

Optimal Controller Design for a Turbogenerator Automatic Voltage Regulator and Governor using Two Degree of Freedom Linear Quadratic Gaussian (2DOFLQG)

Firas M. Tuaimah
University of Baghdad
Baghdad, Iraq

Nihad M. Al-Rawi
University of Baghdad
Baghdad, Iraq

Waleed A. Mahmoud
University of Baghdad
Baghdad, Iraq

ABSTRACT

This paper introduces a computational methodology that adopted a method of Linear Quadratic Gaussian (LQG) controller as Automatic Voltage Regulator (AVR) and Governor to control the generator terminal voltage and the turbine speed. In this method the models were assumed to be Linear, depending on this method the controller power consumption was minimized depending on some performance index, which is assumed to be Quadratic. This method was taken into account the noise and the disturbance in view, considered its distribution as Gaussian. The two degree of freedom (2DOF) structure was adopted, in which two controllers are used. The effectiveness of the proposed control action is demonstrated through some computer simulations on a Single-Machine Infinite- Bus (SMIB) power system.

To accommodate stability requirements, a mathematical model for the generator and the turbine was derived based on the two-axis theorem and starting from the swing equation. Results obtained show that adopting such a controller enhanced the steady state and transient stability.

Keywords

LQG control, generator and turbine modeling, two degree of freedom, damping torque

1. INTRODUCTION

The oldest power generating plants were supplied with continuously acting automatic voltage regulators.

When the number of power plants with AVR increased, it became obvious that the high performance of these voltage controllers or regulators had a destabilizing effect on the power system. Power oscillations of small magnitude and low frequency often sustained for long durations of time. In some cases, this presented a restriction on the amount of power that can be transmitted within the system. Power system stabilizers were developed to add damping torque coefficients of these power oscillations by modulating the excitation supplied to the synchronous machine [1].

The prime mover plays an essential role in causative to the stability of the whole system. Optimum transient response of a closed loop control system to an external disturbance depends not just on the transfer function of the excitation controller, generator and sensors but also the speed/load controller as well [2].

Keeping frequency within adequate limits requires to continuously maintaining a balance between resources and loads. This security action is performed by the Load Frequency

Control (LFC). The LFC induces output variations to generating units, through the operation of Speed Governor, Automatic Generation Control (AGC) and through operator actions [2].

Latest efforts in designing the power system controllers are based on some adaptive and optimal control techniques like

Artificial Neural Network (ANN), Fuzzy logic, Genetic algorithm, Pole placement, Linear Quadratic Regulator (LQR) and on the robust controllers like LQG (H2) and (H ∞).

R. Asgharian and D.C. Macdonald [3] suggested an optimal linear control system for designing auxiliary signal controllers for turbine generators. The design take into the concern the torsional mode oscillation of the rotor to obtain the best performance.

Ranjan Vepa [4] proposed a nonlinear rotor-side controller (RSC) for a wind turbine generator based on nonlinear, LQG optimal control theory. The goal is to express the synthesis of a maximum power point tracking.

Youssef A. Smaili and Ali T. Alouani [5] investigates the application of H-infinity optimal control theory for designing the supplementary excitation and governor control system to improve the stability and performance robustness of an electric power system.

M. Djukanovic et. al. [6] presents a design technique of a new adaptive optimal controller of the low head hydropower plant using artificial neural networks (ANN). Results obtained on the non-linear mathematical model demonstrate that the effects of the NNC closely agree with those obtained using the state-space multivariable discrete-time optimal controllers.

F. Fatehi et.al. [7] presents a combined system identification and controller design methods to dampen low-frequency oscillations in multimachine power systems with Linear quadratic Gaussian controller design with loop transfer recovery.

Gui-chen Zhang [8] proposed an LQG control scheme for output power leveling with unknown dynamics for running of unstable speed exhaust turbine generator using main engine waste heat by high turbulence intensities,

Feilat and Younan [9] Presents an on-line optimal approach for dynamic stability assessment of single-machine infinite-bus system. The approach is based on estimating the synchronizing and damping torque Coefficients of the synchronous machine. The coefficients are estimated from the time responses of the changes in the rotor angle, rotor speed, and electromagnetic torque. These coefficients can be used as indices to provide

insight into the relative stability of the synchronous machine. This approach results in a remarkable reduction in the computational complexity associated with this problem and hence allow for on-line implementation needed for continuous monitoring of the dynamic stability indices.

T. C. Yang et al. [10] designed a decentralized robust load frequency control (LFC) for interconnected power system. This design based on a new Linear Quadratic Regulator design approach.

The interest in designing the optimal and robust controllers has increased tremendously in the last few years because of its rigidity and stability.

In this paper, a mathematical model or a state equation of the turbine and the generator in its standard form has been developed, which is based on the two-axis theorem and starting from the swing equation. This model can be used to simulate the machine behavior under healthy (steady-state) and faulty conditions (transient-state).

2. SOFTWARE IMPLEMENTATION

In this paper to investigate the effectiveness of adopting the LQG controller as AVR and as Governor, the conventional AVR and the conventional Governor was also adopted for comparison. The two degree of freedom 2DOF structure was used in designing the LQG controller. Controller performance will be expressed in terms of performance indices used in feedback control system theory. A 555MW turbogenerator whose details are given in the Appendix A is taken as an example to which the software is employed.

3. TURBINE & GENERATOR MATHEMATICAL MODELLING

Depending on the swing equation viewpoint which is the equations of central importance in power system stability analysis are the rotational inertia equation describing the effect of unbalance between the electromagnetic torque and the mechanical torque of the individual machines.[2]

When there is an unbalance between the torque acting on the rotor, the net torque causing acceleration (or deceleration) is

$$T_a = T_m - T_e \quad (1)$$

The combined inertia of the generator and prime mover is accelerated by the unbalance in the applied torques. Hence, the equation of motion is:

$$J \frac{d\omega_m}{dt} = T_a = T_m - T_e \quad (2)$$

The swing equation then can be expressed as two first order differential equations, becomes

$$\frac{d(\Delta\omega_r)}{dt} = \frac{1}{2H}(\bar{T}_m - \bar{T}_e - K_D\Delta\bar{\omega}_r) \quad (3)$$

$$\frac{d\delta}{dt} = \omega_o \Delta \bar{\omega}_r \quad (4)$$

The block diagram form representation of equations 3 and 4 is shown in Figure 1.

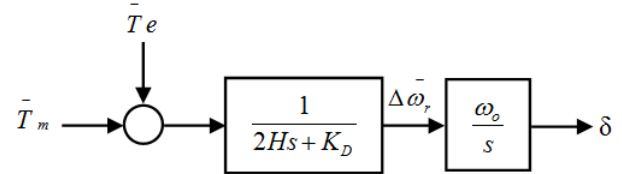


Fig. 1 Block diagram representation of swing equations

Linearizing and writing (3) and (4) in the vector-matrix form, obtain

$$\frac{d}{dt} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \end{bmatrix} = \begin{bmatrix} -\frac{K_D}{2H} & -\frac{K_S}{\omega_o} \\ \frac{2H}{0} & \frac{0}{0} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \end{bmatrix} + \begin{bmatrix} 1 \\ \frac{2H}{0} \end{bmatrix} \Delta T_m \quad (5)$$

where

K_S = Synchronizing torque coefficient in pu torque/rad

K_D =Damping torque coefficient in pu torque/pu speed deviation

 $H =$ Inertia constant in MW.s/MVA
$$\Delta\omega_r = \text{Speed deviation in pu} = (\omega_r - \omega_o) / \omega_o$$
 $\Delta\delta$ = Rotor angle deviation in elect.rad
$$\omega_o = \text{Rated speed in elect. rad/s} = 2\pi f_o = 314 \text{ for a 50Hz system.}$$

Depending on the previous derivations, and inserting the effect of the exciter, then complete model for the exciter-generator can be given as below in Figure 2.

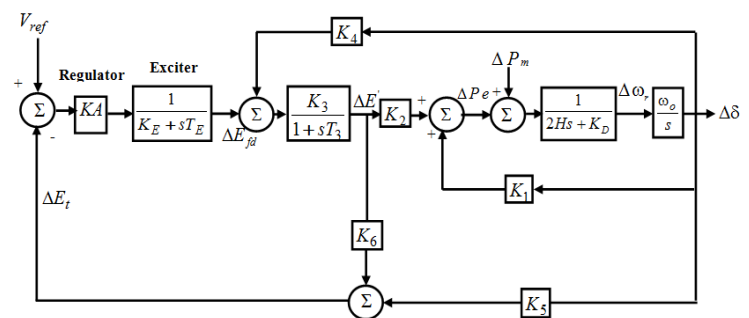


Fig. 2 Exciter generator model

In the vector-matrix form, the effect of excitation circuit can be given as follows, which represents the whole matrix of exciter-generator.

$$\frac{d}{dt} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta E' \\ \Delta E_{fd} \end{bmatrix} = \begin{bmatrix} \frac{-K_D}{2H} & \frac{-K_1}{2H} & \frac{-K_2}{2H} & 0 \\ \omega_o & 0 & 0 & 0 \\ 0 & \frac{-K_3 K_4}{T_3} & \frac{-1}{T_3} & 0 \\ 0 & \frac{-KAK_5}{T_E} & \frac{-KAK_6}{T_E} & \frac{-K_E}{T_E} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta E' \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} \frac{1}{2H} & 0 \\ 0 & 0 \\ 0 & \frac{KA}{T_E} \\ 0 & \frac{1}{T_E} \end{bmatrix} \begin{bmatrix} \Delta P_m \\ V_{ref} \end{bmatrix} \quad (6)$$

In the same manner as in the previous derivations, the complete model for the governor-turbine can be given as in Figure 3.

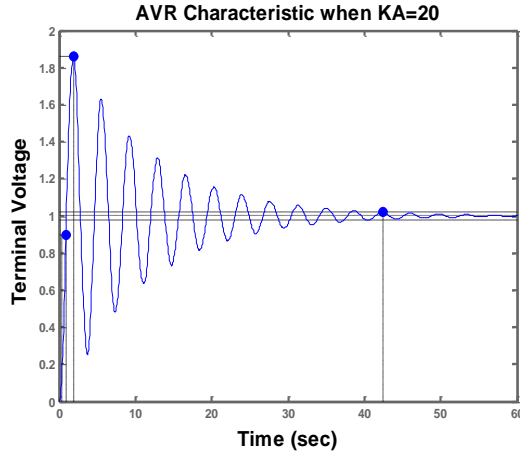


Fig. 5 Terminal voltage of the generator with KA=20

It can be also seen that from (7), which represent the governor-turbine model, as shown in Fig. 3, the input will be taken to be as the ΔP_L , which can be changed as 6%, 8%, 10% and 15% and assuming $\Delta P_{ref}=0$. The output will be chosen to be the changes in mechanical power ΔP_m and the frequency response $\Delta \omega_r$ as shown in Figure 6.

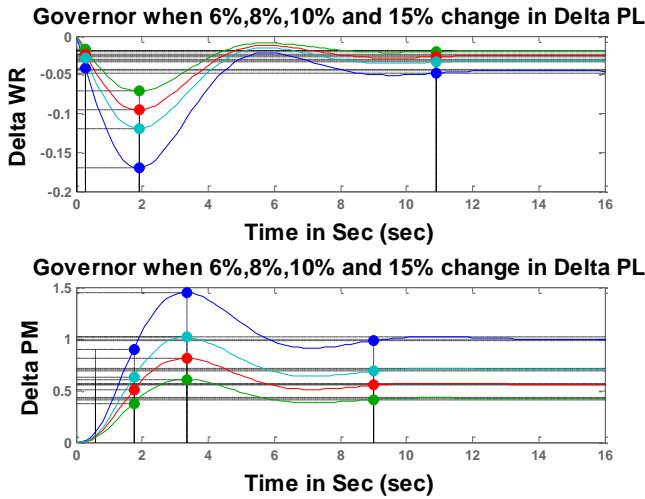


Fig.6 $\Delta \omega_r$ and ΔP_m change for all load changes

The time domain specifications from Figure 6 can be given in Table 2 and Table 3.

TABLE 2 TIME DOMAIN SPECIFICATION FOR CONVENTIONAL GOVERNOR FROM $\Delta \omega_r$ GRAPH

$\% \Delta P_L$	t_s	Peak amp.	t_p	$\%M_P$
6	10.9	-0.0715	1.92	275
8	10.9	-0.0953	1.92	275
10	10.9	-0.119	1.92	275
15	10.9	-0.17	1.92	275

TABLE 3 TIME DOMAIN SPECIFICATION FOR CONVENTIONAL GOVERNOR FROM ΔP_m GRAPH

$\% \Delta P_L$	t_s	Peak amp.	t_p	$\%M_P$
6	9	0.608	3.36	44.8
8	9	0.811	3.36	44.8
10	9	1.01	3.36	44.8
15	9	1.45	3.36	44.8

5. LQG CONTROLLER DESIGN BASED ON SEPARATION PRINCIPLE

The following steps give the design procedure followed in the design of the LQG controller given in Figure 7 that used here. [11, 12, 13 and 14]

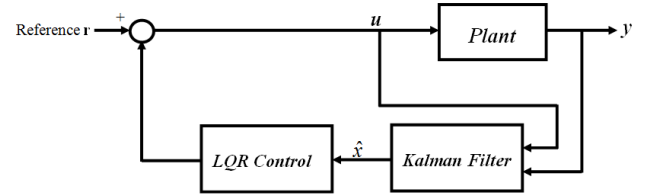


Fig. 7 Block Diagram of the Proposed LQG Control Law

- Design the (Linear Quadratic Regulator) LQR control law $u = -Kx$ which solves the following Problem,

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

$$J_{(x,u,Q,R)} = \int_0^{\infty} (x^T Q x + Ru^2) dt, \quad Q \geq 0, R > 0$$

i.e., compute

$$A^T P + PA - PBR^{-1}B^T P + Q = 0, P > 0,$$

$$K = R^{-1}B^T P$$

- Design a Kalman filter for the given plant, i.e.,

$$\dot{\hat{x}} = A\hat{x} + Bu + K_e(y - \hat{y}),$$

$$\hat{y} = C\hat{x}, \text{ where}$$

$$P_e A^T + AP_e + Q - P_e C^T R^{-1} C P_e = 0, P_e > 0,$$

$$K_e = P_e C^T R^{-1}$$

- The LQG control law is given by $u = -K\hat{x}$, i.e.,

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + K_e(y - C\hat{x}) \\ u = -K\hat{x} \end{cases}$$

Then,

$$\begin{cases} \dot{\hat{x}} = (A - KB - K_e C)\hat{x} + K_e y \\ u = -K\hat{x} \end{cases}$$

- Designing the second controller for the 2DOF LQG which is the integrator

6. TWO DEGREE OF FREEDOM LQG CONTROLLER

For the (2DOF), consider the system shown in Figure 8, where $G_P(s)$ is the transfer function of the plant, for this system, closed loop transfer function G_{yr} , G_{yn} , and G_{yd} are given respectively as follows:[15, 16 and 17]

$$G_{yr} = \frac{Y(s)}{R(s)} = \frac{G_{C1}G_P}{1 + (G_{C1} + G_{C2})G_P},$$

$$G_{yd} = \frac{Y(s)}{D(s)} = \frac{G_P}{1 + (G_{C1} + G_{C2})G_P},$$

$$G_{yn} = \frac{Y(s)}{N(s)} = \frac{-(G_{C1} + G_{C2})G_P}{1 + (G_{C1} + G_{C2})G_P}$$

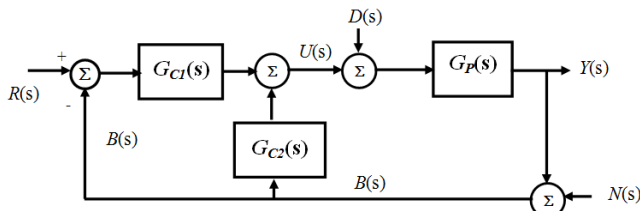


Fig. 8 Two Degree of Freedom Control System

Hence,

$$G_{yr} = G_{C1}G_{yd}, \quad G_{yn} = \frac{G_{yd} - G_P}{G_P}$$

In this case if G_{yd} is given, then G_{yn} is fixed, but G_{yr} is not fixed, because G_{C1} is independent G_{yd} . Thus, two closed loop transfer functions among three closed loop transfer functions G_{yr} , G_{yn} , and G_{yd} are independent. Hence, this system is two degrees of freedom control system.

It will be seen in such a two degree of freedom control system, both the closed loop characteristics and the feedback characteristics can be adjusted independently to improve the system response performance.

The strategy used in this work is to design the proposed two degree of freedom LQG and including an *integrator* action as shown in Figure 9 (i.e. first controller is LQG and the second controller is the integrator). The integral control of the system eliminates the steady state error in the response to the step input.

Under integral control action the control signal (the output signal from the controller) at any instant is the area under the actuating error signal curve up to that instant. The control signal can have a nonzero value when the actuating error signal ($r-y$) is zero.

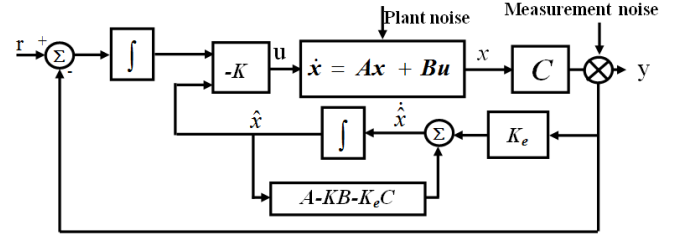


Fig. 9 Two Degree of Freedom LQG

7. PERFORMANCE EVALUATION OF DESIGN THE PROPOSED 2DOFLQG AVR & GOVERNOR

Designing the AVR using the 2DOFLQG gives the values of K_S and K_D and the time domain specifications which are given in Table 4.

TABLE 4 AVR USING 2DOFLQG

ω_n	t_s	K_s	$K_{stotal} = K_1 + K_s$	K_D	Peak amp.	t_p	%M _P
1.12	5.92	0.023	0.7875	7.949	1.08	4.46	8.04

Figure 10 shows the plotting of the output terminal voltage E_t versus t . What is obvious in this technique is the value of the damping torque, which is still high, and the time domain specification (control performance) is enhanced due to the effect of using the LQG controller and the integral controller.

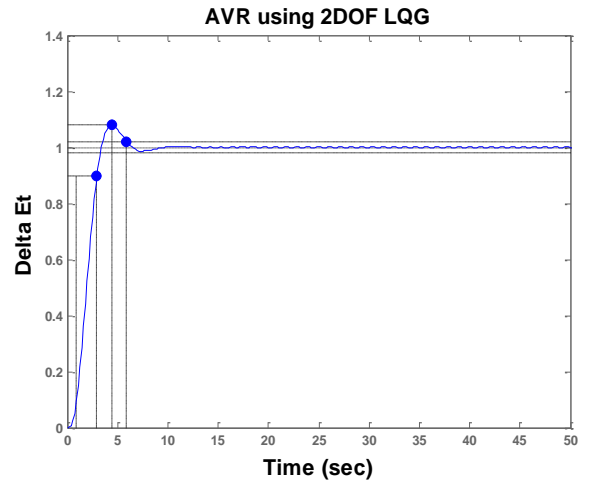


Fig. 10 Terminal voltage of the generator with 2DOF LQG AVR

Designing the Governor using 2DOFLQG gives the time domain specifications shown in Table 5.

TABLE 5 TIME DOMAIN SPECIFICATION FOR 2DOFLQG GOVERNOR FROM $\Delta\omega_r$ GRAPH

$\% \Delta P_L$	t_s	t_r	Peak amp.	t_p	$\%M_p$
6	2.69	0.043	-0.017	0.66	464
8	2.7	0.033	-0.018	0.6	518
10	2.94	0.026	-0.020	0.48	567
15	2.94	0.019	-0.023	0.42	661

TABLE 6 TIME DOMAIN SPECIFICATION FOR 2DOFLQG GOVERNOR FROM ΔP_m GRAPH

$\% \Delta P_L$	t_s	t_r	Peak amp.	t_p	$\%M_p$
6	3.59	0.539	0.101	1.68	52
8	3.58	0.481	0.104	1.5	55.5
10	3.68	0.442	0.106	1.38	58.1
15	3.76	0.389	0.109	1.26	62

Figure 11 shows the plotting of $\Delta\omega_r$ and ΔP_m for 6%, 8%, 10% and 15% of ΔP_L change versus t on the same graph. As seen also the integral action has been enhanced the time domain specifications (control performance).

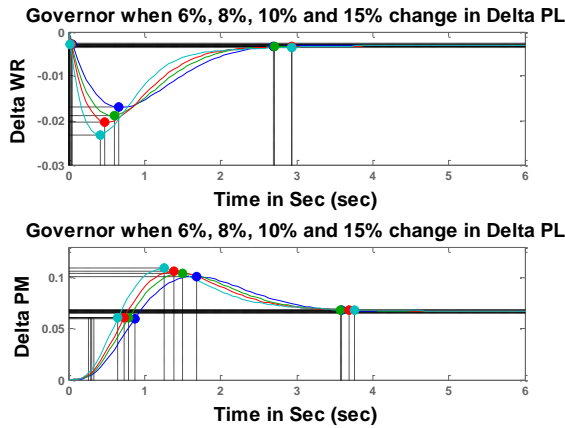


Fig. 11 $\Delta\omega_r$ and ΔP_m change for 6%, 8%, 10% and 15% of the load change using 2DOFLQG Governor

8. CONCLUSION

In this paper a controller based on a two degree of freedom Linear Quadratic Gaussian (2DOFLQG) designed to control the generator voltage via the AVR and the turbine speed via the governor, this controller has been compared with the conventional one. The plant noise and the measurement noise were considered. This technique which depends on the 2DOFLQG gives best damping torque, synchronizing torque and time domain specification with comparison with the conventional techniques, shown clearly in Tables (1, 2, 3, 4, 5 and 6 which leads to improving the stability of the whole system.

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APPENDIX A

GENERATOR

S(Apparent power)	555MVA
P (Active power)	0.9 p.u.
Q (Reactive Power)	0.3 p.u.(overexcited)
E _t (Terminal voltage)	24 kV or 1 p.u.
Speed	50 S ⁻¹
Frequency	50 HZ
E _B (Infinite bus voltage)	0.995 p.u.
Connection	Y
H	3.5 MW.s/MVA
K _D	0
K ₁	0.7643 p.u.
K ₂	0.8649 p.u.
K ₃	0.323 p.u.
K ₄	1.4187 p.u.
K ₅	-0.1463 p.u.
K ₆	0.4168 p.u.
T ₃	2.365s

EXCITER

KA	30
T _R	0.02s
K _E	-0.02
T _E	0.56

TURBINE

KG	20 MW/Hz
F _{HP}	0.3
F _{IP}	0.4
F _{LP}	0.4
T _{SR}	0.1s
T _{SM}	0.3s
T _{CH}	0.18s
T _{RH}	7s
T _{CO}	0.4s