# ROBUST CONTROLLER DESIGN FOR LOAD FREQUENCY CONTROL BASED ON H∞ AND LINEAR QUADRATIC GAUSSIAN TECHNIQUES

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***ABSTRACT-*** In this paper, robust controllers design based on $H_\infty$ and Linear Quadratic Gaussian (LQG) techniques for load frequency control problem in a single area power system are presented. The proposed controllers have been designed in order to achieve both robust stability and good dynamic performance against the variation of system parameters as well as load disturbance.

The $H_\infty$ controller design has been described and formulated in the standard form with emphasis on the selection of weighting functions that reflect optimal robustness and performance goals. Also, the full states of the single area power system including the frequency deviation are estimated using the standard Kalman filter technique. These states have been used by LQG state feedback controller to produce the optimal control signal. Comparison between the system dynamic performance obtained with the proposed controllers and the dynamic performance obtained with other controllers ($H_\infty$ controller only and PI controller) are presented. The results show that the proposed controllers lead to ensuring stability and reasonable dynamic performance against variation of system parameters and load disturbance compared to other controllers.

***Keywords***: Load frequency control (LFC), $H_\infty$ approach, (LQG) techniques, proportional integral control (PI), and Kalman filter.

## I. Introduction

Load frequency control (LFC) becomes an important function of power system operation where the main objective is to regulate the output power of each generator at prescribed levels while keeping the frequency fluctuations within pre-specified limits.

Today, control system designers are trying to apply different control algorithms in order to find the best controller parameters to obtain optimum solutions. Fixed parameter controllers, such as an integral controller or a proportional integral (PI) controller, is also widely employed in the LFC application.

Fixed parameter controllers are designed at nominal operating points, and may no longer be suitable in all operating conditions. For this reason, adaptive gain scheduling approaches have been proposed for LFC synthesis [1]. This method overcomes the disadvantages of the conventional Proportional Integral and Derivative (PID) controllers which need adaptation of controller parameters. However, it faces some difficulties like the instability of transient response as a result of abrupt changes in the system parameters, in addition to the impossibility of obtaining accurate linear time invariant models at variable operating points [1-11]. In addition to dealing with changes in system parameters, fuzzy logic controllers have been used in many reports for LFC design in a two area power system [3-4]. The applications of artificial neural network and genetic algorithms in LFC have been reported in [5, 6]. In spite of these efforts, it seems that, although estimation of parameters is not required, the parameters of the controllers can be changed generally very quickly; but despite the promising results achieved, the control algorithms are complicated and unstable transient response could still be observed. Therefore, some other elegant techniques are needed to achieve a more desirable performance.

Recently, some papers have reported the application of Model Predictive Control (MPC) technique on load frequency control issue [7, 8]. In [7], the use of MPC in a multi area power system is discussed. From [7, 8], fast response and robustness against parameter uncertainties and load changes can be obtained using MPC. Moreover the application of Coefficient Diagram Technique has been proposed in [18]. The results of [18] show fast response with high and robustness against parameter uncertainties.

During the past decade, the $H_\infty$ control theory has been widely celebrated for its robustness in counteracting uncertainty perturbations and external disturbances. As a consequence, some applications of this approach to various plants such as machine drives and other control systems [12-17] have been published. The main point of the $H_\infty$ control is to synthesize a feedback law that renders the closed loop system to satisfy a prescribed $H_\infty$-norm constraint. This would satisfy the desired stability and the tracking requirements. In fact, due to increase in the complexity and change of the power system structure, other techniques are needed to achieve a desirable performance.

In this paper, load frequency control for a single-area power system has been developed based on both of $H_\infty$ technique and Linear Quadratic Gaussian (LQG) method. The proposed controllers have been designed in order to achieve both robust stability and good dynamic performance against the variation of system parameters as well as load disturbance. The $H_\infty$ controller design has been described and formulated in the standard form with emphasis on the selection of weighting functions that reflect optimal robustness and performance goals. Also, the full states of the single area power system including the frequency deviation are estimated using the standard Kalman filter technique. These states have been used by LQG state feedback controller to produce the optimal control signal. Kalman filter has been employed to estimate the full states of the system. The optimal state feedback gains and the Kalman state space model have been calculated off-line in order to reduce the computational burden. The effects of the physical constraints such as generation rate constraint (GRC) and speed governor dead band [1] are considered. A comparison has been made between the proposed method and $H_\infty$ alone controller confirming the superiority of the proposed $H_\infty$ + LQG technique. The rest of the paper is organized as follows: the description of the dynamics of the power system is given in section II. A general consideration about $H_\infty$ and its design are presented in section III. LQG with Kalman filter is presented in section IV. The implementation scheme of a single area power system together with the $H_\infty$+ LQG technique is described in section V. Simulation results and general remarks are presented in section VI. Finally, the conclusion is given in section VII.

## II. Power System Dynamics Model

In this section, a simplified frequency response model for a single-area power system with an aggregated generator unit is described [14]. The overall generator–load dynamic relationship between the incremental mismatch power ($\Delta \mathbf{P_m} - \Delta \mathbf{P_L}$) and the frequency deviation ($\Delta \mathbf{f}$ ) can be expressed as:

$$\boldsymbol{p}.\Delta \mathbf{f} = \left(\frac{\mathbf{1}}{\mathbf{2H}}\right).\Delta \mathbf{P_m} - \left(\frac{\mathbf{1}}{\mathbf{2H}}\right).\Delta \mathbf{P_L} - \left(\frac{\mathbf{\acute{D}}}{\mathbf{2H}}\right).\Delta \mathbf{f} \qquad (1)$$

The linearized dynamic model of the turbine can be expressed as:

$$p.\Delta P_m = \left(\frac{1}{T_t}\right).\Delta P_g - \left(\frac{1}{T_t}\right).\Delta P_m \qquad (2)$$

Also, the linearized dynamic model of the governor can be expressed as:

$$p.\Delta P_g = \left(\frac{1}{T_g}\right).\Delta P_c - \left(\frac{1}{R.T_g}\right).\Delta f - \left(\frac{1}{T_g}\right).\Delta P_g \qquad (3)$$

Figure 1 illustrates the overall functional block diagram of the linearized power system model described by the above equations. Equations (1-3) represent a simplified frequency response model for one generator unit and can be combined in the following matrix form of state space model:

$$\begin{bmatrix} p.\Delta P_g \\ p.\Delta P_m \\ p.\Delta f \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_g} & 0 & -\frac{1}{R.T_g} \\ \frac{1}{T_t} & -\frac{1}{T_t} & 0 \\ 0 & \frac{1}{2H} & -\frac{\acute{D}}{2H} \end{bmatrix} \begin{bmatrix} \Delta P_g \\ \Delta P_m \\ \Delta f \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{2H} \end{bmatrix} \Delta P_L + \begin{bmatrix} \frac{1}{T_g} \\ 0 \\ 0 \end{bmatrix} \Delta P_c \qquad (4)$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta P_g \\ \Delta P_m \\ \Delta f \end{bmatrix} \qquad (5)$$

$\Delta P_g$ : The incremental change of governor output (p.u.MW);

$\Delta P_m$ : The incremental change of mechanical power (p.u.MW);

$\Delta f$ : The incremental frequency deviation (Hz);

$\Delta P_L$ : The load disturbance (p.u.MW);

$\Delta P_c$ : The incremental change of Supplementary control action (p.u.M HZ);

$p$ : Differential operator.

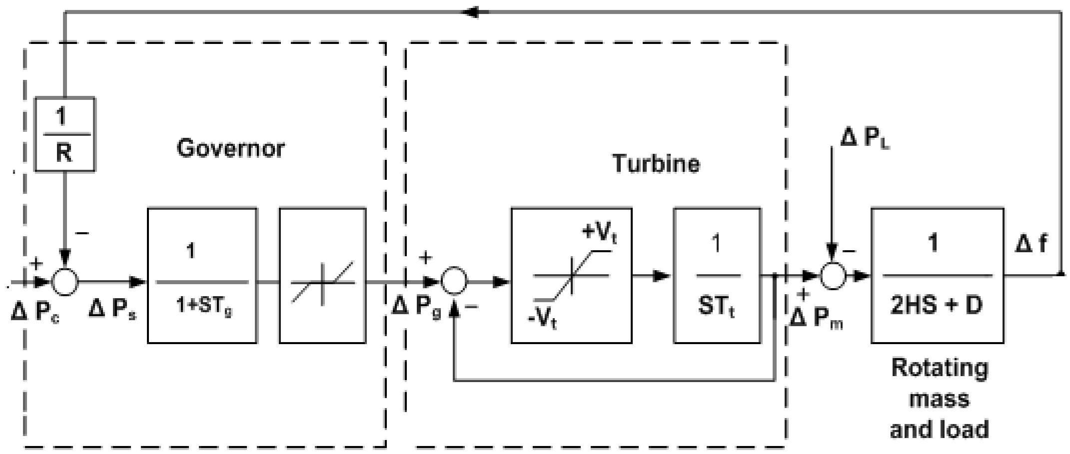


Figure 1. The block diagram of uncontrolled single-area power system.

$\left(\frac{1}{s}\right)$ : Integral Laplace operator.

$T_g,\ T_t$ : Governor and turbine time constants (sec.).

$y$ : The system output (HZ).

$H$ : Equivalent inertia constant (p.u MW sec$^2$.).

$D$ : Equivalent damping coefficient (p.u.MW sec.).

$R$ : Speed droop characteristic (HZ/p.u.MW).

**III. Design of the proposed controller for LFC using H∞ approach**

The $H_\infty$ theory provides a direct, reliable procedure for synthesizing a controller which optimally satisfies singular value loop shaping specifications [16]. The standard setup of the $H_\infty$ control problem consists of finding a static or dynamic feedback controller such that the $H_\infty$ norm (a standard quantitative measure for the size of the system uncertainty) of the closed loop transfer function is less than a given positive number under constraint that the closed loop system is internally stable.

The $H_\infty$ synthesis is carried out in two stages:

i. Formulation: weighting the appropriate input-output transfer functions with proper weighting functions. This would provide robustness to modeling errors and achieve the performance requirements. The weights and the dynamic model of the system are then augmented into $H_\infty$ standard plant.

ii. Solution: the weights are iteratively modified until an optimal controller that satisfies the $H_\infty$ optimization problem is found.

Figure (2) shows the general setup of the $H_\infty$ design problem where:

P(s): The transfer function of the augmented plant (nominal plant G(s) plus the weighting functions that reflect the design specifications and goals).

u2: The exogenous input vector, typically consists of command signals, disturbance, and measurement noises.

u1: the control signal.

y1: The output to be controlled, its components typically being tracking errors, filtered actuator signals.

The objective is to design a controller F(s) for the augmented plant P(s) such that the input/output transfer characteristics from the external input vector $u_2$ to the external output vector $y_1$ is desirable. The $H_\infty$ design problem can be formulated as finding a stabilizing feedback control law $u_1$ (s) = F(s) . $y_1$(s) such that the norm of the closed loop transfer function is minimized.

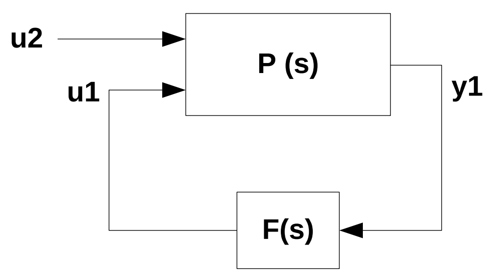


Figure 2: General setup of the $H_\infty$ design problem

In the proposed load frequency control system including $H_\infty$ controller, a feedback loops is designed for adjusting the terminal voltage and for regulating the output frequency as shown in Fig. (3). The nominal system G(s) is augmented with weighting transfer functions $W_1(s)$, $W_2(s)$ and $W_3(s)$ penalizing the error signals, control signals, and output signals respectively. The choice of proper weighting functions is the essence of $H_\infty$ control. A bad choice of weights will certainly lead to a system with poor performance and stability characteristics, and can even prevent the existence of a solution to the $H_\infty$ problem.

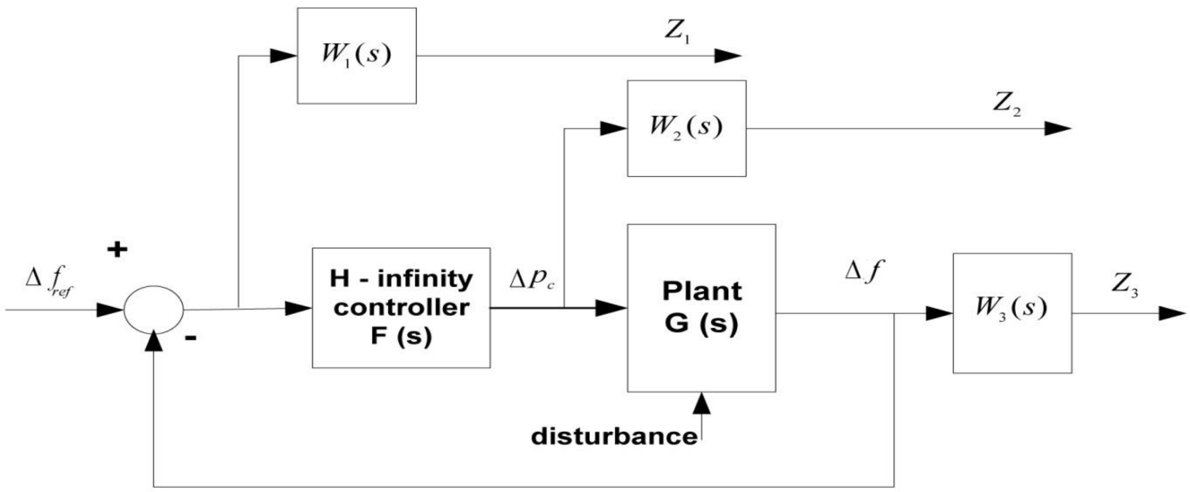


Figure 3: Simplified block diagram of the augmented plant including H∞ controller

Consider the augmented system shown in Fig. (3). the following set of weighting transfer functions are chosen to reflect desired robust and performance goals as follows:

A good choice of $W_1(s)$ is helpful for achieving good tracking of the input references, and good rejecting of the disturbances. The weighted error transfer function matrix $Z_1$ ; which is required to regulate, can be written as :

$$Z_1 = W_1(s)\left\lfloor \Delta f_{ref} - \Delta f \right\rfloor \qquad (6)$$

A good choice of the second weight $W_2(s)$ will aid for avoiding actuators saturation and provide robustness to plant additive perturbations. The weighted control function matrix $Z_2$ can be written as:

$$Z_2 = W_2(s)\Delta Pc \qquad (7)$$

Where $u(s)$ the transfer function matrix of the control is signals output of the H∞ controller.

Also a good choice of the third weight $W_3(s)$ will limit the closed loop bandwidth and achieve robustness to plant output multiplicative perturbations and sensor noise attenuation at high frequencies. The weighted output variable can be written as:

$$Z_3 = W_3(s)\Delta f \qquad (8)$$

In summary, the transfer functions of interest which determine the behavior of the voltage and power closed loop systems are:

a) Sensitivity function: $S = [\, I + G(s) \,.\, F(s) \,]^{-1}$

Where G(s) and F(s) are the transfer functions of the nominal plant and the $H_\infty$ controller respectively, and I is the identity matrix. Minimizing S at low frequencies will insure good tracking and disturbance rejection.

b) Control function : $C = F(s)\,[\,I + G(s)\,.\,F(s)]^{-1}$

Minimizing C will avoid actuator saturation and achieve robustness to plant additive perturbations.

c) Complementary function : $T = I - S$

Minimizing T at high frequencies will insure robustness to plant output multiplicative perturbations and achieve noise attenuation.

## IV. Design of LFC controller based on LQG techniques

Decentralized load frequency control for a single area power system has been developed based on both of H∞ and LQG techniques in this paper. The name LQG arises from the use of a linear model, an integral cost function, and Gaussian white noise processes to model disturbance and noise signals. The LQG controller consists of an optimal state feedback gain "k" and the Kalman estimator. The optimal feedback gain is calculated such that the feedback control law u = -kx minimizes the performance index:

$$J = \int_0^\infty (X^T QuX + u^T Ru)dt \qquad (9)$$

Where Q and R are positive definite or semi definite Hermittian or realsymmetric matrices [15]. The optimal state feedback u = -kx could not be implemented without full state measurement. In this case, the states are chosen to be the frequency deviation Δf, mechanical power change $\Delta P_{mi}$, and the governor output change$\Delta P_g$. The frequency deviation Δf and the supplementary control action $\Delta P_c$ are chosen to be the only measured signals which are fed to the Kalman estimator. The Kalman filter estimator is used to drive the state estimation:

$\hat{x} \quad = [\Delta\hat{f} \quad \Delta\hat{p}_m \ \ \Delta\hat{p}_g]$

Such that u = -kx remains optimal for the output feedback problem. The state estimation is generated from

$$(\dot{\hat{x}}) = (A - Bk - LC)\hat{x} + Ly \qquad (10)$$

Where L is the Kalman gain which is determined by knowing the system noise and measurement covariance $Q_n$ and $R_n$. However, the accuracy of the filter's performance depends heavily upon the accuracy of these covariance. On the other hand the matrices A and B containing the power system are not required to be very accurate due to the inherent feedback nature of the system. Fortunately, the Kalman filter performs best for linear systems. The optimal state feedback gains and the Kalman state space model have been calculated off-line which results in great saving in computational burden. Consequently, the implementation of the proposed controller becomes easier and the hardware will be reduced to minimum.

## V. Description of the proposed system

The block diagram of a simplified frequency response model for a single-area power system with aggregated unit including the proposed controllers based on $H_\infty$ and LQG techniques is shown in Figure 4.

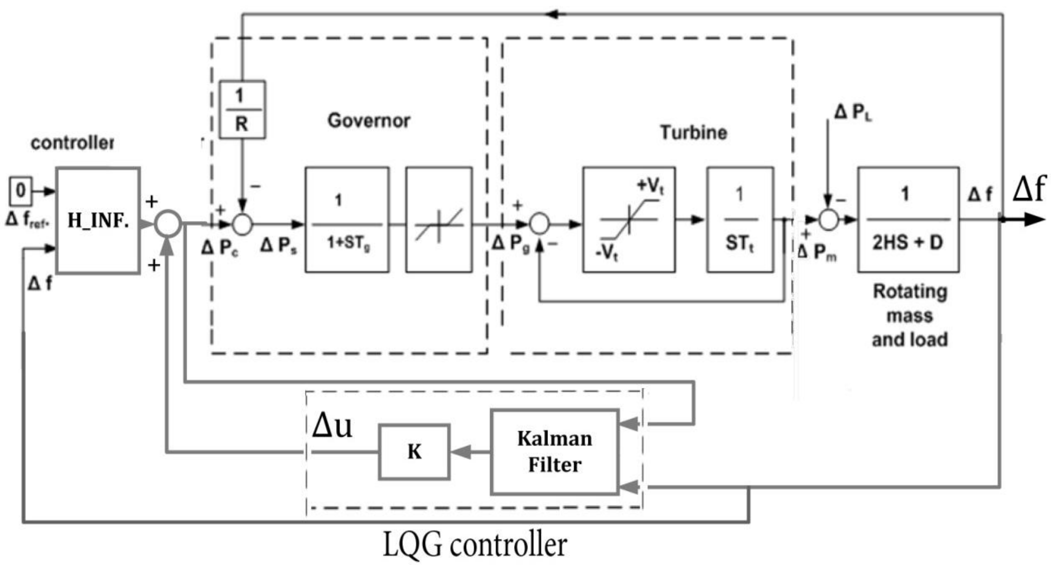


Figure 4: The block diagram of single area power system including the proposed H∞.+LQG controllers

The system consists of the rotating mass and load, nonlinear turbine, and governor with dead-band constraint [1]. On the other hand, the frequency deviation is used as a feedback signal for the closed loop control system. The measured $\Delta f$ and reference frequency deviations $\Delta f_{ref}$ ($\Delta f_{ref} = 0$ Hz) are fed to the $H_\infty$ controller in order to obtain the supplementary control action $\Delta P_c$ which is added to the negative frequency feedback signal. The resulting signal $\Delta P_s$ is fed to the governor giving the governor valve position which supplies the turbine to give the mechanical power change $\Delta P_m$ .

In addition, the frequency deviation $\Delta f$ and supplementary control action $\Delta P_c$ have been applied to the input of the Kalman filter to estimate the system states $\hat{x} = [\Delta \hat{f} \quad \Delta \hat{p}_m \ \Delta \hat{p}_g]$ , these estimated states have been multiplied by optimal state feedback gain "k" to give the optimal control signal which added to the main control signal obtained from $H_\infty$ controller to give supplementary control action $\Delta P_c$ , which add to the negative frequency feedback signal. The resulting signal is fed to the governor giving the governor valve position which supplies the turbine to give $\Delta P_m$ which is the mechanical power change. $\Delta P_m$ which is affected by the load change, $\Delta P_L$. The error between $\Delta P_m$ and $\Delta P_L$ effect gives input of the rotating mass and load block to provide the actual frequency deviation $\Delta f$ .

The following sets of weighting functions are chosen after many iteration in order to achieve both robust stability and performance goals against the variations of system parameters and load disturbance:

$W_1 = \frac{s+0.3}{s+0.56}$ , $W_2 = \frac{s}{s+0.04}$ and $W_3 = \frac{1}{s+2}$

## VI. Simulation Results and Discussions

Computer simulations have been carried out in order to validate the effectiveness of the proposed system using scheme of figure 4. Matlab /Simulink software package has been used for this purpose Consider single area power system where the simulation parameters [1] are listed in Table I.

Table I Nominal parameters and data specification of a practical single control area power system.

| $D$(pu/Hz) | $2H$(pu.sec) | $R$(Hz/pu) | $T_g$(sec) | $T_t$(sec) |
|---|---|---|---|---|
| 0.015 | 0.1667 | 3.00 | 0.08 | 0.40 |

The simulation studies are carried out for the proposed controllers with generation rate constraint (GRC) of 10% per minute and the maximum value of dead band for governor is specified as 0.05 p.u. [1].

Firstly, the dynamic performance of the system under study are examined without controller when a step load change of .02 p.u (i.e $\Delta P_L$ =.02 p.u) is applied to the system, assuming that the governor and turbine times constants of the system are increased by 125% and 260% from their nominal values respectively, (Tg=.18 sec. and Tt=1.4 sec.). Figure 5 shows the time response of incremental frequency deviation with controller. This figure show that, the frequency deviation response exhibits oscillation which is rapidly growing due to large change in system parameters, this leads to system instability

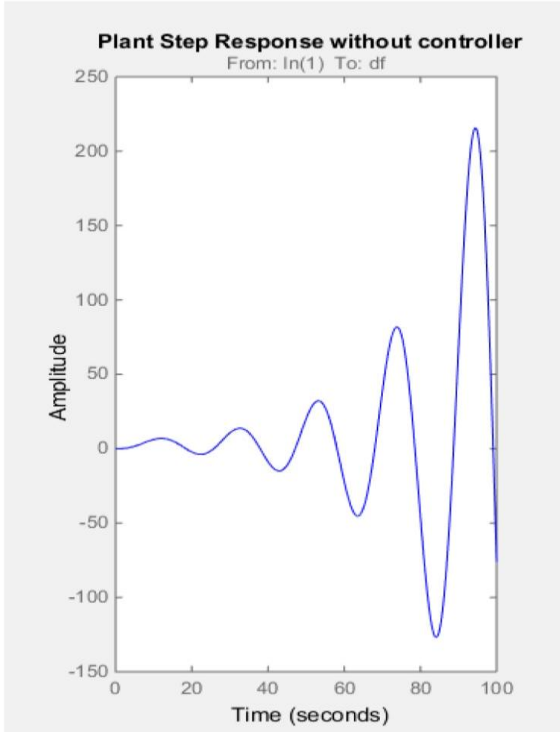


Figure 5. The dynamic performance of the control plant without controller

**Case 1**: In order to validate the proposed hybrid H∞ + LQG controllers, the dynamic performance of the proposed system is studied with nominal system parameters and a step load change of .02 p.u i.e ( $\Delta P_L$ =.02 p.u) is subjected to the system at t=30 sec.

Figure 6.a, 6.b and 6.c show the time response of $\Delta P_m$ , $\Delta\hat{p}_g$ and Δf respectively with the application of the proposed controllers and other controllers, (H∞ controller only and conventional controller (PI controller)). The following remarks can be made considering the proposed controllers in comparison with other controllers (H∞ and PI controllers)

i. The proposed controllers lead to a better time response of the $\Delta\hat{p}_g$ and $\Delta P_m$ where a smaller settling time and a larger overshoot are obtained as shown in figures 6.a, 6.b, 6.c
ii. The dip of time response of Δf due to step load disturbance has a smaller value with good and fast rejection compared to other controllers.

**Case 2:** the system performance is studied at high value of step load change of .06 (i.e $\Delta P_L$ = 0.06 pu ) is subjected to the system at t=30 sec. with nominal system parameters, Figure 7.a, 7.b and 7.c show the time response of $\Delta\hat{p}_g$ , Δf and $\Delta P_m$ with the application of the proposed controllers, compared to other controllers . From these figures,

i. The proposed controllers give a better time response of the $\Delta\hat{p}_g$ and $\Delta P_m$ with respect to settling time and overshoot as shown in figures 7.a, 7.b and 7.c. Also, the dip of time response of Δf due to high load disturbance has a smaller value with good, much faster rejection, zero steady-state error compared to other controllers, as shown in figure 7.c.

**Case 3**: The system performance is studied against a wide range of parameters variations. In this case, both of the governor and turbine time constants are increased to Tg = 0.12 sec (≅31% change from its nominal value), and Tt = 0. 975 sec (≅140 % change from its nominal value), respectively. Figure 8.a, 8.b and8.c show the time response of $\Delta\hat{p}_g$ , Δf and $\Delta P_m$ with the application of the proposed controllers, compared to other controllers. From these figures, the time response of the $\Delta\hat{p}_g$ and $\Delta P_m$ with the proposed controllers have smaller settling time, less over shoot and more stable compared to other controllers as shown in figurers 8.a and 8.b. Also, the time response of Δf has a fast and good rejection with zero steady-state error compared to other controllers as shown in figure 8.c.

**Case 4**: The system dynamic performance is investigated against a wide range of all parameters uncertainty and more sever change. In the tested scenarios, the governor and turbine time constants of the area is increased to Tg1= 0.18 s (≅125% change), Tt1= 1.4 s (≅260% change), respectively with changing M=.225 and D=.0195. Figure 9.a, 9.b and 9.c show the time response of $\Delta\hat{p}_g$ , Δf and $\Delta P_m$ with the application of the proposed controllers and other controllers for comparison purpose. Figures 9.a and 9.b show that, the time response of $\Delta\hat{p}_g$ and $\Delta P_m$ with the proposed controllers have good dynamic performance with respect to settling time and overshot in comparison with other controllers. Also, fast rejection, robust stability and zero steady-state error are achieved in the time response of Δf with the proposed controllers compared to other controllers as shown in figure 9.c.

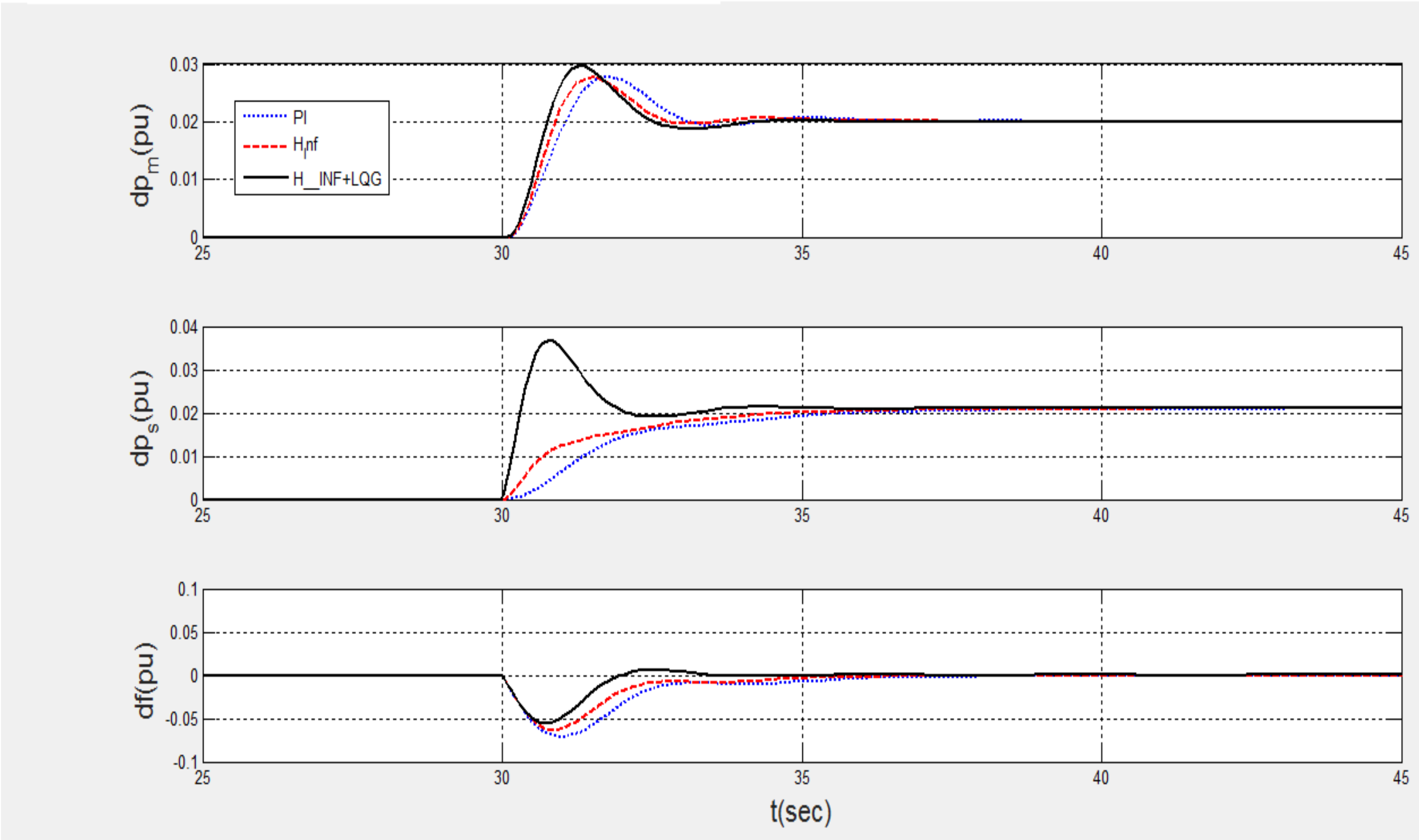


Figure 6: Power system responses to the case 1; a) the governor valve position ΔPm, b) the governor's control signal ΔPs , and c) the frequency deviation Δf

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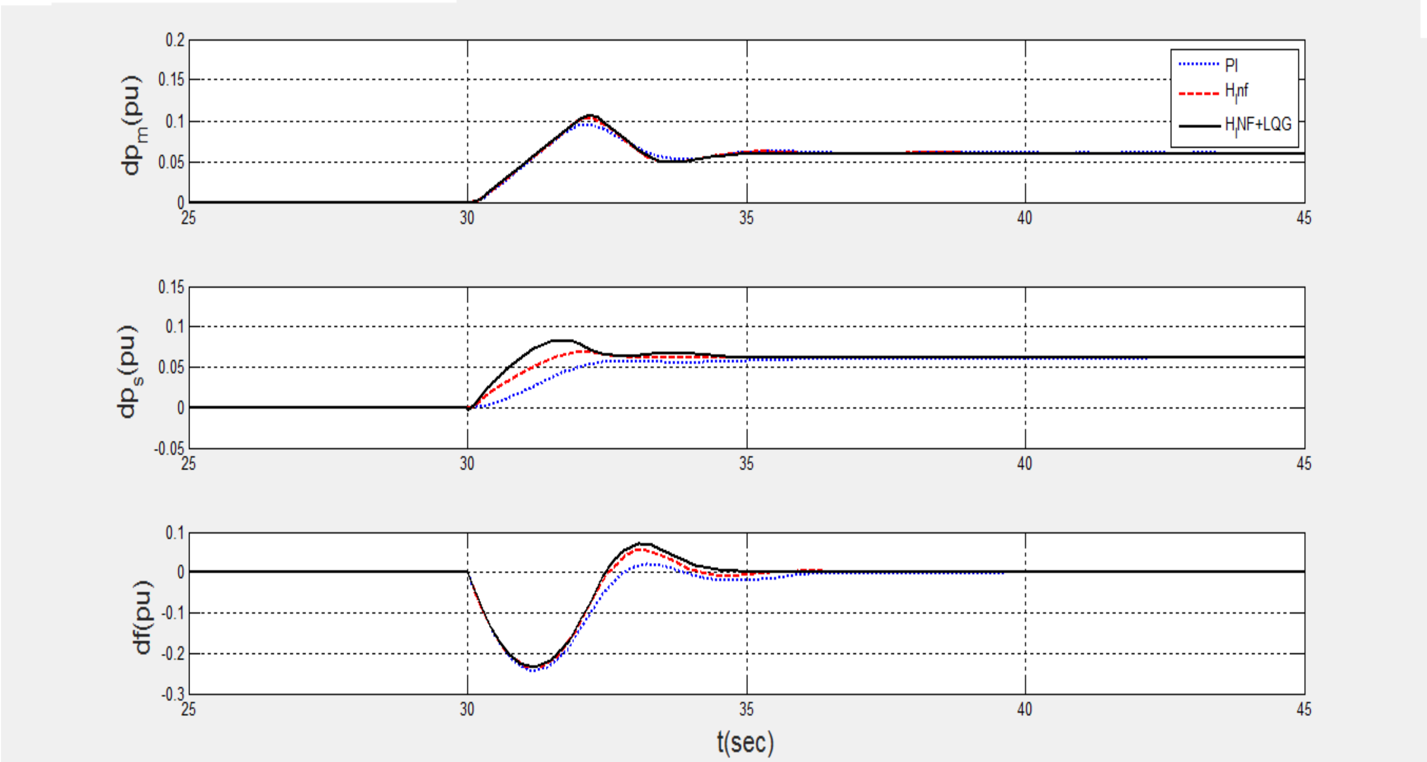


Figure 7: Power system responses to the case 2; a) the governor valve position ΔPm, b) the frequency deviation Δf, and c) the governor's control signal ΔPs.

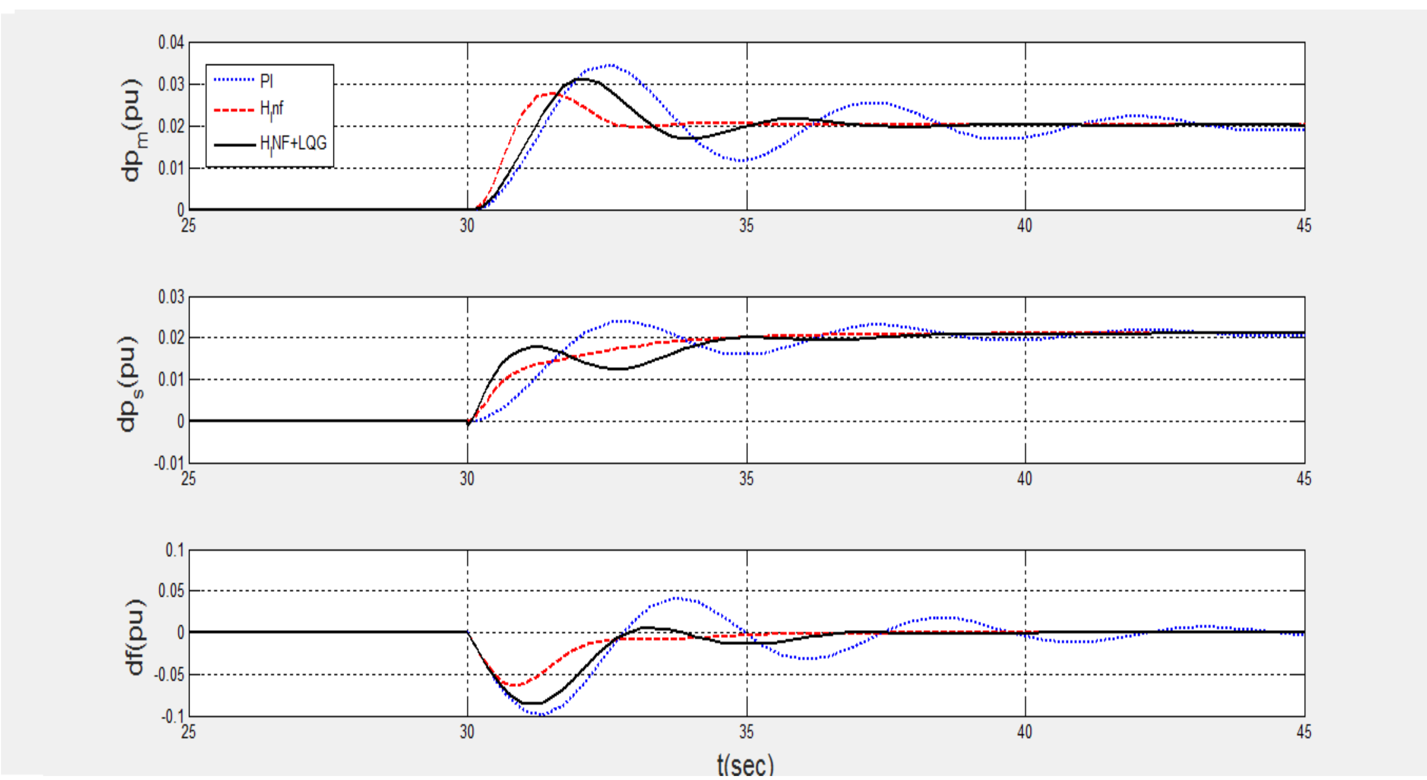


Figure 8: Power system responses to the case 3; a) the governor valve position ΔPm, b) the governor's control signal ΔPs, and c) the frequency deviation Δf, and

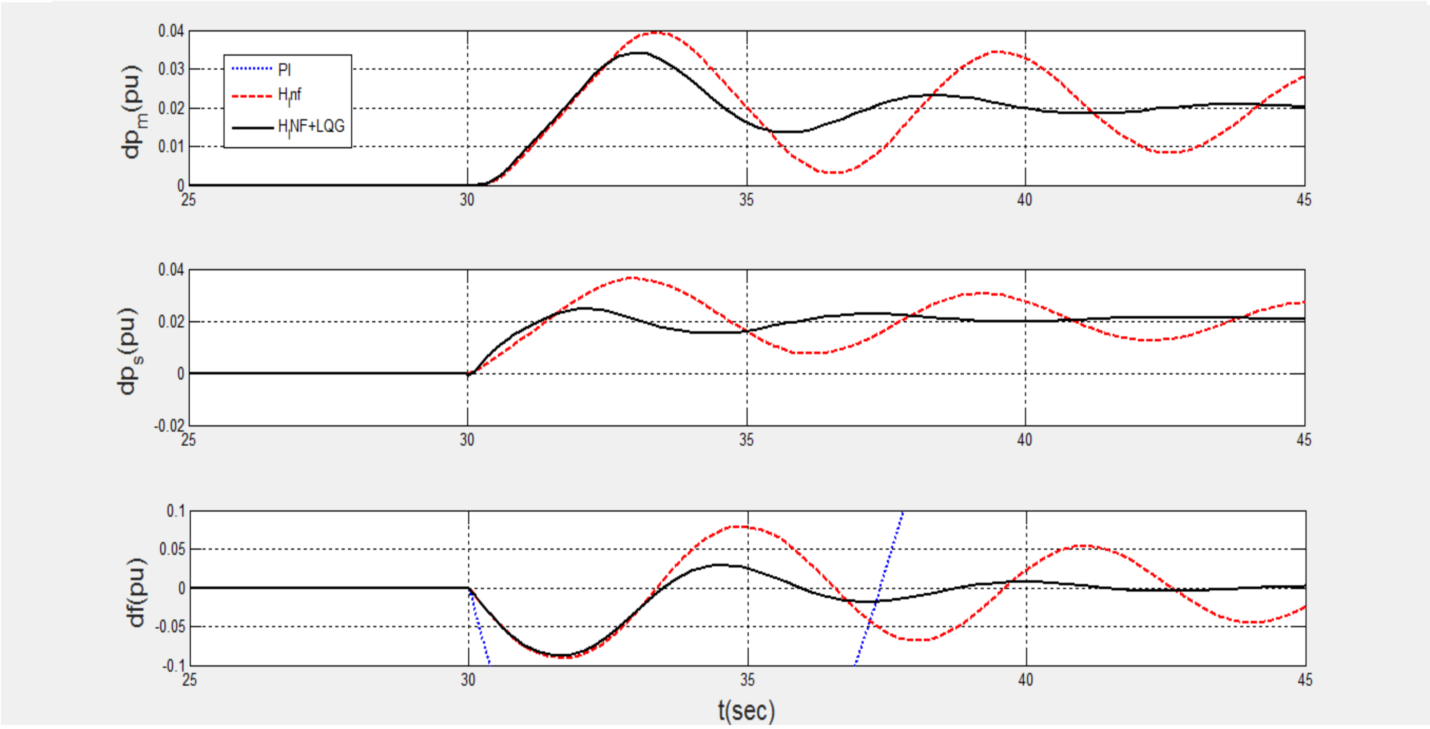


Figure 9: Power system responses to the case 4; a) the governor valve position ΔPm, b) the governor's control signal ΔPs, and c) the frequency deviation Δf

## VI. Conclusion

In this paper, robust controller's designs for load frequency control problem in a single area power system have been proposed. These controllers are based on $H_\infty$ approach and LQG technique to achieve both robust stability and good dynamic performance of the power system against different variation in the system parameters and load disturbance. Digital simulations have been performed to investigate the effectiveness of the proposed controllers compared to other controllers ($H_\infty$ and PI controllers). In view of the analysis and investigations presented, one can draw the following main conclusions:

1- The use of are $H_\infty$ approach and LQG technique to design the controllers offer many advantages over other control schemes used so far in the area of stabilizing power system.

i. The dynamic performance can be adjusted by choosing the weighted functions to satisfy all design requirements.

ii. The $H_\infty$ design problem can be formulated as finding a stabilizing feedback control low such that the norm of the closed loop transfer function is minimized.

iii. Simple implementation, where the incremental frequency deviation of the power system is chosen as the only feedback signal through the controllers to obtain the control signal and the Kalman filter in LQG is used to estimate all states.

2- The system dynamic response has excellent and robust stability is achieved with the proposed controllers against variations of system parameters.
3- With the proposed controllers, fast response good disturbance and noisy rejection and the steady-state error of the frequency deviation is zero for certain range of system parameters variations.
4- In comparison with other controllers, the system response with the proposed controllers is much better with respect to both settling time and overshoot when the system is subjected to different values of step load disturbance and in all cases of the system parameter variations.

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**الملخص العربي**

## تصميم حاكمات متينة للتحكم فى التردد لنظام قوى كهربيه باستخدام طريقة $H_\infty$ وطريق المربعات الخطية لجاوس

يتم تصميم حاكمات متينة اعتمادا علي طريقة $H_\infty$ وطريق المربعات الخطية لجاوس للتحكم فى التردد في نظام وحيد لتوليد القدرة الكهربية. والهدف من تصميم الحاكمات المقترحة هو تحقيق كل من الاستقرار والاتزان للنظام بالاضافة الي الحصول علي الأداء الديناميكي العالي المطلوب من النظام في حالة تغيير ثوابت النظام وكذلك التغيير المفاجئ للحمل. يتم تصميم حاكم بطريقة $H_\infty$ اعتمادا علي النموذج الخطي للنظام حول نقطة تشغيل معينة وذلك باختيار الدوال الموزونة التي تعكس المتانة والاستقرار للنظام وكذلك تحقيق الأهداف المطلوبة من الأداء. وأيضا الحاكم المصمم بطريقة المربعات الخطية لجاوس للحصول علي اشارة التحكم يعتمد علي مرشح كالمن لتقييم جميع متغيرات الحالة للنظام وذلك بقياس التغير في التردد فقط. تم استخدام حزمة برامج الماتلاب لحساب الأداء الديناميكي للنظام مع الحاكمات المقترحة بهدف المقارنة مع الأداء الديناميكي لنفس النظام باستخدام الحاكم التقليدي وكذلك باستخدام حاكم $H_\infty$ فقط. وقد أوضحت النتائج المعروضة ان الأداء الديناميكي للنظام باستخدام الحاكمات القديمة المقترحة يكون اكثر استقرارا واتزانا بالاضافة للأداء الديناميكي العالي والمتميز مقارنة بالحاكمات الاخري.