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Modelling of Load Frequency Control Using PI Controller and Stability Determination with Linear Quadratic Regulator

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Abstract:*Load frequency control has a very important role in power system operation and control. The main objective of load frequency control are to keep the frequency deviation and tie line power deviation within acceptable limit when a load change occurs in that power system. This paper demonstrates an integral controller action to minimize the frequency deviation and the tie line power deviation. Also to determine the stability of the system, an optimal controller which is known as 'Linear Quadratic Regulator' is used. The results are illustrated by using MATLAB/SIMULINK.*
Keywords*: Load Frequency Control, LQR, Proportional Integral controller. SIMULINK/MATLAB.*

I. Introduction

Load frequency control is a control mechanism which minimizes frequency deviation and tie line power deviation to an acceptable limit. To model a load frequency control model it is necessary to model governor, turbine and generator-load model [5].

Governor Model: The governor has two inputs.

i. ΔP_{ref}i.e change in speed changer position.
ii. Δfi.e change in frequency.

An increase in ΔP_{ref} causes an increase in output whereas a decrease in Δf causes an increase in output. Therefore governor command is given as.

$\Delta P_0 = \Delta P_{ref} - \frac{1}{R}\Delta f$ ……(1)

Where, R = Speed regulation of governor in Hz/MW

If T_g is the time constant and K_g is the gain of the governor, then governor output ΔP_V can be expressed as
$\Delta P_v(s) = \Delta P_{ref}(s) - \frac{1}{R}\ \Delta F(s)$ …(2)

Turbine Model: The response of non-reheat turbine can be expressed as

$\Delta P_m(s) = \frac{K_t}{1+T_t s}\Delta P_v(s)$….(3)

Where, K_t = turbine gain constant
T_t = turbine time constant
ΔP_m = change in power developed by turbine

Generator-Load Model: The change in power developed by turbine causes a change in alternator output ΔP_G . The difference between the change in alternator output and change in load (ΔP_L) tends to change in system frequency.

The power system response is given by

$\Delta F(s) = \frac{K_P}{1+sT_P}[\Delta P_G(s) - \Delta P_L(s)]$……….(4)

Where, K_P = Power system gain constant
T_P = Time constant

If two control areas are connected by a single tie line, change in frequency in area 1 is given by

$$\Delta F_1(s) = \frac{K_P}{1+sT_P}[\Delta P_{G1}(s) - \Delta P_{L1}(s) - \Delta P_{TL1}(s)] \text{ ....(5)}$$

Where ,ΔP_{TL1} = change in tie line power in area 1

$$\Delta P_{TL1}(s) \quad = \frac{2*pie*T_0}{s}(\Delta F_1(s) - \Delta F_2(s)) \text{ ....(6)}$$

Where, T_0 = Synchronizing coefficient
ΔF_2 = Change in frequency in area 2

PI Controller: The steady-state frequency can be adjusted to the desired limit by adjusting the speed changer setting of the governor. Proportional integral controller has been developed to improve the dynamic response of the system to minimize the steady-state error [3, 4].

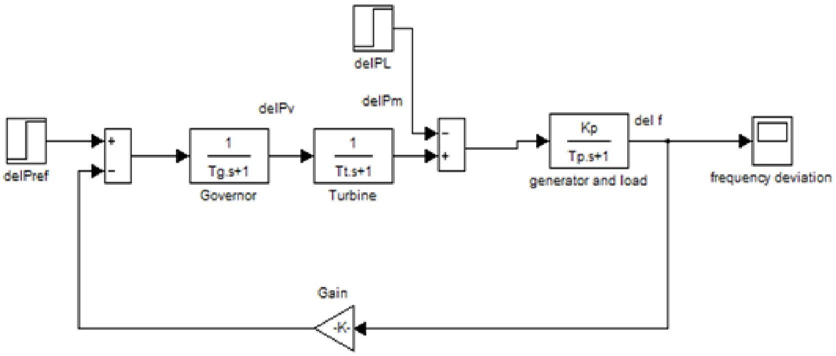
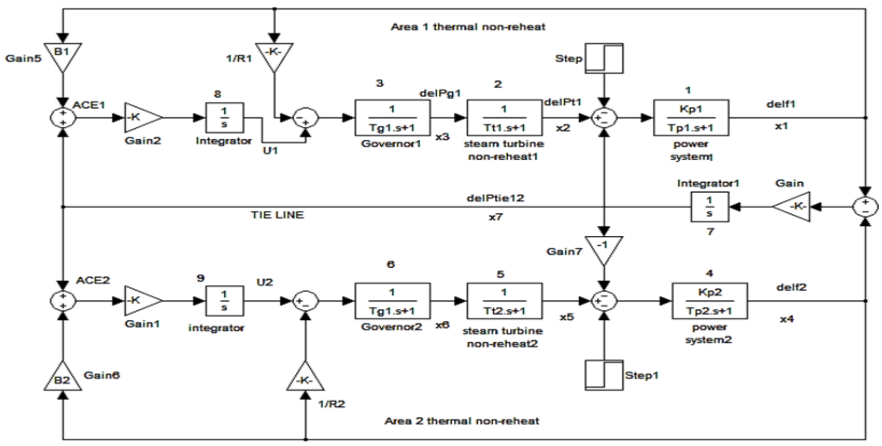


Fig (1): Complete block diagram of single area load frequency control

State-Space Representation: Consider a two area thermal system with non-reheat turbine as shown in fig (2).



Fig(2):Block diagram of two area thermal system connected by tie line

State Matrix:
$X = [\, x_1 \; x_2 \; x_3 \; x_4 \; x_5 \; x_6 \; x_7 \; x_8 \; x_9 \,]^T$
Control Matrix : $u = [\, u_1 \, u_2 \,]^T$
Disturbance Matrix : $d = [d_1 \, d_2 \,]^T$

$x_1 = \Delta f_1$; $x_2 = \Delta P_{t1}$; $x_3 = \Delta P_{g1}$; $x_4 = \Delta f_2$; $x_5 = \Delta P_{t2}$; $x_6 = \Delta P_{g2}$; $x_7 = \Delta P_{tie(1,2)}$; $x_8 = \int ACE_1 dt$; $x_9 = \int ACE_2 dt$; $d_1 = \Delta P_{d1}$; $d_2 = \Delta P_{d2}$

State Equations :

$\frac{d}{dt}x_1 = -\frac{1}{T_{p1}}x_1 + \frac{K_{p1}}{T_{p1}}x_2 - \frac{K_{p1}}{T_{p1}}x_7 - \frac{K_{p1}}{T_{p1}}d_1$ ……………………….(7)

$\frac{d}{dt}x_2 = -\frac{1}{T_{t1}}x_2 + \frac{1}{T_{t1}}x_3$ ……………………………………………….(8)

$\frac{d}{dt}x_3 = -\frac{1}{R_1T_{g1}}x_1 - \frac{1}{T_{g1}}x_3 + \frac{1}{T_{g1}}u_1$…………………………………....(9)

$\frac{d}{dt}x_4 = -\frac{1}{T_{p2}}x_4 + \frac{K_{p2}}{T_{p2}}x_5 + \frac{K_{p2}}{T_{p2}}x_7 - \frac{K_{p2}}{T_{p2}}d_2$ …………………………..(10)

$\frac{d}{dt}x_5 = -\frac{1}{T_{t2}}x_5 + \frac{1}{T_{t2}}x_6$ ………………………………………………. (11)

$\frac{d}{dt}x_6 = -\frac{1}{R_2T_{g2}}x_4 - \frac{1}{T_{g2}}x_6 + \frac{1}{T_{g2}}u_2$………………………………..….(12)

$\frac{d}{dt}x_7$ = 2*pi*T_0*x_1 - 2*pi*T_0*x_4 ……………………………………...(13)

$\frac{d}{dt}x_8$ = B_1*x_1 + x_7 …………………………………..……………….(14)

$\frac{d}{dt}x_9$ = B_2*x_4 - x_7 …………..…………(15)

The vector representation of above state equation is…..

$\frac{d}{dt}$ x = Ax + Bu + Jd ………………..…(16)

A = state matrix of dimension 9×9
B = control matrix of dimension 9*2
J = Disturbance matrix of dimension 9*2
x = state vector of dimension 9×1
u = control vector of dimension 2*1
d = Disturbance vector of dimension 2*1

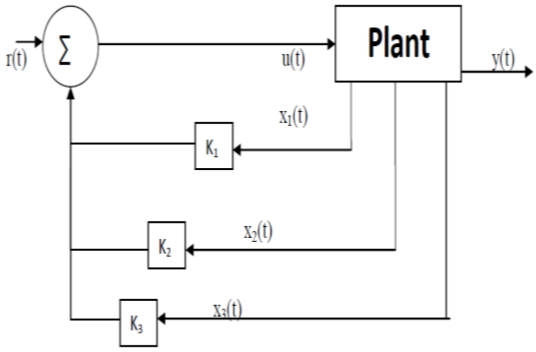
$$A=\begin{bmatrix} -\frac{1}{T_{p1}} & \frac{K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & -\frac{K_{p1}}{T_{p1}} & 0 & 0 \\ 0 & -\frac{1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{R_1T_{g1}} & 0 & -\frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{p2}} & \frac{K_{p2}}{T_{p2}} & 0 & \frac{K_{p2}}{T_{p2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_2T_{g2}} & 0 & -\frac{1}{T_{g2}} & 0 & 0 & 0 \\ 2\pi T_0 & 0 & -2\pi T_0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & B_2 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

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

$$J=\begin{bmatrix} -\frac{K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_{p2}}{T_{p2}} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

II. Design of Linear Quadratic Regulator

In this two area thermal system there are nine state variablesIn case of optimal control technique the inputs are taken as linear combination of all nine states being feedback [2].



The nine states being feedback are x_1, x_2 … x9 and the control inputs can be written as below:

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

$u_2=k_{21}x_1+k_{22}x_2+k_{23}x_3+k_{24}x_4+k_{25}x_5+k_{26}x_6+k_{27}x_7+k_{28}x_8+k_{29}x_9$ ………..…(18)

k is a (2*9) matrix called feedback gain matrix.

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

The state equation of the system

$\frac{d}{dt}x = Ax + Bu$ ………. (19)

Y= Cx …………. (20)

The equation for control input is given by : u= -kx ………..(21)

III. Determination Of Feedback Gain Matrix (k):

To design the optimal gain problem first we have to find out the feedback gain matrix by minimizing a performance index.

$PI = \frac{1}{2}\int_0^{inf} [x^T Qx + u^T Ru]dt$ …………….. (22)

Q= state weighing matrix which is real, symmetric and positive semi-definite
R= control weighing matrix which is real, symmetric and positive definite
The two matrices Q and R are obtained by the following requirements:

(i) The deviation of area control errors about the steady state values are minimized.

$ACE_1 = B_1\Delta f_1 + P_{tie(1,2)} = B_1x_1 + x_7$ …………..(23)
$ACE_2 = B_2\Delta f_2 - P_{tie(1,2)} = B_2x_4 - x_7$ ………..…(24)

(ii) The deviation of $\int ACEdt$ (x_8 and x_9) about the steady state values are minimized.

(iii) The deviations of control inputs (u_1 and u_2) about the steady state values are minimized.
By these considerations,

$PI=\frac{1}{2}\int_0^{inf} [(B_1 x_1 + x_7)^2 + (B_2x_4 - x_7)^2 + x_8^2 + x_9^2 + u_1^2 + u_2^2]dt$ …………………………………....(25)

$PI=\frac{1}{2}\int_0^{inf} [B_1^2 x_1^2 + 2 * B_1x_1x_7 + 2 * x_7^2 + B_2^2x_4^2 - 2 * B_2x_4x_7 + x_8^2 + x_9^2 + u_1^2 + u_2^2]dt$ ………………. (26)

The matrices Q and R can be represented as

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

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

The optimal control law is given by
U= -kx ……………... (27)
The feedback gain matrix 'k' is given by

k= $R^{-1}B^TS$……………(28)

Where 'S' is a real, symmetric and positive definite matrix which is obtained by solving the matrix Riccati equation given by

$A^TS + SA - SBR^{-1}B^TS + Q = 0$ ………..…...(29)
The overall closed loop equation with state feedback control is

$$\frac{d}{dt}x = Ax + B(-kx) = (A - B)x$$

$$= A_f x\text{……. … (30)}$$

The Eigen values of A_f will show the stability of the system with state feedback controller.

IV. Result

By putting the appropriate values of parameters, the matrices A, B, Q and R are calculated[1]. Proper MATLAB code is written in MATLAB-R2009b to obtain the matrices S, k and A_f. A MATLAB command [k,S]=lqr(A,B,Q,R) is being used in this case to find out the values of the matrices 'k' and 'S[6].

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

$$B=\begin{bmatrix}0 & 0 & 12.5 & 0 & 0 & 0 & 0 & 0 & 0\\0 & 0 & 0 & 0 & 0 & 12.5 & 0 & 0 & 0\end{bmatrix}^T$$

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

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

$$S = \begin{bmatrix} .179 & .212 & .0338 & -.046 & -.039 & -.0050 & .1026 & .330 & -0.0226 \\ .212 & .368 & .0664 & -.039 & -.057 & -.0092 & -.0673 & .461 & -0.0080 \\ .034 & .066 & .0123 & -.005 & -.009 & -.0016 & -.0219 & .080 & 0.0000 \\ -.046 & -.039 & -.0050 & .179 & .212 & .0338 & -.1026 & -.023 & 0.3305 \\ -.039 & -.057 & -.0092 & .212 & .368 & .0664 & .0673 & -.008 & 0.4615 \\ -.005 & -.009 & -.0016 & .0338 & .066 & .0123 & .0219 & .000 & 0.0800 \\ .103 & -.067 & -.0219 & -.1026 & .067 & .0219 & .6086 & .153 & -0.1527 \\ .330 & .461 & .0800 & -.0226 & -.008 & .0000 & .1527 & 1.854 & 0.0088 \\ -.023 & -.008 & -.0000 & .3305 & .461 & .0800 & -.1527 & .009 & 1.8540 \end{bmatrix}$$

$$k = \begin{bmatrix} 0.4226 & 0.8294 & 0.1538 & -0.063 & -0.115 & -0.020 & -0.2737 & 1.0 & 0.00 \\ -0.063 & -0.115 & -0.020 & 0.4226 & 0.8294 & 0.1538 & 0.2737 & 0.0 & 1.00 \end{bmatrix}$$

$\mathbf{A_f}$ =

$$\begin{bmatrix} -0.05 & 6 & 0 & 0 & 0 & 0 & -6 & 0 & 0 \\ 0 & -2.5 & 2.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ -10.4908 & -10.3673 & -14.4230 & 0.7871 & 1.4444 & 0.2504 & 3.4207 & -12.5000 & -0.0000 \\ 0 & 0 & 0 & -0.05 & 6 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2.5 & 2.5 & 0 & 0 & 0 \\ 0.7871 & 1.4444 & 0.2504 & -10.4908 & -10.3673 & -14.4230 & -3.4207 & -0.0000 & -12.5000 \\ 0.4442 & 0 & 0 & -0.4442 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0.425 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

The Eigen values of matrix $A_f$are

-13.0594; -13.0758;-1.0340 + 3.4077i ;-1.0340 - 3.4077i; -1.4791 + 2.5810i; -1.4791 - 2.5810i;-1.3520 ; -0.7439 ;-0.6887

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

Using PI controller the response of change in frequency and change in tie line power aregiven as

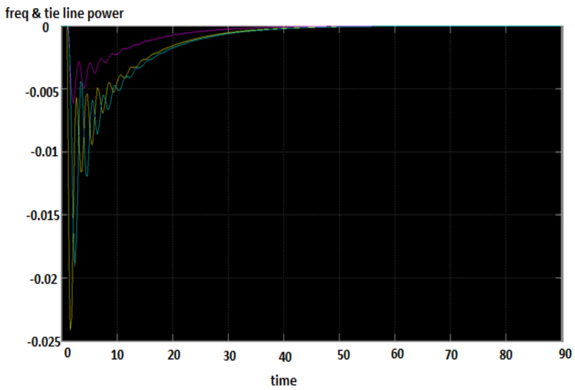


Fig.(3) : Response of frequency and tie line power interchange for 1% load variation

V. Conclusion

In this study, the optimal LQR controller is used to develop and secure the system performance when changes occur in the power system parameters. Using this optimal controller we can determine the stability of the system. With this high quality and performance controller, no modification is made in the controller structure against to change in parameters and loads. This demonstrates us that optimal LQR controller is more robust against to changes occur in the system than the other traditional controllers.

Appendix:
$T_{p1} = T_{p2} = 20$ sec; $K_{p1}= K_{p2} = 120$; $T_{t1} = T_{t2} = 0.4$ sec; $T_{g1} = T_{g2} = 0.08$
$R_1 = R_2 = 2.4$ Hz/p.u MW; $2\pi T_0 = 0.4442$; $B_1 = B_2 = 0.425$

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