac{T_2}{T_3}\left[-\frac{1}{R_2T_1}x_5 - \frac{1}{T_1}x_8 + \frac{1}{T_1}u_2\right]$$

$$\therefore \dot{x}_7 = \frac{-T_2}{R_2T_1T_3}x_5 - \frac{1}{T_3}x_7 + \left(\frac{1}{T_3} - \frac{T_2}{T_1T_3}\right)x_8 + \frac{T_2}{T_1T_3}u_2$$

For block 8: $x_8 + T_1\dot{x}_8 = \frac{-1}{R_2}x_5 + u_2$

$$\therefore \dot{x}_8 = \frac{1}{R_2T_1}x_5 - \frac{1}{T_1}x_8 + \frac{1}{T_1}u_2$$

For block 9: $\dot{x}_9 = 2\pi T^0 x_1 - 2\pi T^0 x_5$

For block 10: $\dot{x}_{10} = B_1x_1 + x_9$

For block 11: $\dot{x}_{11} = B_2x_5 - x_9$

Above equations are arranged in vector matrix which ate known as **STATE EQUATION**:

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

State vector $(x) = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} \end{bmatrix}^T$

$$A = \begin{bmatrix} \frac{-1}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_{P1}}{T_{P1}} & 0 & 0 \\ 0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-K_{r1}}{T_{g1}R_1} & 0 & \frac{-1}{T_{t1}} & \left(\frac{1}{T_{t1}} - \frac{K_{r1}}{T_{g1}}\right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1T_{g1}} & 0 & 0 & \frac{-1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & 0 & -\frac{K_{P2}}{T_{P2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2T_2}{R_2T_1T_3} & \frac{-2}{T_w} & \left(\frac{2}{T_w} + \frac{2}{T_3}\right) & \left(\frac{2T_2}{T_1T_3} - \frac{2}{T_3}\right) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-T_2}{R_2T_1T_3} & 0 & \frac{-1}{T_3} & \left(\frac{1}{T_3} - \frac{T_2}{T_1T_3}\right) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{R_2T_1} & 0 & 0 & \frac{-1}{T_1} & 0 & 0 & 0 \\ 2\pi T^0 & 0 & 0 & 0 & -2\pi T^0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & & & & & & & & 1 & & \\ & & & & B_2 & & & & -1 & & \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{K_{r1}}{T_{g1}} & 0 \\ \frac{1}{T_{g1}} & 0 \\ 0 & 0 \\ 0 & \frac{-2T_2}{T_1T_3} \\ 0 & \frac{T_2}{T_1T_3} \\ 0 & \frac{1}{T_1} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Where, A(9*9) **state matrix** and B (9*2) **control matrix.**

Control vector

$$(u) = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

In optimal control the control inputs are chosen as a linear combination of feedback from all nine system states $(x_1, x_2, ..., x_9)$ as given below:

$$u = -Kx$$

Where K (2*9) is a feedback gain matrix given by;

$$K = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} & k_{17} & k_{18} & k_{19} & k_{10} & k_{1-11} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} & k_{27} & k_{28} & k_{29} & k_{20} & k_{2-11} \end{bmatrix}$$

The system $\dot{x} = Ax + Bu$ state equation is:

(For step load change of constant magnitude, $\Gamma d = 0$

The output equation is, $y = Cx + Du$

However for a feedback control system the matrix 'D' is assumed zero.

Hence, **finally** the state space model of system under consideration takes a form as

$$\dot{x} = Ax + Bu \;\&\; y = Cx$$

The control inputs are linear combinations of system states given by,

$$u_1 = k_{11}x_1 + k_{12}x_2 + ... + k_{1-11}x_{11}$$

$$u_2 = k_{21}x_1 + k_{22}x_2 + ... + k_{2-11}x_{11}$$

5. LQR (optimal controller) design

The system state equation is $\dot{x} = Ax + Bu + \Gamma d$
For step load change of constant magnitude, $\Gamma d = 0$

$$\therefore \dot{x} = Ax + Bu$$

The output equation is $y = Cx + Du$
For feedback control system D=0 $\therefore\; y = Cx$
Hence, control input $u = -Kx$ where K is 1*n constant feedback gain vector.
We have found out the value of K which minimizes the performance index J to obtain optimal results.

$$J = \int_{t_0}^{t_f} (x'Qx + u'Ru)dt$$

For linear time- invariant system when the process is of infinite duration, Riccati equation can be written as,

$$pA + A'p + Q - pBR^{-1}B'p = 0$$

Where, Q= Real, symmetric and positive semi-definite matrix
R= Real, symmetric and positive definite matrix

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

6. Simulations

6.1 State space model simulation (Thermal-Thermal):

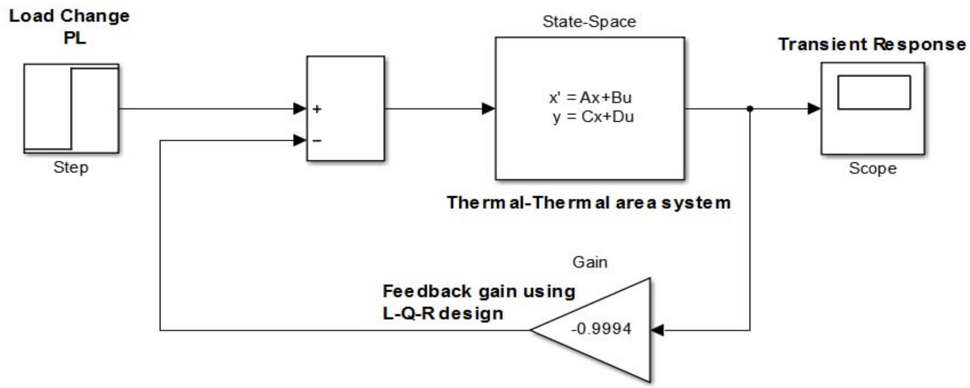


Figure 6: State Space Model of two area (Thermal -Thermal) system with L-Q-R Controller

6.2 State space model simulation (Thermal-Hydro):

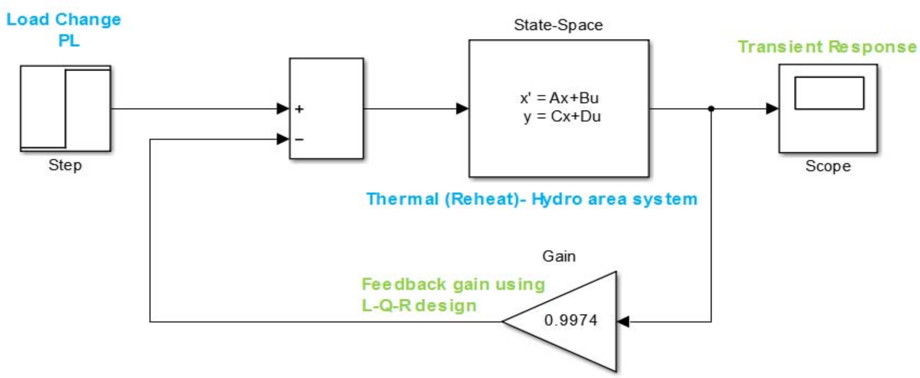


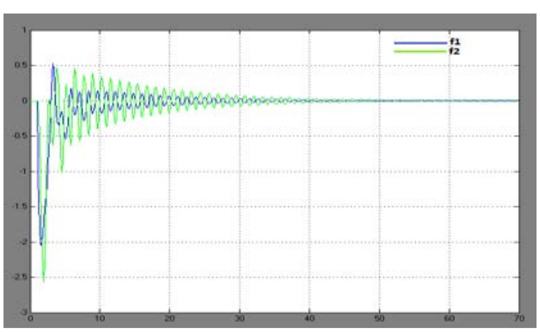
Figure 7: State Space Model of two area (Thermal -Hydro) system with L-Q-R controller

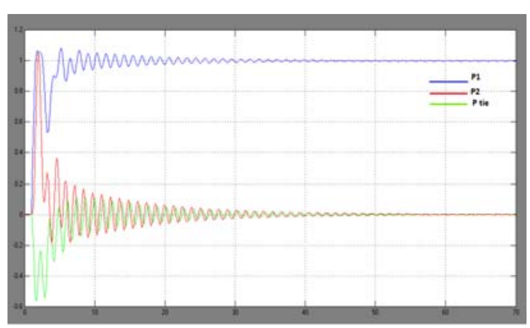
7. RESULTS

8.1RESULTS OF THERMAL-THERMAL (BOTH NON-REHEAT):

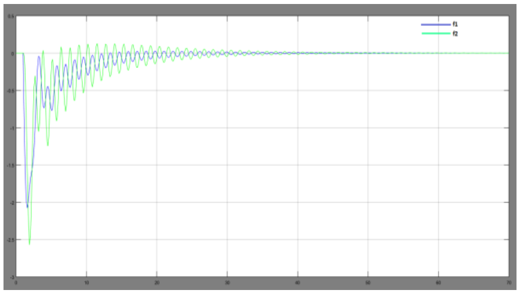
(A) Using conventional (integral) controller:

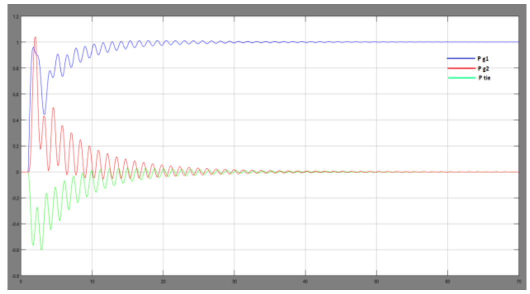
Graph showing variation in frequencies, power and tie line power of two areas.



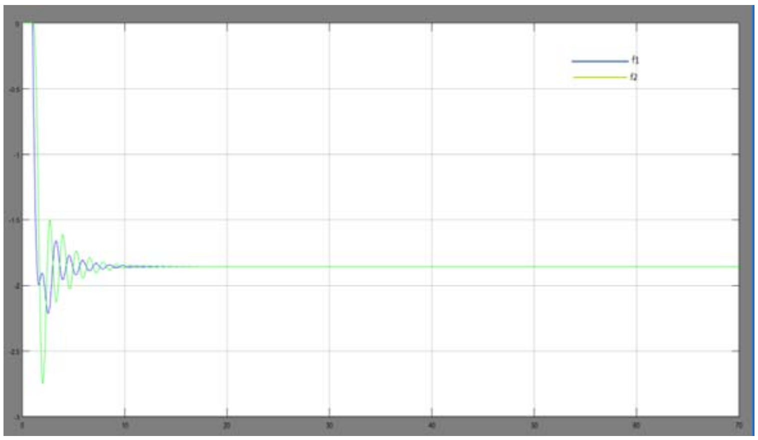


(B) Using conventional (Proportional - integral) controller:



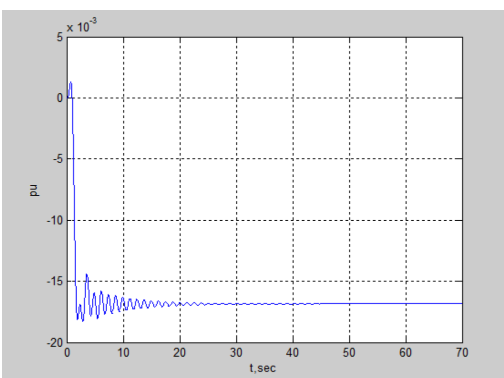


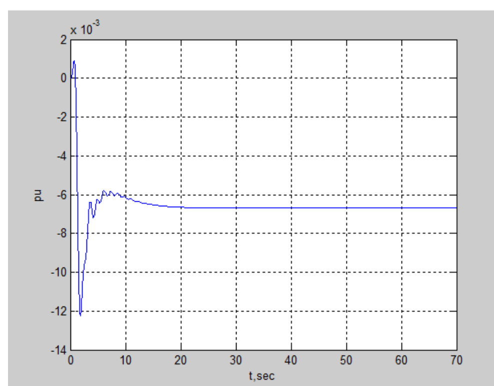
(C) Response of LQR from MATLAB simulink:



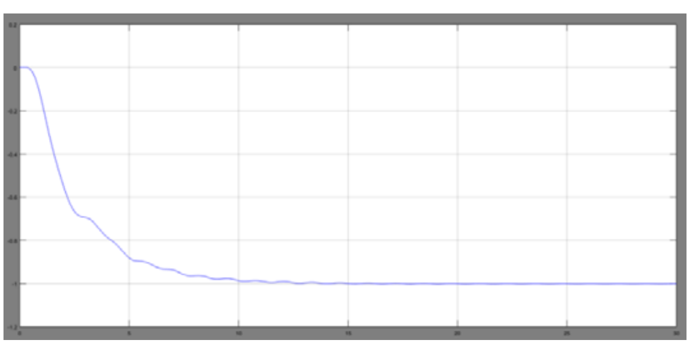
(D) By MATLAB programming:

Without L-Q-R **With L-Q-R**





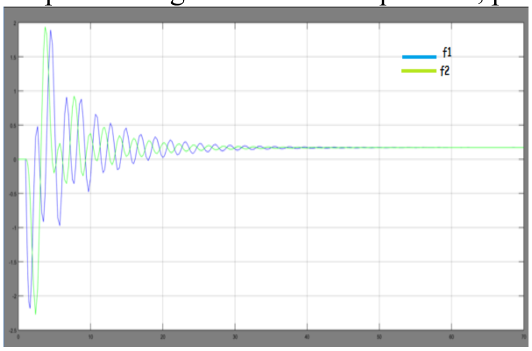
(E) By state space modeling: (With LQR)

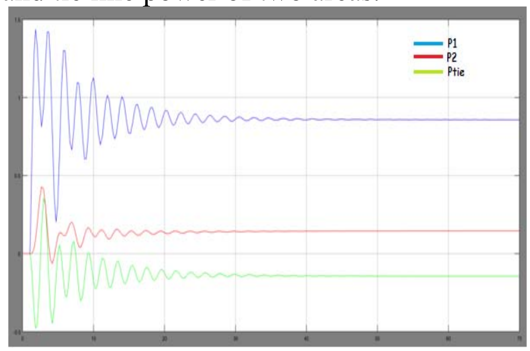


8.2 RESULTS OF THERMAL-THERMAL:

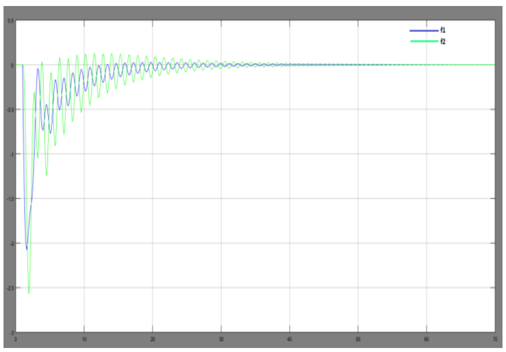
(A) Using conventional (integral) controller:

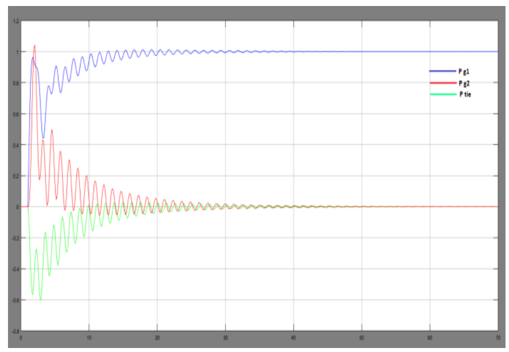
Graph showing variation in frequencies, power and tie line power of two areas.



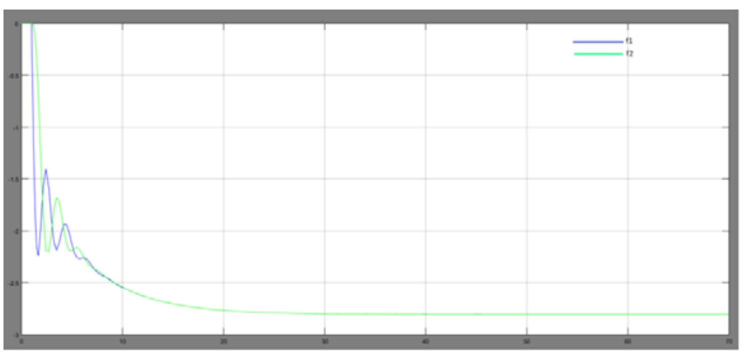


(B) Using Conventional (Proportional - integral) Controller:

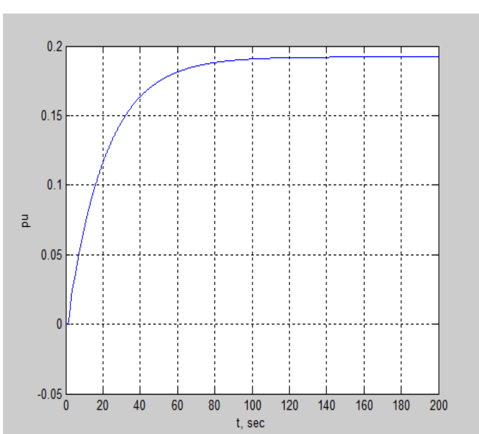


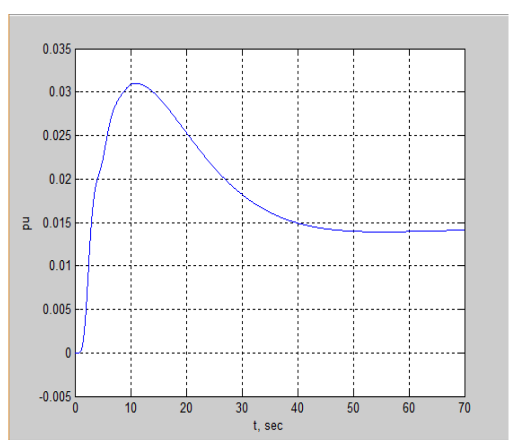


(C) Response of LQR from MATLAB simulink:

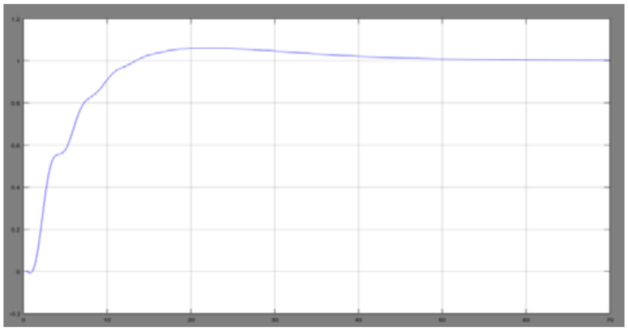


(D) By MATLAB programming:





(E) By state space modeling: (with LQR)



9. ANALYSIS

Controllers	Frequency Response Stability time (in second) for Thermal – Thermal (Non- Reheat) Two Area System	Frequency Response Stability time (in second) for Thermal (Reheat) – Hydro Two Area System
Integral Controller	50 sec	45 sec
Proportional Controller	40 sec	35 sec
By L-Q-R Controller	18 sec	20 sec

Analysis of simulation models

10. CONCLUSION

In this we study that First of all mathematical modeling was done of two areas i.e. thermal-thermal and thermal-hydro after which simulation was. From simulation responses the improvement obtained in frequency deviation and power deviation for the system is within 40-50sec with integral controller and within 40sec with proportional integral controller i.e. for the case thermal-thermal system. As for the case of thermal-hydro it is 50-60sec with integral controller and within 40-50sec with proportional integral controller.By applying L-Q-R method there was increase in the stability of the system in less time compared to all conventional methods (i.e. in this case integral and proportional integral controller). By L-Q-R method the improvement is obtained within 10-20sec for both cases i.e. thermal - thermal and thermal-hydro. Hence by this we have tried to achieve our desired targetof maintaining the stability of the system in less time.

11.APPENDIX

10.1 For Thermal-Thermal (Both Non-Reheat):

PARAMETERS	NOTATION	AREA 1 (THERMAL)	AREA 2 (THERMAL)
Power System Gain Constant	K_{PS}	120	120
Power System Time Constant	T_{PS} (sec)	20	20
Speed Regulation	R (Hz/Mw)	2.5	2.5
Normal frequency	f (Hz)	50	50
Governor time constant	T_{gs} (sec)	0.04	0.04
Turbine time constant	T_{ts} (sec)	0.5	0.6
Integrator constant	K_i	0.4	0.4
Frequency- Sensitive load coefficient.	D (Mw/Hz)	0.00834	0.00834

10.2 For Thermal (Reheat)-Hydro:

PARAMETERS	NOTATION	AREA 1 (THERMAL)	NOTATION	AREA 2 (Hydro)
Power System Gain Constant	K_{PS1}	120	K_{PS2}	120
Power System Time Constant	T_{PS1} (sec)	20	T_{PS2}	20
Speed Regulation	R_1 (Hz/Mw)	1.2	R_2	1.2
Normal frequency	f_1 (Hz)	50	f_2	50
Governor time constant	T_{gs1} (sec)	0.08	T_1 T_2 T_3	0.3 5 28.75
Turbine time constant	T_{t1} (sec) T_{r1} (sec)	0.3 10 0.2	Tw	0.3

	K_{r1} (sec)			
Integrator constant	K_{i1}	1	K_{i2}	1
Frequency- Sensitive load coefficient.	D_1 (Mw/Hz)	0.0085	D_2 (Mw/Hz)	0.0085
Frequency bias constant	B_1	0.8417	B_2	0.8417

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