Stability of Multi-Machine Power System by used LQG Controller

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Abstract:- This paper has been designed optimize feed-back controller for dynamic response of the power systems. The power system consists of the infinite bus through a transmission line supplied by a synchronous machine and also multi machine power system. The effect of two control signals fed to the voltage regulator and the mechanical system is investigated. Robust Linear quadratic Gawssian (LQG) control technique based power system stabilizer is developed for excitation system control and the mechanical system control. The proposed robust LQG-PSS is simple, effective, and can ensure that the system is asymptotically stable for all admissible uncertainties and abnormal operating conditions. To validate the effectiveness of the proposed power system stabilizer, a sample power system consists of multi machine and single machine are simulated and subject to different disturbance and parameter variations. Kalman Filter is used for compound with LQR to get robust LQG control. The results prove the robustness and powerful of proposed LQG controller stabilizer than LQR controller in terms of fast damping response and less settling time of power system states responses.

Key-word:- LQR controller , LQG controller, power system stabilizer and multi-machine power system

1 Introduction

Many papers have been published on the synthesis of the power system stabilizer (PSS) control system. Some approach it by complex frequency methods using the concept of synchronizing and damping torques [1, 2], some by optimal control methods and also, by using pole placement methods [3-5]. In control system designed a satisfactory controller cannot be obtained by considering the internal stability objective alone. The interconnected power system can be achieved by conventional controller as[1, 3]. A brief overview of the theoretical foundation of H_∞ synthesis is introduced in [7]. The H_∞ formulation and solution procedures are explained, and guidelines on how to choose proper weighting functions that reflect the robustness and performance goals are given in [8,9,10]. H_∞ synthesis is carried out in two stages. First, in what is called the H_∞ formulation procedure, robustness to modeling errors and weighting the appropriate input-output transfer functions usually reflects performance requirements. The weights and the dynamic model of the power system are then augmented into an H_∞ standard plant [9]. Second, in what is called the H_∞ solution procedure, the standard plat is programmed into a computer aided design software,

such as MATLAB[11], and the weights are iteratively modified until an optimal controller that satisfies the H_∞ optimization problem is found. Time response simulations are used to validate the results obtained and to illustrate the dynamic system response to state disturbances. The effectiveness of such controllers is examined at different extreme operating conditions. Using the linear quadratic regulator (LQR) for comparison with the proposed robust H_∞ controller.
The present paper used the LQR approach and Kalman filter to design a robust LQG power system stabilizer for stabilization the dynamic responses at different operating conditions.

2 Power System Model

Two power system models are studying in this research as follow:

2.1. Single machine model

A synchronous machine connected to infinite bus through transmission line is obtained in a an interconnected power system between automatic voltage regulation and load frequency control as shown in a block diagram of Fig.1. Where :

ω = the mechanical speed.
Δω = speed deviation
R = regulation constant.
μ_s = damping factor
K_A = exciter constant.
T_A = exciter time constant.
Δδ = change in torque angle.
ΔE_{fd} = change equivalent excitation voltage
$\Delta E'_q$ = change internal voltage behind transient reaction
K_1 to K_6 = constant of linear Zed model of synchronic machine

The state space formulation can be obtained as follows :

Steady-state Representation

$$\Delta \dot{\text{¢}} = \Delta w \quad (1)$$

$$\Delta \dot{w} = -(K_1/M)\Delta \text{¢} - (D/M)\Delta w - (K_2/M)\Delta E'q + (1/M)\Delta T_m - (1/M)\Delta P_d \quad (2)$$

$$\Delta \dot{E}'_q = -(K_4/T'do)\Delta \text{¢} - (1/K_3 T'do)\Delta E'q + (1/T'do)\Delta E_{fd} \quad (3)$$

$$\Delta \dot{T}_m = -(1/T_t)\Delta T_m + (1/T_t)\Delta P_g \quad (4)$$

$$\Delta \dot{P}_g = -(1/RT_g)\Delta w - (1/T_g)\Delta P_g + (1/T_g)U_2 \quad (5)$$

$$\Delta \dot{E}_{fd} = -(1/T_A)\Delta E_{fd} - (K_A K_5/T_A)\Delta \text{¢} - (K_A K_6/T_A)\Delta e'q + (K_A/T_A)U_1 \quad (6)$$

In a matrix form as follows:

$$\Delta \dot{X} = A\Delta X + B\Delta U + \text{¦}\Delta P_d \quad (7)$$

where;

$$\Delta X = \left[\Delta \text{¢} \quad \Delta \mu \quad \Delta E'_q \quad \Delta T_m \quad \Delta P_g \quad \Delta E_{fd}\right]^t$$

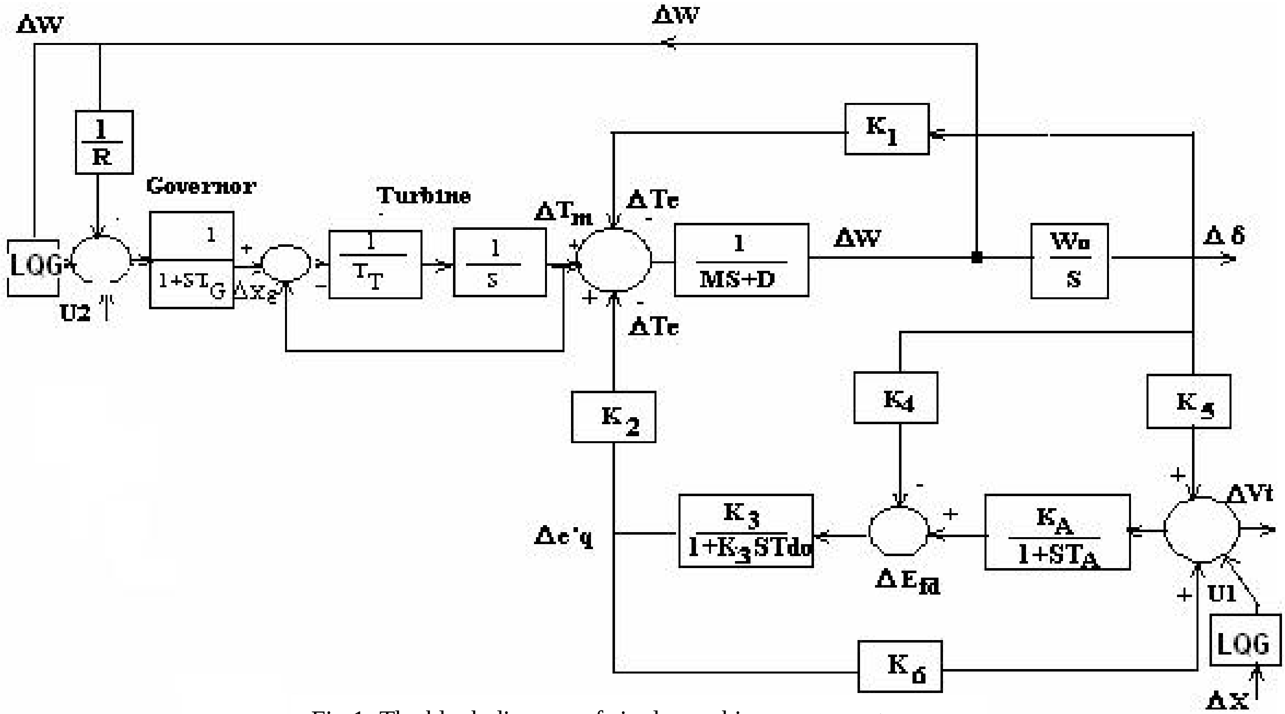

Fig.1: The block diagram of single machine power system.

$$A=\begin{bmatrix} 0 & wo & 0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & \frac{-D}{M} & \frac{-K_2}{M} & \frac{1}{M} & 0 & 0 \\ \frac{-K_4}{T_{do}^{'}} & 0 & \frac{-1}{(K_3 T_{do}^{'})} & 0 & 0 & \frac{1}{T_{do}^{'}} \\ 0 & 0 & 0 & \frac{-1}{T_t} & \frac{1}{T_t} & 0 \\ 0 & \frac{-1}{RT_g} & 0 & 0 & \frac{-1}{T_g} & 0 \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & 0 & 0 & \frac{-1}{T_A} \end{bmatrix}.$$

$$B=\begin{bmatrix} B_1 \\ B_2 \end{bmatrix}^t = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \frac{K_A}{T_A} \\ 0 & 0 & 0 & 0 & \frac{1}{T_g} & 0 \end{bmatrix}^t ,$$

$$\Delta U = [\Delta U_1 \quad \Delta U_2]^t \;\text{¦}\; = \begin{bmatrix} 0 & \frac{-1}{M} & 0 & 0 & 0 & 0 \end{bmatrix}^t$$

2.2. Multi-machine model

The power system in this model consists of three synchronous machines connected to infinite bus and its dynamic performance is represented in the state variables form. The single line diagram model for the system is shown in the Fig.2 and is based upon the following assumptions

1- Saturation is neglected,
2- Armature transformer voltage is neglected,
3- Damper winding effect is neglected.

Once the A, B and C matrices are determined, applying the Linear Quadratic Gaussian LQG controller on it. The multi machine power system data and load flow are displayed in tables 1, 2 [2, 12].

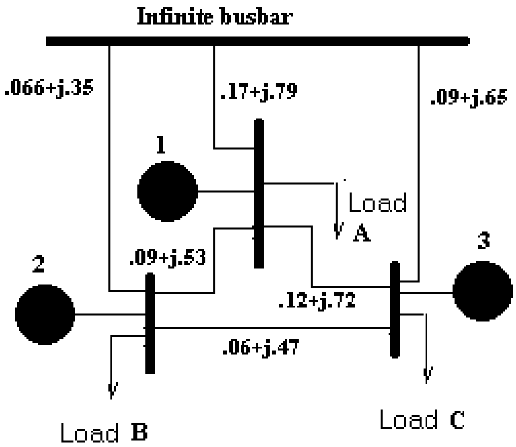

Fig.2: Three machine-infinite bus system.

Table 1: The Multi-machine Power System Data

M/C	Machine data							
	X_d	X_q	X_j	T_{do}	H	K_A	T_A	Base quantities
1	1.68	1.66	0.32	4.0	2.31	40.0	0.05	360 MVA, 13.8KV
2	0.88	0.53	0.33	8.0	3.40	45.0	0.05	503 MVA, 13.8KV
3	1.02	0.57	0.20	7.76	4.63	50.0	0.05	1673 MVA, 13.8KV

Table 2 : The Multi-machine load flow data.

Bus	Power flow P_o, MW	Q_o MVA	V_{to} pu.	¢ $_o$. degrees
1	26.5	37.0	1.3	10
2	518	-31.5	1.025	32.52
3	1582	-69.9	1.3	45.82
4	410.0	49.1	1.6	20.69

Each plant is represented by a 4th -order generator equipped with a static exciter. The state equation of this system is given by

$$\dot{X} = AX + BU \qquad (8)$$

Where

X = [ΔW1, ΔW2, ΔW3, Δ ¢ 1, Δ ¢ 2, Δ ¢ 3, Δ e'_q1, Δ e'_q2, Δ e'_q3, Δ $e_{FD}1$, Δ $e_{FD}2$, Δ $e_{FD}3]^T$
U = $[u_1 \quad u_2 \quad u_3]^T$
A = Matrix system
B = input matrix
Is the input vector .The system A and B are given as follows

$$A=\begin{bmatrix}
-0.039 & 0.004 & 0.02 & -0.147 & 0.022 & 0.046 & -0.013 & 0 & 0.003 & 0.0 & 0.0 & 0.0 \\
-0.034 & 0.032 & -0.028 & 0.004 & -0.149 & 0.079 & -0.00645 & -0.008 & 0.0 & 0.0 & 0.0 & 0.0 \\
-0.017 & -0.01 & -0.017 & 0.001 & 0.017 & -0.056 & -0.003 & 0.0 & -0.009 & 0.0 & 0.0 & 0.0 \\
377 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 377 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 377 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
-3.393 & 0.754 & 1.131 & -0.266 & -0.087 & -0.25 & -0.922 & 0.024 & 0.072 & 1 & 0.0 & 0.0 \\
1.131 & -1.885 & 0.754 & 0.121 & -1.6 & 0.46 & 0.021 & -0.21 & 0.06 & 0.0 & 1 & 0.0 \\
0.0 & 0.0 & -1.131 & 0.083 & 0.22 & -1.2 & -0.002 & 0.011 & -0.197 & 0.0 & 0.0 & 1.0 \\
-309.14 & -91.99 & -1675 & -30.1 & 24.599 & 62.051 & -60.943 & -3.501 & -10.194 & -20 & 0.0 & 0.0 \\
-64.47 & -516.11 & -171.91 & -18.48 & 106.09 & 16.99 & -12.55 & -21.67 & -11.41 & 0.0 & -20 & 0.0 \\
-33.93 & -46.37 & -893.49 & -10.1 & 1.7 & 70.1 & -6.78 & -2.1 & -54.4 & 0.0 & 0.0 & -20
\end{bmatrix}$$

$$B = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1000 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 900 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 800 & 0 & 0
\end{bmatrix}^T$$

3 Control Design Strategy

3.1 Optimal LQR control design

The object of the optimal control design is determining the optimal control law *u(t,x)* which can transfer system from its initial state to the final state such that given quadratic performance index is minimized.

$$[K_{LQR}, S, E] = lqr(A,B,Q,R,N) \qquad (9)$$

Where: Q is positive semi definite matrix and R is real symmetrical matrix. The problem is to find the vector feedback *K* of control law, by choosing matrix Q and R to minimize the quadratic performance index J is described by :

$$J = \int_0^{\infty} (\Delta x^t Q \; \Delta x + \Delta u^t R^{-1} \Delta u) dt$$

The optimal control law is written as

$$\Delta u(t) = K \, \Delta x(t)$$

$$K_{LQR} = - R^{-1} B^t P \qquad (10)$$

The matrix P is positive definite, symmetric solution to the matrix Riccati equation, which has written as:

$$P A + A^t P + Q - P B R^{-1} B^t P = 0 \quad (11)$$

3.2 optimal compensator LQG control

We have introduced the Kalman filter, which is an optimal observer for multi-output plants in the presence of process and measurement noise, modeled as white noises. The optimal compensator Linear Quadratic Gaussian (LQG) consists of combine between optimal LQR control and Kalman filter as shown in Figs.3,4. In short, the optimal compensator LQG design process is the following:

1- Design an optimal regulator LQR for a linear plant assuming full-state feedback (i.e. assuming all the state variables are available for measurement) and a quadratic objective function.
2- Design a Kalman filter for the plant assuming a known control input, u(t), a measured output, y(t), and white noises, v(t) and z(t). The Kalman filter is designed to improve an optimal estimate of the state-vector.
3- Combine the separately designed optimal regulator LQR and Kalman filter into an optimal compensator LQG.
4- The optimal regulator feedback gain matrix, K, and the Kalman filter gain matrix, L, are used to complete closed compensator system LQG as follows:

From Eq. 10 get optimal regulator gain matrix $\boldsymbol{K_{LQR}}$. Calculate the Kalman filter gain as follows. Let the system as

$$\dot{x} = Ax + Bu + Gw \quad \{\text{State equation}\} \quad (12)$$
$$y = Cx + Du + v \quad \{\text{Measurements}\}$$

with unbiased process noise **w** and measurement noise **v** with covariance's

$$E\{ww'\} = Q, \quad E\{vv'\} = R, \quad E\{wv'\} = N,$$

$$[L,P,E] = LQE(A,G,C,Q,R,N) \quad (13)$$

Returns the observer gain matrix ***L*** such that the stationary Kalman filter.

$$x\_e = Ax\_e + Bu + L(y - Cx\_e - Du)$$

Produces an optimal state estimate ***x_e*** of ***x*** using the sensor measurements ***y.*** The resulting Kalman estimator can be formed with estimator. The noise cross-correlation ***N*** is set to zero when omitted. Also returned are the solution ***P*** of the associated Riccati equation.

$$AP+PA'-(PC'+G*N)R(CP+N'*G')+G*Q*G'=0 \quad (14)$$

and the estimator poles ***E = EIG(A-L*C).***

Using MATLAB function readymade command ***reg*** to construct a state-space model of the optimal compensator LQG, given a state-space model of the plant, ***sysp***, the optimal regulator feedback gain matrix ***K***, and the Kalman filter gain matrix ***L***. This command is used as follows:

$$sys\_closed = reg(sysp, K_{LQR}, L) \quad (15)$$

Where;
sys_closed is the state-space model of the **LQG** compensator. The final, get the system overall feedback ***sysCL*** as:

$$sysCL = feedback(sysp, \quad sys\_closed) \quad (16)$$

Where, sysCL is the state-space of **LQG** plus state-space of system with open-loop

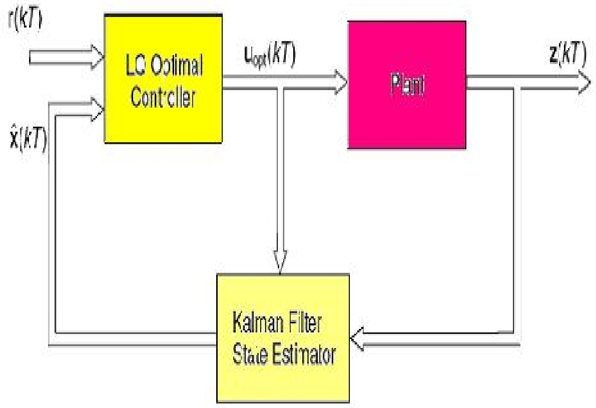

Fig. 3: Linear Quadratic Gaussian (LQG) control system.

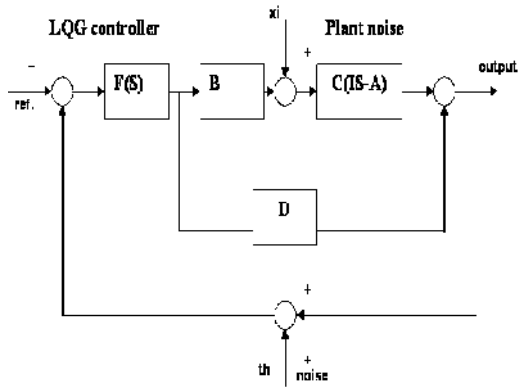

Fig.4 : The LQG synthesis.

Where: A = system matrix
B = control matrix
C = output matrix
S =laplace operator

3.3 State estimation using Kalman filter

Alternatively, it is possible to estimate the whole state vector by using a Kalman filter. The Kalman filter optimally filters noise in the measured variables and allows the estimation of unmeasured states. The Kalman filter uses a model of the system to find a state estimate **ˆx(t)** by integrating the following state observer equation:

$$\dot{\hat{x}} = A\hat{x} + Bu + K_f(y_m - C\hat{x}) \quad (17)$$

where y_m is the measured output and K_f is the Kalman filter gain. The Kalman filter assumes that the measurements obey the following model:

$$\dot{x} = Ax + Bu + Gw$$
$$y_m = Cx + v \quad (18)$$

Where **G** is a noise distribution matrix, ***w*** and ***v*** are white noise processes. v is the measurement noise and is assumed to have a covariance matrix $\boldsymbol{R_f}$. w is known as process noise and is assumed to have a covariance matrix $\boldsymbol{Q_f}$. The Kalman filter gain $\boldsymbol{K_f}$ is found as follows:

$$K_f = PC^T R_f^{-1}$$

where ***P*** is the solution of the algebraic Ricatti equation:

$$AP + PA^T + GQ_fG^T - PC^T R_f^{-1} CP = 0 \quad (19)$$

If we use the control law given in Equation 17 with a state estimate obtained using a Kalman filter, then we are using the LQG (Linear Quadratic Gaussian) control law:

$$u = -K\hat{x} \quad (20)$$

4 Digital Simulation Results

4.1 Simulation of single machine model

From LQR control (Eqn. 10), the feedback gain and solution of Reccati equation are :

$$K_{LQR} = \begin{bmatrix} 0.0655 & -3.9708 & 0.4493 & 0.0040 & -0.1071 & 0.0831 \\ -0.0214 & 1.7302 & -0.1779 & -0.0015 & 0.0413 & -0.0032 \end{bmatrix}$$

$$S = 1000* \begin{bmatrix} 0.0004 & 0.0025 & -0.0005 & 0.0000 & -0.0002 & 0.0000 \\ 0.0025 & 1.6524 & -0.1226 & -0.0005 & 0.0138 & -0.0010 \\ -0.0005 & -0.1226 & 0.0293 & -0.0001 & -0.0014 & 0.0001 \\ 0.0000 & -0.0005 & -0.0001 & 0.0000 & -0.0000 & 0.0000 \\ -0.0002 & 0.0138 & -0.0014 & -0.0000 & 0.0003 & -0.0000 \\ 0.0000 & -0.0010 & 0.0001 & 0.0000 & -0.0000 & 0.0000 \end{bmatrix}$$

From LQG and Kalman filter control (Eqn. 13), the observer gain matrix ***L*** and solution of reccati equation P are :

$$L = \begin{bmatrix} 14.4339 & 0.2762 \\ 0.2762 & 0.0156 \\ -0.1471 & -0.0007 \\ 8.7476 & 0.0534 \\ 0.0390 & 0.0006 \\ -0.1305 & -0.0043 \end{bmatrix}$$

$$P = \begin{bmatrix} 21.7952 & 0.4171 & -0.2221 & 13.2088 & 0.0589 & -0.1971 \\ 0.4171 & 0.0235 & -0.0010 & 0.0806 & 0.0009 & -0.0065 \\ -0.2221 & -0.0010 & 0.0559 & -0.7356 & -0.0006 & 0.0010 \\ 13.2088 & 0.0806 & -0.7356 & 17.4002 & 0.0380 & -0.0708 \\ 0.0589 & 0.0009 & -0.0006 & 0.0380 & 0.0326 & -0.0025 \\ -0.1971 & -0.0065 & 0.0010 & -0.0708 & -0.0025 & 0.0115 \end{bmatrix}$$

Table 3: Eigen values calculation with and without controllers of single machine power system.

Operating point	Without control	LQR-Control	With Kalman	LQG+Feedback Control
P=1, Q=0.25 pu. Lag p.f load	-0.0367 +6.9961i -0.0367 - 6.9961i -14.2953 -12.4821 -2.7625 -3.7201	-1.1161 + 7.2542i -1.1161 - 7.2542i -43.3537 -14.2787 -5.6556 -2.9596	-7.24 +10.0732i -7.24 -10.0732i -14.3023 -12.4881 -3.7076 -2.8026	-7.2411 +10.0732i -7.2411 -10.0732i -1.1161 + 7.2542i -1.1161 - 7.2542i -43.3537 -14.3023 -14.2787 -12.4881 -5.6556 -3.7076 -2.8026 -2.9596
P=1, Q= -0.25 pu Lead p.f	0.1033 + 6.3047i 0.1033 - 6.3047i -14.9008 -12.4804 -2.4303 -3.7285	-1.2812 + 6.6267i -1.2812 - 6.6267i -6.1062 -1.5921 -43.3498 -14.8640	-2.28 + 6.6889i -2.28 - 6.6889i -3.7220 -2.3389 -14.9022 -12.4809	-1.2812 + 6.6267i -1.2812 - 6.6267i -2.2857 + 6.6889i -2.2857 - 6.6889i -14.9022 -14.8640 -12.4809 -6.1062 -1.5921 -2.3389 -3.7220 -43.3498

Figure 5 shows the rotor angle deviation response due to 0.1 load disturbance with and without LQG and LQR controllers at lag power factor load (P=1, Q=0.25 pu). Fig.6 depicts the rotor speed deviation response due to 0.1 load disturbance with and without LQG and LQR controllers at lag power factor load (P=1, Q=0.25 pu). Fig. 7 shows the rotor speed deviation response due to 0.1 load disturbance with LQG compared with LQR controllers at lag power factor load (P=1, Q=0.25 pu). Fig. 8 displays the rotor speed deviation response due to 0.1 load disturbance with LQG compared with LQR controllers at lead power factor load (P=1, Q= - 0.25 pu). Fig. 9 shows the rotor speed deviation response due to 0.1 load disturbance with and without LQG and LQR controllers at lead power factor load (P=1, Q= -0.25 pu) .Moreover, Table 3 displays the Eignvalues calculation with and without controllers for single machine power system. Also, Table 4 shows the Settling time for single machine model with and without controllers

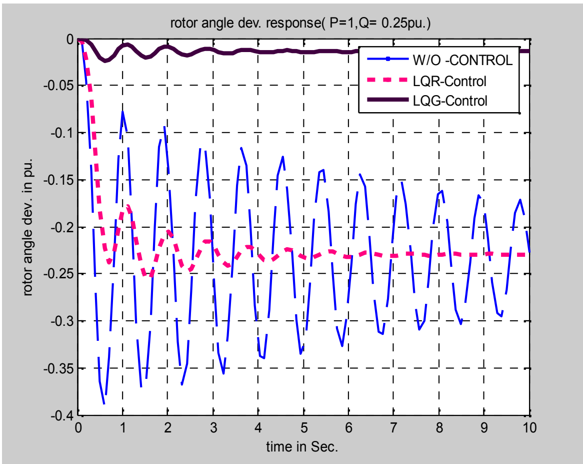

Fig.5: Rotor angle dev. Response due to 0.1 load disturbance with and without LQG and LQR controllers at lag power factor load (P=1, Q=0.25 pu).

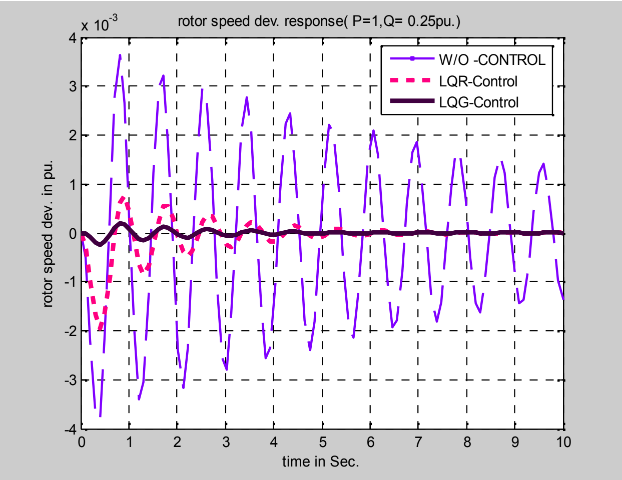

Fig.6: Rotor speed dev. Response due to 0.1 load disturbance with and without LQG and LQR controllers at lag power factor load (P=1, Q=0.25 pu).

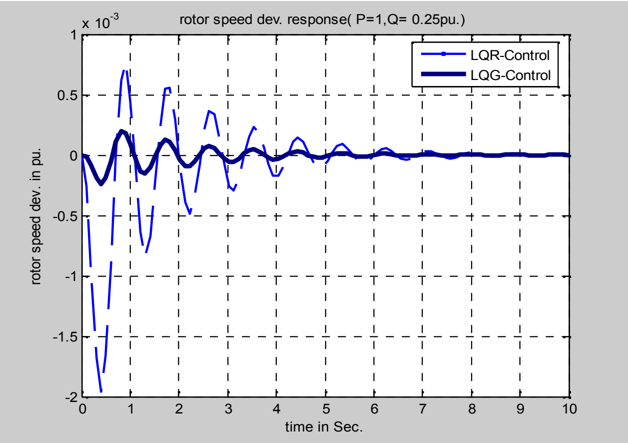

Fig. 7: Rotor speed dev. Response due to 0.1 load disturbance with LQG compared with LQR controller at lag power factor load (P=1, Q=0.25 pu).

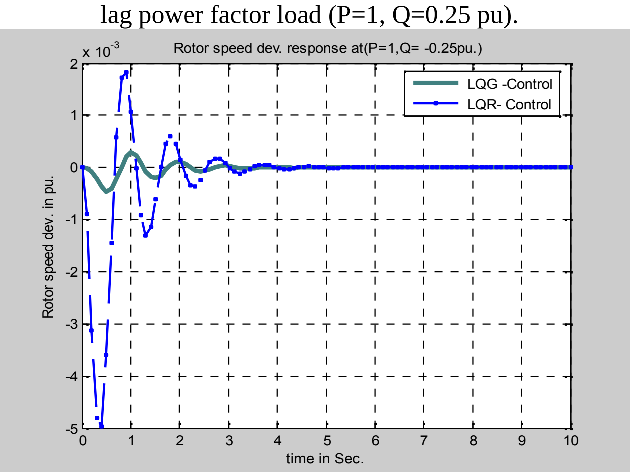

Fig. 8: Rotor speed dev. Response due to 0.1 load disturbance with LQG compared with LQR controller at lead power factor load (P=1, Q= - 0.25 pu).

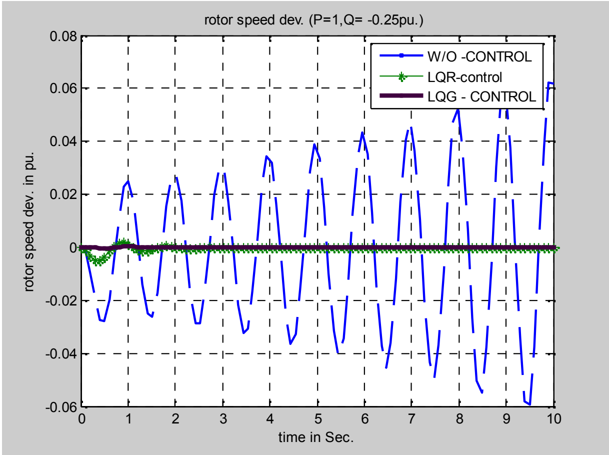

Fig. 9: Rotor speed dev. Response due to 0.1 load disturbance with and without LQG and LQR controllers at lead power factor load (P=1, Q= -0.25 pu).

Table 4: Settling time for single machine model with and without controllers

	States	Without Control	LQR-Control	LQG-Control
P=1, Q=0.25 pu.	Rotor Speed	> 10 Sec.	7 Sec.	4 Sec.
	Rotor Angle	>10 Sec.	5 Sec.	2.5 Sec.
P=1, Q= -0.25 pu.	Rotor Speed	∞	3.5 Sec.	2 Sec.
	Rotor Angle	∞	2 Sec.	0.5 Sec.

4.2 Simulation results of multi-machine system

From LQR control (Eqn. 10), the feedback gain is:

$$K_{LQR}=\begin{bmatrix} -0.3427 & -0.9033 & -6.1716 & 0.0007 & -0.0034 & 0.1117 & 0.0077 & 0.0023 & 0.0222 & 0.0004 & 0.0001 & 0.0033 \\ -0.1203 & -0.3101 & -5.3269 & -0.0314 & 0.2118 & -0.0105 & 0.0051 & 0.0232 & 0.0090 & 0.0004 & 0.0171 & 0.0005 \\ -0.0014 & -0.0060 & -0.0310 & -0.0000 & 0.0001 & 0.0002 & 0.0000 & 0.0000 & 0.0001 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix}$$

From LQG and Kalman filter control (Eqn. 13), the observer gain matrix L and solution of reccati equation P for multimachine power system are calculated as:

$$P = 1.0e+005 * \begin{bmatrix} 0.0001 & 0.0000 & 0.0000 & 0.0001 & 0.0004 & 0.0009 & 0.0005 & -0.0001 & -0.0000 & 0.0011 & 0.0027 & 0.0026 \\ 0.0000 & 0.0001 & 0.0000 & -0.0003 & 0.0001 & 0.0010 & -0.0007 & -0.0023 & -0.0005 & 0.0030 & -0.0041 & 0.0041 \\ 0.0000 & 0.0000 & 0.0001 & -0.0009 & -0.0010 & 0.0002 & -0.0017 & -0.0027 & -0.0017 & -0.0016 & -0.0015 & -0.0002 \\ 0.0001 & -0.0003 & -0.0009 & 0.2884 & 0.1248 & 0.1732 & 0.0556 & 0.1493 & 0.0834 & 0.1157 & 0.3554 & 0.3037 \\ 0.0004 & 0.0001 & -0.0010 & 0.1248 & 0.3536 & 0.2411 & 0.1331 & 0.2132 & 0.1238 & 0.6116 & 1.5001 & 0.5219 \\ 0.0009 & 0.0010 & 0.0002 & 0.1732 & 0.2411 & 0.5262 & 0.1730 & 0.3027 & 0.1688 & 0.9288 & 0.9817 & 1.1909 \\ 0.0005 & -0.0007 & -0.0017 & 0.0556 & 0.1331 & 0.1730 & 0.1409 & 0.2372 & 0.1310 & 0.3025 & 0.4897 & 0.3297 \\ -0.0001 & -0.0023 & -0.0027 & 0.1493 & 0.2132 & 0.3027 & 0.2372 & 0.5376 & 0.2360 & 0.3970 & 0.6862 & 0.4796 \\ -0.0000 & -0.0005 & -0.0017 & 0.0834 & 0.1238 & 0.1688 & 0.1310 & 0.2360 & 0.1333 & 0.2607 & 0.3948 & 0.2980 \\ 0.0011 & 0.0030 & -0.0016 & 0.1157 & 0.6116 & 0.9288 & 0.3025 & 0.3970 & 0.2607 & 2.4141 & 2.8773 & 2.5029 \\ 0.0027 & -0.0041 & -0.0015 & 0.3554 & 1.5001 & 0.9817 & 0.4897 & 0.6862 & 0.3948 & 2.8773 & 7.2526 & 2.3344 \\ 0.0026 & 0.0041 & -0.0002 & 0.3037 & 0.5219 & 1.1909 & 0.3297 & 0.4796 & 0.2980 & 2.5029 & 2.3344 & 3.0502 \end{bmatrix}$$

$$L = \begin{bmatrix} 5.6175 & 0.5023 & 0.5642 \\ 0.5023 & 6.2919 & 0.7404 \\ 0.5642 & 0.7404 & 5.1533 \\ 5.5492 & -18.7586 & -61.8858 \\ 29.3742 & 6.6030 & -64.0363 \\ 57.6099 & 67.9089 & 10.6301 \\ 31.0354 & -45.7872 & -109.9142 \\ -6.6915 & -153.5171 & -175.6031 \\ -2.9718 & -33.9607 & -114.5776 \\ 74.3507 & 197.8533 & -103.3462 \\ 180.2242 & -269.7776 & -97.1338 \\ 169.9381 & 272.6171 & -16.0888 \end{bmatrix}$$

Figure 10 depicts the rotor speed deviation response due to 0.1 load disturbance with and without LQG control of M/C-1. Fig.11 shows the rotor speed deviation response due to 0.1 load disturbance with and without LQG control of M/C-2. Also, Fig.12 shows the rotor speed deviation response due to 0.1 load disturbance with LQG compared with LQR controllers of M/C-2. Fig. 13 depicts the rotor speed deviation response due to 0.1 load disturbance with and without LQG control of M/C-3. Fig.14 shows the rotor speed deviation response due to 0.1 load disturbance with and without LQG and LQR control of M/C-3. Moreover, Fig. 15 depicts the rotor speed deviation response due to 0.1 pu load disturbance with LQR control for three machines. Also, Fig. 16displays the rotor speed deviation response due to 0.1 pu load disturbance with LQG control for three machines. Table 5 displays the Settling time for multi-machine model with and without controllers. Also, table 6 shows the Eignvalues calculation with and without controllers of multi- machine model

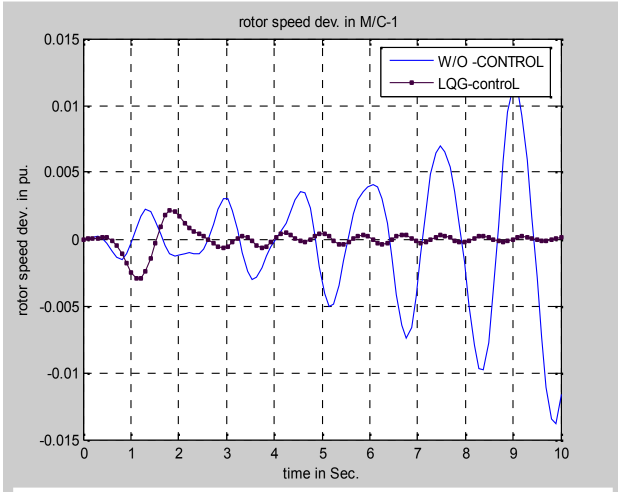

Fig. 10: Rotor speed dev. Response due to 0.1 load disturbance with and without LQG control of M/C-1.

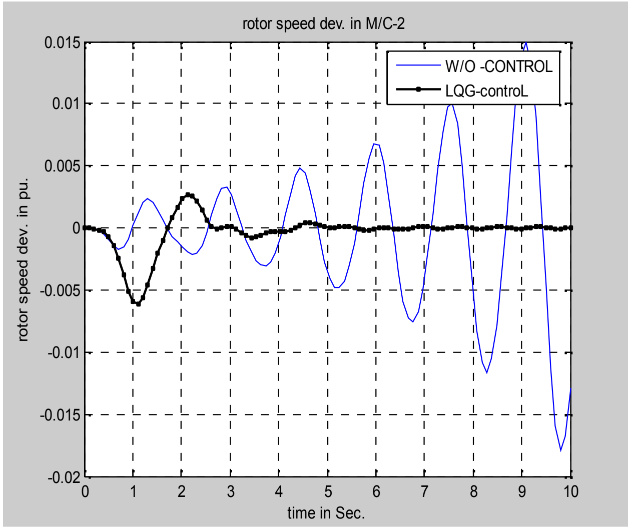

Fig.11: Rotor speed dev. Response due to 0.1 load disturbance with and without LQG control of M/C-2.

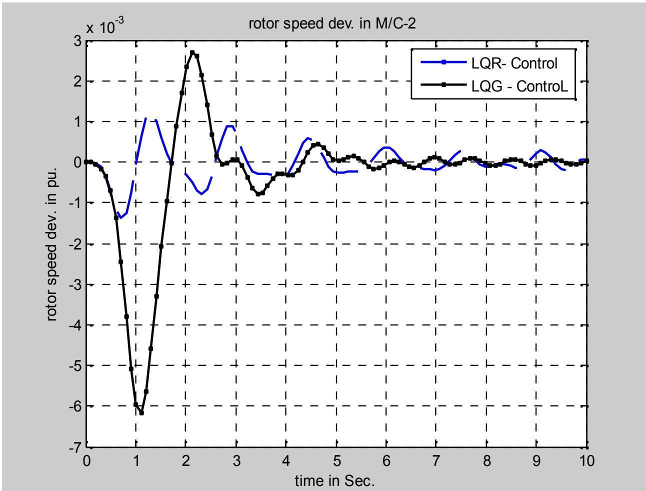

Fig.12: Rotor speed dev. Response due to 0.1 load disturbance with LQG and LQR controllers of M/C-2.

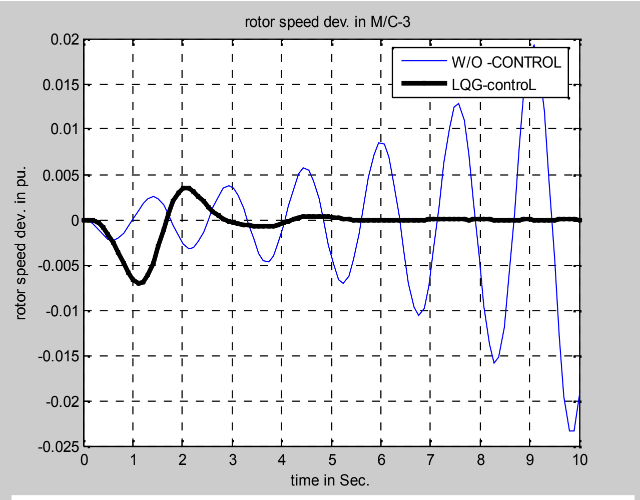

Fig. 13: Rotor speed dev. Response due to 0.1 load disturbance with and without LQG control of M/C-3.

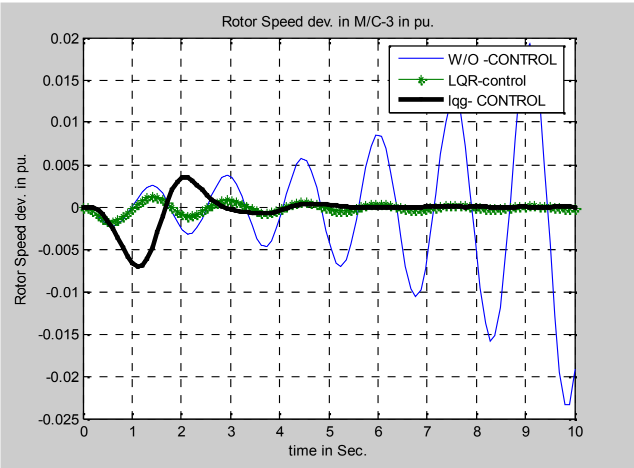

Fig.14: Rotor speed dev. Response due to 0.1 load disturbance with and without LQG and LQR control of M/C-3.

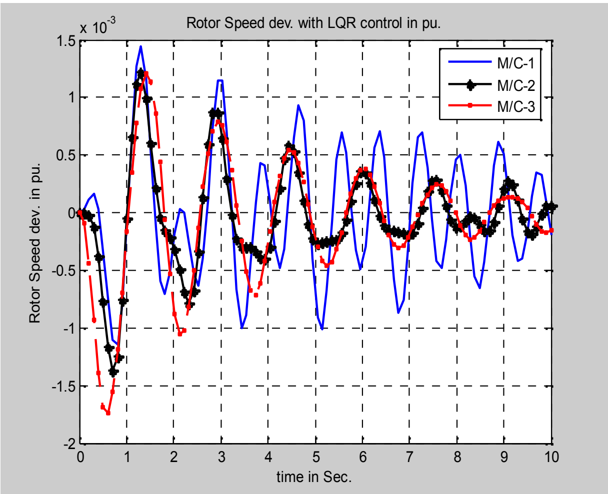

Fig. 15: Rotor speed dev. Response due to 0.1 pu load disturbance with LQR control for three machines.

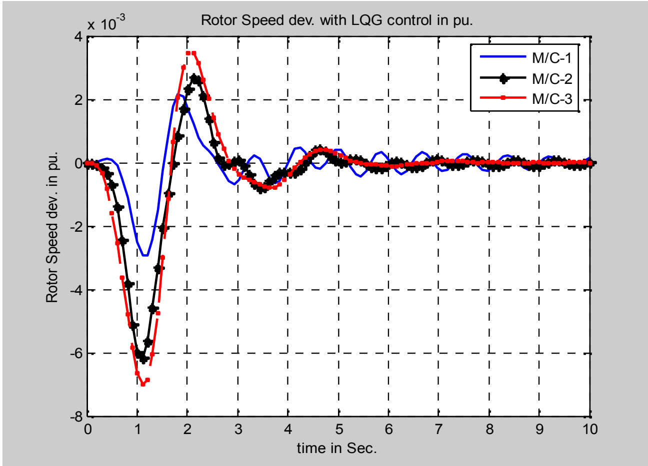

Fig. 16: Rotor speed dev. Response due to 0.1 pu load disturbance with LQG control for three machines.

Table 5: Settling time for multi-machine model with and without controllers

Operating Point	Rotor speed of	Without controller	With LQR-Control	With LQG – Control
P=1, Q=0.25 pu	M/C-1	∞	12 Sec.	7 Sec.
	M/C-2	∞	9 Sec.	5.5 Sec.
	M/c-3	∞	5 Sec.	3 Sec

5 Discussion

From Table 6, the eignvalues with the Linear Quadratic Gaussian controller(LQG) is the best than Linear Quadratic Regulator (LQR) controller. Kalman Filter using with the regulator LQR to produced the LQG. Also, Table 5 displays the decreasing in the settling time for three machines with using LQG controller than other controller. Moreover, the three machines on multi machine system are unstable without control but with proposed LQG controller all machine become stable with less settling time.

Table 6: Eigen values calculation with and without controllers of multi- machine model

	Without control	With LQR	With Kalman	With LQG	With LQG + Feedback control
Certain Operating Point	-18.8713 -15.1893 -17.0519 0.0953 + 7.8364i 0.0953 - 7.8364i -0.0627 + 7.3692i -0.0627 - 7.3692i 0.2637 + 4.0915i 0.2637 - 4.0915i -5.8914 -3.4305 -1.5112	-34.1322 -19.5804 -15.7307 -0.0721 + 7.8603i -0.0721 - 7.8603i -0.0776 + 7.3715i -0.0776 - 7.3715i -0.2581 + 4.0793i -0.2581 - 4.0793i -5.5632 -3.0683 -1.1913	-18.8684 -17.0507 -15.1612 -2.7296 + 7.4647i -2.7296 - 7.4647i -2.8210 + 7.0795i -2.8210 - 7.0795i -6.4027 -2.4204 + 2.8257i -2.4204 - 2.8257i -3.4688 -1.5217	-34.1388 -19.6481 -15.7647 -2.9275 + 7.5560i -2.9275 - 7.5560i -2.8056 + 7.1482i -2.8056 - 7.1482i -4.1097 + 3.2205i -4.1097 - 3.2205i -4.7248 -2.0980 -1.0843	-34.1250 -19.5046 -18.8652 -17.0493 -15.6930 -15.1210 -0.2888 + 7.9098i -0.2888 - 7.9098i -0.0909 + 7.3805i -0.0909 - 7.3805i -2.4990 + 7.3546i -2.4990 - 7.3546i -2.8479 + 6.9797i -2.8479 - 6.9797i -0.9751 + 4.7816i -0.9751 - 4.7816i -7.5320 -0.8193 + 2.4713i -0.8193 - 2.4713i -5.7117 -3.6632 -3.3731 -1.2828 -1.5345

6 Conclusion

The present paper introduces an application of a robust linear quadratic Gaussian LQG controller to design a power system stabilizer. The LQG optimal control has been developed to be included in power system in order to improve the dynamic response and give the optimal performance at any loading condition. The LQG controller design gives good performance in terms of fast damping dynamic oscillation. The LQG is better than LQR controller in terms of small settling time and less overshoot and under shoot. The digital results show that the proposed PSS based upon the LQG can achieve good performance over a wide range of operating conditions.

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