# LQR Based LFC for Two Area Interconnected Power System with AC/DC Link

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## ABSTRACT

***Recently, LQR controllers have received extensive attention and research. Accordingly, there is an increasing interest in LQR controller. The widely used classical integer order proportional integral controller and proportional integral derivative controller are usually adopted in the load frequency control (LFC) and automatic generation control (AGC) to improve the dynamic response and to eliminate or reduce steady state errors. In this paper LQR controllers are used to improve dynamic stability and response of LFC and AGC system.This paper presents the MATLAB simulink dynamic model of the load frequency control (LFC) of a realistic two area power system having diverse sources of power generation. The DC link is used in parallel with AC tie line for the interconnection of power system. The power system simulation is done using MATLAB simulink and control problem is solved using MATLAB programming. An optimal output feedback controller with pragmatic viewpoint is presented. Optimal Gain settings of the output feedback controller with DC tie line are obtained following a step load disturbance in either area by minimizing the quadratic performance index. Simulation results show that the system with AC-DC parallel tie line achieves better performance in the presence of plant parameter changes and system nonlinearities.***

**Keywords:** *Automatic Generation Control (AGC), Area Control Error (ACE), Optimal Linear Quadratic Regulator (LQR), DC Link Introduction Introduction*

$\Delta F_i$ : Incremental change in frequency subscript referring to area (i=1,2,3; j=1,2,3)
$\Delta P_{gi}$: Incremental change in generator power output
$\Delta P_{di}$ : Incremental change in load demand
$\Delta X_{gi}$: Incremental change in governor valve position
$\Delta P_{tiei,j}$ : Incremental change in tie-line power (MW)
$T_p$: Electric system time constants
$R_i$ : Speed regulation parameter, Hz/p.u.MW
$T_{gi}$: Speed governor time constant of area, s
$K_{ri}$,$T_{ri}$: Reheat coefficient's & reheat time's

$B_i$ : Frequency bias constant (p.u.MW/Hz*)*
ΔACEi: Change in Area control error's
$T_{ti}$: Turbine time constants
$K_{gi}$: Speed governor gai***n***
$K_{t1}$: Reheat thermal turbine gain constant
Ti,j: Synchronizing coefficient of ac tie-line
A, B, C, System matrices associated with state, control, output
D: and disturbance vectors respectively
X, U, Y, State, control, output and disturbance vectors
Pd: respectively

## 1. INTRODUCTION

AGC regulates the power output of electric generators within prescribed area in response to changes in system frequency, tie-line loading, and relation of these to each other.This maintains the scheduled system frequency and established interchange with other areas within predetermined limits.The operation and control of these interconnected power systems is no longer a simple task for power engineers. In the event of availability of a suitable AGC scheme, the selection of proper approach for its effective implementation has a vital role [1-3].

Regulator design for interconnected power system AGC function is a multivariable system design problem and its effective study can be justified using modern control techniques for investigations [4-7]. The recent advancement in optimal control theory and availability of high speed digital computers coupled with enormous capability of handling large amount of data motivated the power system engineers/researchers to devise advanced AGC strategies.

Through various research publications, it has been established that with optimal control strategies designed using linear regulator theory, ameliorated system dynamic performance with greater stability margins as compared to that obtained with conventional AGC regulators can be achieved [10].

From the study of research papers reported in literature relating AGC of power systems, it is evident that almost all the works have been carried out considering area interconnection as AC transmission link. However, the works incorporate novel concepts relating to control aspects, power system structures and their operational and economic considerations. The transmission systems have gone through major changes in the form of transmitting electrical power at higher and higher voltage levels over the large distances. One of the major development in this area is the use of HVDC transmission systems on power scenario in India in late ninety's. Due to the inherent technical and economic merits of HVDC transmission systems over AC/EHVAC transmission systems, more DC Equations transmission systems up to a voltage level of 765 kV were developed in 2007 and more HVDC transmission systems have been envisaged for future [9].

Therefore, it becomes necessary to incorporate the dynamics of HVDC systems while designing the AGC scheme for interconnected power systems. A two-area interconnected power The requirements and benefits of using parallel AC/DC transmission links as system interconnection are highlighted [8, 9].This paper is dedicated to represent the optimal AGC regulator designs based on an optimal Linear Quadratic Regulator theory. The optimal AGC regulator is designed for a multi-area interconnected reheat type power system with AC Tie-line only and DC Link parallel with AC transmission lines considering 0.01 p.u.MW perturbation in one of the area are considered for the study. Power system dynamic performance has been studied by investigating the response plots of the disturbed areas ΔF1, ΔF2, ΔF3, ΔACE1, ΔACE2 and ΔACE3,with nominal system parameters.

***A. LQR controller***

The theory of optimal control is concerned with operating a dynamic system at minimum cost. The case where the system dynamics are described by a set of linear differential equations and the cost is described by a quadratic functional is called the LQ problem .The optimal control problem for a linear multivariable system with the quadratic criterion function is one of the most common problems in linear system theory. it is defined below:

***Given the completely controllable plant***

$$X^{\cdot} = AX + BU \qquad (1)$$

Where x is the n×1 state vector, **u** is the **p**×1input vector. A and B are, respectively $n \times n$ and $n \times p$ real constant matrices, and the null state x=0 is the desired steady-state.

***The control law***

$$U = -K\,x(t) \qquad (2)$$

K minimizes the following performance index subject to the initial conditions $X(0) \cong X^0$ ;

$$J = \frac{1}{2}\int_0^\infty (X^T Q X + U^T RU)dt \qquad (3)$$

Where Q is $n \times n$ positive definite, real, symmetric, constant matrix and R is $p \times p$ positive definite, real, symmetric, constant matrix. The optimal controller that minimizes the cost of the system in state variable form is a function of the present states of the system weighted by the components of a constant gain matrix K1 of dimension m*n and can be defined by .

K1 can be obtained from the solution of the reduced matrix Riccati equation given below

$$A^T P_1 + P_1 A - P_1 B R^{-1} B^T P_1 + Q = 0 \quad , \quad K = R^{-1} B^T P_1$$

The acceptable solution of K is that for which the system remains stable. For stability all the eigen values of the matrix (A-BK) should have negative real parts. From equation (4), we get the optimal control of our choice. So for it was assumed that all the states are available for feedback. Practically it is very difficult and costly to measure and to have readily available information of all the states in most of the large power systems. Usually reduced number of state variables or a linear combination thereof is available. The output feedback controller is as described below

$$U = -Kx \tag{5}$$

where K is an output feedback gain matrix of dimension (n×p). In the optimal control scheme the control inputs are generated by means of feedbacks from all the controlled output states with feedback constants to be determined in accordance with optimality criterion

There are several ways to solve this optimal control problem. we use the Lyapunov function approach.

Substituting (2) into (1), we obtain

$$X^{\cdot} = AX - BKX = (A - BK)X \tag{6}$$

Since the (A,B) pair is completely controllable, there exists a feedback matrix K such that (A-BK) is a stable matrix.

## 2. MULTI-AREA INTERCONNECTED POWER SYSTEM MODEL

The transfer function model of two area interconnected power system under consideration is shown in Fig. 2. The system dynamic equations in state space for this model can be givenas:

$$d/dt\,(X) = AX + B\,U + D\,P_d \tag{7}$$

$$Y = C\,X \tag{8}$$

Where, A, B, C & D are system state, control, measurement and disturbance matrices respectively and X, U, Y & $P_d$ are state, control, output and disturbance vectors of compatible dimensions respectively. From the transfer function model of Fig.2, the structure of vectors X, U and $P_d$ may be developed as follows

***System State Vector***

$[X] = [\Delta F_1\ \Delta P_{g1}\ \Delta P_{r1}\ \Delta X_{g1}\ \Delta F_2\ \Delta P_{g2}\ \Delta P_{r2}\ \Delta X_{g2}\ \Delta P_{tie}\ u_1\ u_2]^T$ Without DC link

Where

$u_1 = \int ACE_1 dt$ , $u_2 = \int ACE_2 dt$

$[X] = [\Delta F_1\ \Delta P_{g1}\ \Delta P_{r1}\ \Delta X_{g1}\ \Delta F_2\ \Delta P_{g2}\ \Delta P_{r2}\ \Delta X_{g2}\ \Delta P_{tie}\ u_1\ u_2\ \Delta P_{dc}]^T$ Parallel AC/DC link

***Control Vector***

$[U] = [\Delta P_{c1}, \Delta P_{c2}]^T$

***Disturbance Vector***

$[P_d] = [\Delta P_{d1}, \Delta P_{d2}]^T$

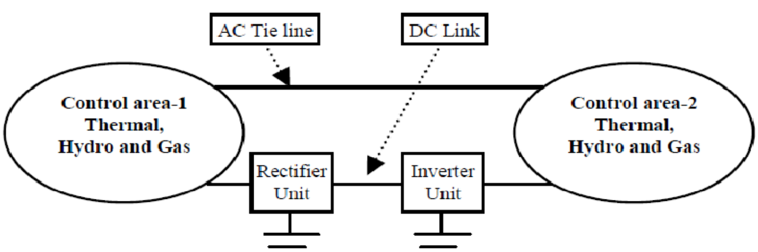


**Figure 1: Two equal area power system interconnected through AC-DC parallel tie lines**

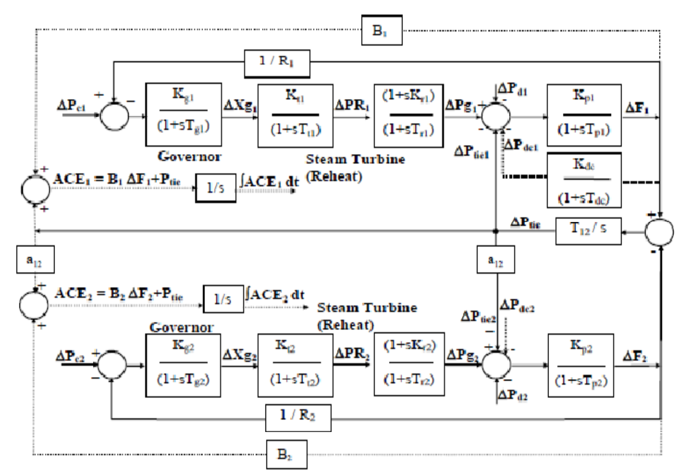


**Fig.2. Transfer Function Block diagram of Power System model**

## *3.* SYSTEM MATRICES

The matrices, A, B and D as appeared in equations (1) and (2) can be obtained using the structures of state, control and disturbance vectors and the transfer function model representation of Fig.1. Using the numerical values of system variables as given in Appendix, the corresponding coefficient matrices are derived as

$$A = \begin{bmatrix} -0.05 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & -6 & 0 & 0 \\ 0 & -0.1 & -1.566 & 1.666 & 0 & 0 & 0 & 0 & 0 & & 0 \\ 0 & 0 & -3.333 & 3.333 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -5.208 & 0 & 0 & -12.500 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.05 & 6 & 0 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.1 & -1.566 & 1.666 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -3.333 & 3.333 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -5.208 & 0 & 0 & -12.500 & 0 & 0 & 0 \\ 5.378 & 0 & 0 & 0 & -5.378 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.425 & 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$B^T = \begin{bmatrix} 0 & 0 & 0 & 12.500 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12.500 & 0 & 0 & 0 \end{bmatrix}$$

$$D^T = \begin{bmatrix} -6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -6 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The appropriate modification can be done in the structure of matrix ‘A’ to consider the area interconnection as AC link in parallel with DC link in power system model. Consideration of DC link dynamic model as state variable will have the additional non-zero elements of ‘A’ matrix as;

A(1, 12) = -5.988, A(12, 1) = 5.0, A(12, 12)= -5.0 The rest of the additional elements are zero.

### *Design Matrices*

The state cost weighting matrix ‘Q’ and control cost weighting matrix ‘R’ are selected as an identity matrix of compatible dimensions respectively.

## 4. SIMULATION RESULTS AND ANALYSIS

The optimum values of the for the output feedback controller by minimizing the cost function for the power system with AC tie line corresponding to nominal system parameters is K

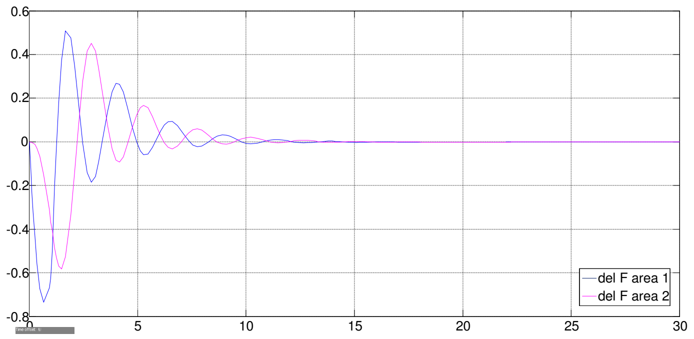


**Fig. 3 Dynamic Response of F for area 1 and 2 with aclink**

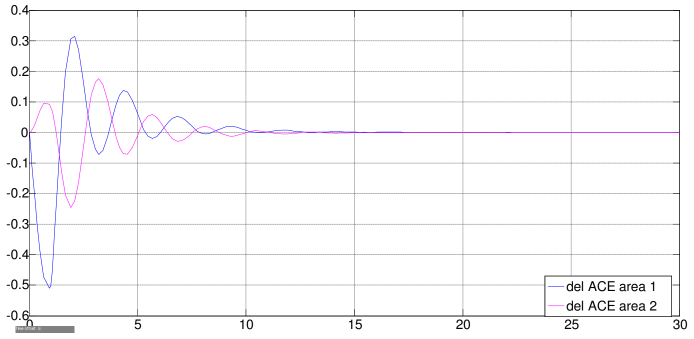


**Fig. 4 Dynamic Response of ACE for area 1 and 2 with ac link**

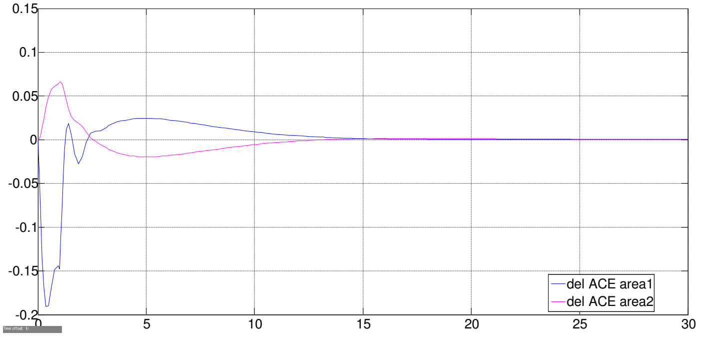


**Fig. 5 Dynamic Response of ACE for area 1 and 2 with ac-dc link**

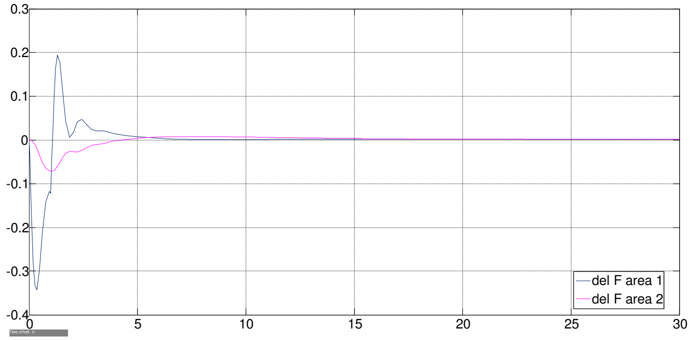


**Fig. 6 Dynamic Response of ΔF for area 1 and 2 with ac-dc link**

## 5. CONCLUSION

The system dynamic performance in the wake of load disturbance in either of the area of interconnected power system has been investigated. The optimal AGC regulator using LQR control strategy is designed and their feasibility is studied. This proposed optimal LQR gives much better results than the Integral regulator. The power system dynamic performance of reheat thermal power plants can be compensated effectively by incorporating DC link in parallel with AC Tie-line in place of AC Tie-line only as area interconnection between power system areas.

*TABLE I*

| Quantity | Symbol | | Quantity | Symbol | |
|---|---|---|---|---|---|
| nominal freq. | F | 50Hz | Electric system time constants | Tp1 = Tp2 | 20sec |
| Frequency bias constant | $B_1$=$B_2$ | 0.425 | Incremental change in load demand | $\Delta P_d$ | 0.02 p.u.MW |
| Speed regulation parameter, Hz/p.u.MW | $R_1$=$R_2$ | 2.4 Hz/ p.u. MW | Synchronizing coefficient of AC tie-line | $2\pi T_{12}$ | 0.545p.u.MW |
| Speed governor time constant of area, s | $T_{g1} = T_{g2}$ | 0.08 sec | | $a_{12}$ | -1 |
| Reheat coefficient's | $K_{r1} = K_{r2}$ | 0.5 sec | DC gain constant | $K_{dc}$ | 1 |
| reheat time's | $T_{r1} = T_{r2}$ | 10 sec | DCtime constant | $T_{dc}$ | 0.2 |
| Turbine time constants | $T_{t1} = T_{t2}$ | 0.3 sec g | Electric system gain | $K_{p1} = K_{p2}$ | 120 Hz/ p.u. MW |

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