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LQR Based Load Frequency Controller for Two Area Power System

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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 investigates LFC and AGC for interconnected power systems and shows that LQR controllers perform better than classical integer order controllers in these systems.

Keywords: Power system control, AGC, PID controller, LQR controller, frequency control, power systems stability.

I.INTRODUCTION

Power systems are used to convert natural energy into electric power. Once power is generated it is transferred electricity to factories and houses to satisfy all kinds of power needs. During the transportation, both the active power balance and the reactive power balance must be maintained between generating and utilizing the AC power. Those two balances correspond to two equilibrium points: frequency and voltage. When either of the two balances is broken and reset at a new level, the equilibrium points will float.

Although the active power and reactive power have combined effects on the frequency and voltage, the control problem of the frequency and voltage can be decoupled. The frequency is highly dependent on the active power while the voltage is highly dependent on the reactive power. Thus the control issue in power systems can be decoupled into two independent problems. One is about the active power and frequency control while the other is about the reactive power and voltage control. The active power and frequency control is referred to as Load Frequency Control (LFC) and reactive power and voltage control is referred to as automatic voltage control (AVC) [1-3]. Automatic generation control is a system for adjusting the power output of multiple generators at different power plants, in response to changes in the load.

With computer based control systems and multiple inputs, an automatic generation control system can take into account such matters as the most economical units to adjust, the coordination of thermal, hydroelectric, and other generation types, and even constraints related to the stability of the system and capacity of interconnections to other power grids[4]. A proportional integral derivative controller (PID controller) is a generic loop feedback (controller) widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then instigating a corrective action that can adjust the process accordingly and rapidly, to keep the error minimal. The PID controller calculation involves three separate parameters; the proportional, the integral and derivative values. The proportional value determines the reaction to the current error, the integral value determines the reaction based on the sum of recent errors, and the derivative value determines the reaction based on the rate at which the error has been changing [5].The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element.

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. One of the main results in the theory is that the solution is provided by the Linear-Quadratic Regulator (LQR). In layman's terms this means that the settings of a (regulating) controller governing either a machine or process (like an airplane or chemical reactor) are found by using a mathematical algorithm that minimizes a cost function with weighting factors supplied by a human (engineer). The "cost" (function) is often defined as a sum of the deviations of key measurements from their desired values. In effect this algorithm therefore finds those controller settings that minimize the undesired deviations, like deviations from desired altitude or process temperature. Often the magnitude of the control action itself is included in this sum so as to keep the energy expended by the control action itself limited [6].The LQR algorithm is, at its core, just an automated way of finding an appropriate state feedback controller. And as such it is not uncommon to find that control engineers prefer alternative methods like full state feedback (also known as pole placement) to find a controller over the use of the LQR algorithm. With these the engineer has a much clearer linkage between adjusted parameters and the resulting changes in controller behaviour. Difficulty in finding the right weighting factors limits the application of the LQR based controller synthesis.

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This paper is organized as follows section I give the introduction of Load frequency control. Section II gives basic about different controllers .Section III gives the simulation results and Section IV gives the conclusions.

II. BACK GROUND

A. Classical integer order PID controller:

The PID control is a widely used approach for designing a simple feedback control system, wherein three constants are used to weight the effect of the error (the P term), the integral of the error (the I term), and the derivative of the error (the D term). A typical structure of the classical IOPID-controlled system is shown in Fig. 1.

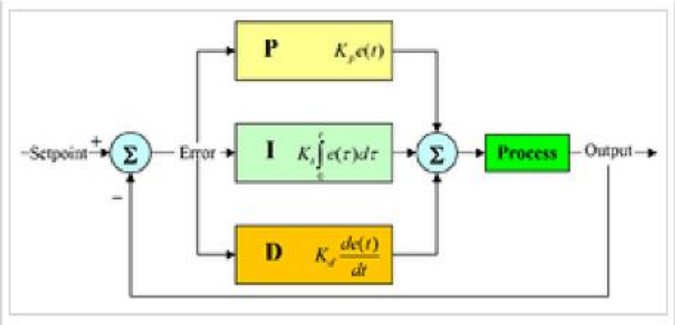

Fig.1 Block diagram of PID controller.

As the figure shows, in a PID controller, the error signal *e(t)* is used to generate the proportional, integral, and derivative actions, with the resulting signals weighted and summed to form the control signal *u(t)* applied to the plant model (system). A mathematical description of the PID controller is [7]:

$$u(t) = K_p e(t) + K_i \int_0^t e(T)dT + K_d \frac{d}{dt} e(t) \text{.........................(1)}$$

Where

$u(t)$ is the input signal to the plant to be controlled

$e(t)$ the error signal for a unity feedback system is defined as

$$e(t) = r(t) - y(t) \quad \text{........................... (2)}$$

$y(t)$ is the output plant and

$r(t)$ is the reference input signal

The transfer function $G_c(s) = U(s)/E(s)$ of the PID controller is expressed as

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \quad \text{.......................... (3)}$$

To implement a PID controller that meets the design specifications of the system under control, the three parameters of the controller must be determined for the given system. Other than trial-and-error approach, several rules and methods have been presented in control system literature such as the Zeigler–Nichols-based methods, root locus-based methods, and performance index-based methods. The later ones will be adopted in this paper. In control system design and analysis or for optimal control purposes, performance indices are calculated to be used as quantitative measures to evaluate a system’s performance, where a control system is judged as an optimum system when the system parameters are adjusted so that the index used in the design reaches its minimum value, while constraints of the controlled system are respected. The commonly used indices are integral of the square of the error (ISE), integral of the absolute value of the error

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(IAE), integral of the ITAE, integral of time multiplied by the squared error (ITSE). The ITAE measure, which will be implemented, is given by the following equation:

$$\text{ITAE} = \int_0^\infty t|e(t)|dt \quad \text{..............................} (4)$$

The optimal values for PID controller gains are obtained as the outputs of the constrained optimization of the performance measure. The constraints are the lower and upper limits
of the controller gains. The optimization problem can be formulated as:
Minimize ITAE (K_p, K_i, K_d)
Subject to

$$K_p^{\min} \le K_p \le_p^{\max}$$

$$K_i^{\min} \le K_i \le K_i^{\max}$$

$$K_d^{\min} \le K_d \le K_d^{\max}$$

In this paper, the MATLAB function *fmincon* will be used to solve the optimizations problems. *fmincon* is referred to as constrained nonlinear optimization or nonlinear programming. It is included in the MATLAB optimization toolbox, which finds a constrained minimum of a scalar function of several variables starting at an initial estimate. This function is well known and traditionally used in optimal control design as it is mature and a reliable algorithm.

B. 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

$$\dot{X} = AX + Bu \text{...........}(5)$$

where x is the n$\times 1$ state vector, **u** is the **p**$\times 1$input 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

$$U=-K\,x(t) \quad \text{...............} (6)$$

Where K is $p \times n$ real constant unconstrained gain matrix, that minimizes the following performance index subject to the initial conditions $X(0) \cong X^0$;

$$J = \frac{1}{2}\int_0^\infty (X^T Q X + u^T R u)dt \quad \text{.........} (7)$$

Where Q is $n \times n$ positive definite, real, symmetric, constant matrix and R is $p \times p$ positive definite, real, symmetric, constant matrix.

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

Substituting (6) into (5), we obtain

$$\dot{X} = AX - BKX = (A - BK)X \quad \text{............} (8)$$

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

C.LFC AND AGC SYSTEMS:

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The LFC system has three main objectives: keeps the power system frequency at an acceptable value, divides the load between the generators in a system, and controls the agreed upon load exchange through the tie-lines between interconnected areas [8]. In this system, changes (error signals) in frequency and active power of tie-lines are measured (i.e., Δf and ΔP_{tie}), which indicate the change in the machine's rotor angle. The error signals are then amplified, mixed and finally transformed into an actuating control signal of active power, which is sent to the prime mover or turbine to make the appropriate change (increment or decrement) in mechanical torque to produce a change in the active power output of generator, ΔP_g, needed to keep the power balance and thus affecting the values of Δf and ΔP_{tie} to be in acceptable ranges. The block diagram representation of the LFC of an isolated power system is shown in Fig. 3 [9]. The isolated system does not take changes in power interchange into consideration. If a sudden load change in the system shown in Fig. 3, it will cause, relatively, a large steady state frequency deviation, which makes frequency lie beyond the acceptable level.

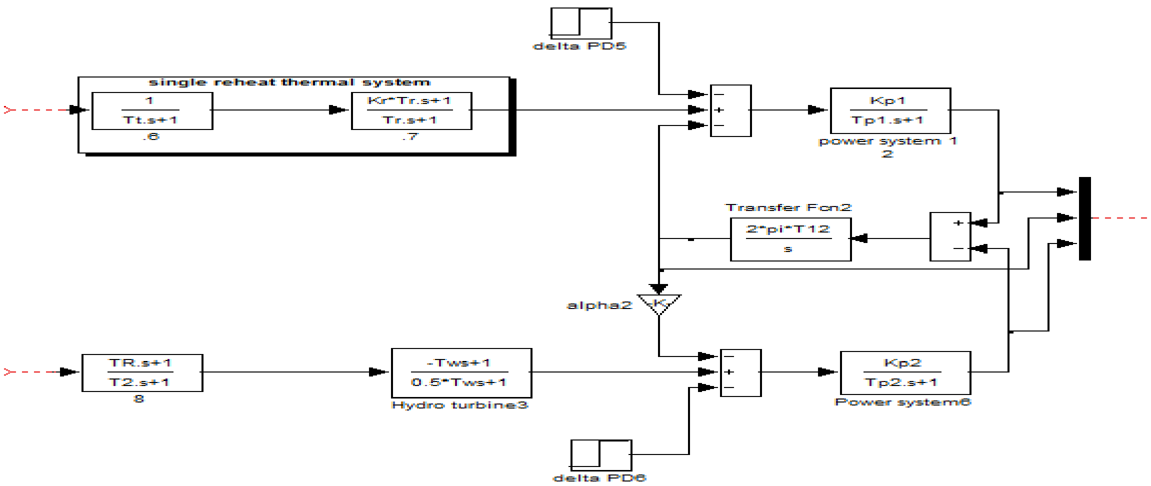

Fig. 2 Block diagram of AGC for a two area system with primary LFC

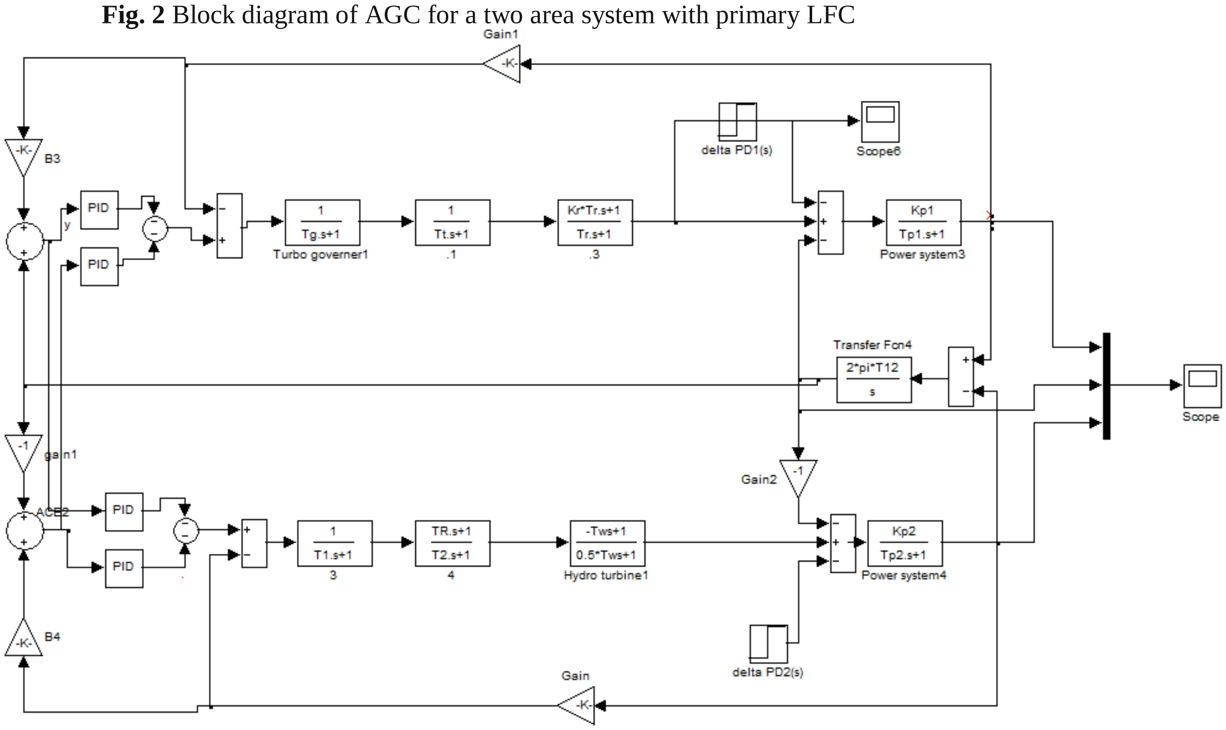

Fig.3 Block diagram of an AGC for a two area system with secondary LFC with PID controller.

Figure 2 shows an AGC for an interconnected system with only primary LFC, which is a two-area system. With only a primary LFC loop, frequency deviations and tie-line flow deviations from nominal values are non-zero, which lie beyond the acceptable level, if a sudden load change in the any area occurs. Figure 3 shows a block diagram representation of an AGC for the same interconnected system but with

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secondary LFC loops are utilized. In both figures (Figs. 2, 3), each area is represented by an equivalent machine with inertia constant *H* and a damping constant *D*, turbine, and a governor with a regulation *R*. The tie-line is represented by an accelerating power coefficient *Ps*. As load change in any area will result in a change in system's frequency in both areas and a change in power flow of tie-line.

The ACE is a linear combination of tie-line power flow changes and frequency deviation, therefore, the ACE of area *i* is expressed as:

$$ACE_i = \sum_{j=1}^{N} \Delta P_{ij} + B_i \Delta\omega_i \qquad (9)$$

Where *N* is number of areas interconnected with area *i*, ΔP_{ij} is the deviation of power interchange between areas *i* and *j* from the scheduled values P_{ij}, $\Delta\omega_i$ is deviation in speed

(frequency) of area *i*, and B_i is the frequency bias factor of area *i*, which is given by:

$$B_i = \frac{1}{R_i} + D_i \qquad (10)$$

The actuating error signal ACE_i is used to activate changes in the frequency set point of area *i* and when steady-state is reached, ΔP_{ij} and $\Delta\omega_i$ will be zero. The optimal value of the constants K_{i1} and K_{i2} for IOPI controllers of the two-area system are obtained by solving the optimization problem:

Minimize $ITAE_1(K_{i1}, K_{i2}) + ITAE_2(K_{i1}, K_{i2})$

Subject to

$$K_{i1}^{\min} \le K_{i1} \le K_{i1}^{\max}$$

$$K_{i2}^{\min} \le K_{i2} \le K_{i2}^{\max}$$

In this paper IOPID controllers shown Fig 3 are replaced by LQR controllers and the results were compared.

III. SIMULATION RESULTS

This section presents simulation results of the LFC and AGC systems using both IOPID (classical PID) controller and using the LQR controller. For each case of them, criteria of ITAE have been used to find the optimal values of controller parameters. System data of the LFC of the two area systems used in this paper are given in Appendix. In this paper, the lower limit for each of K_p, K_d and K_i is assumed zero and the maximum limit is 50 for each of them.

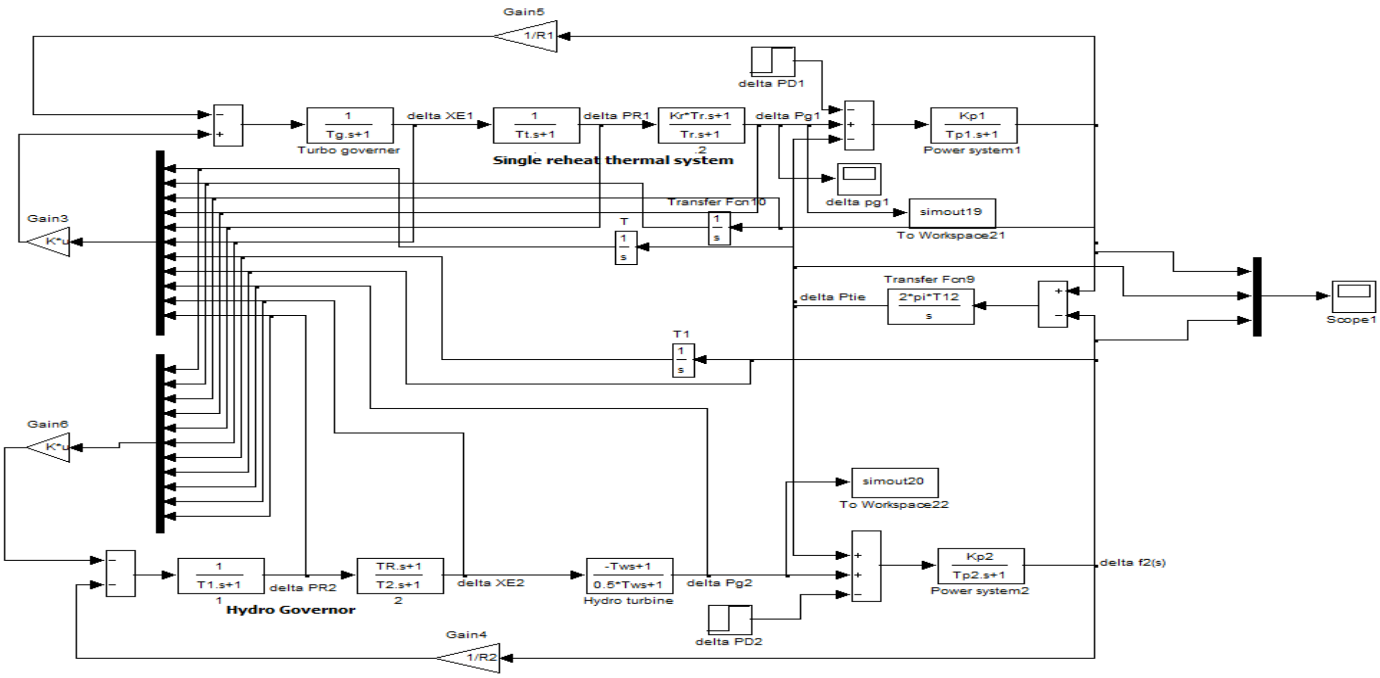

Fig 4 Simulation diagram of LQR controller with LFC

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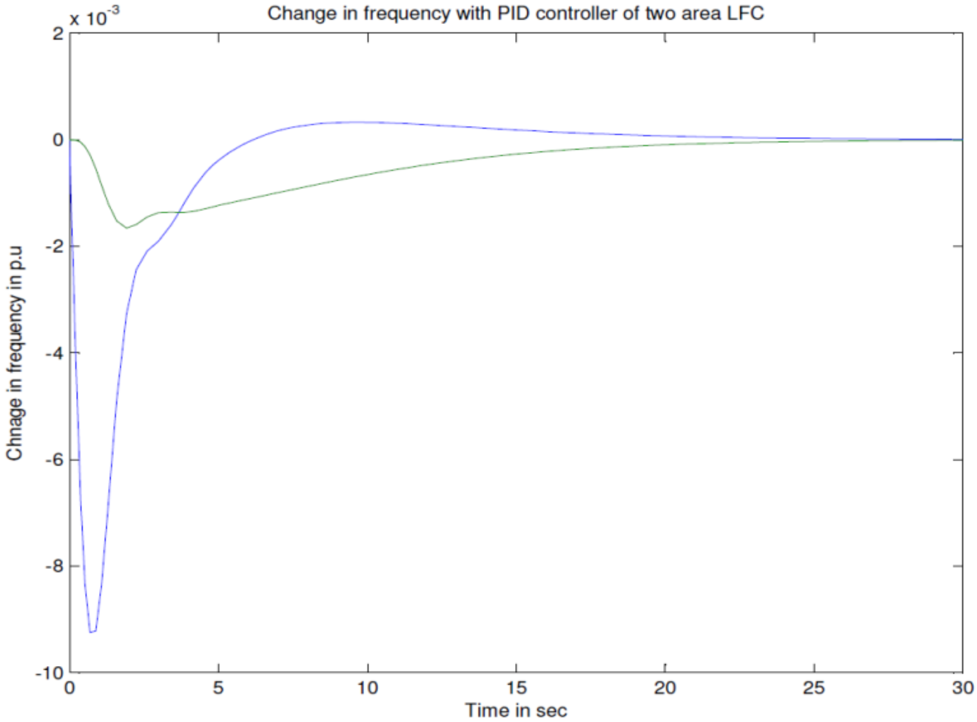

Fig.5. Response of the two area system with only primary LFC loop to a sudden load changes

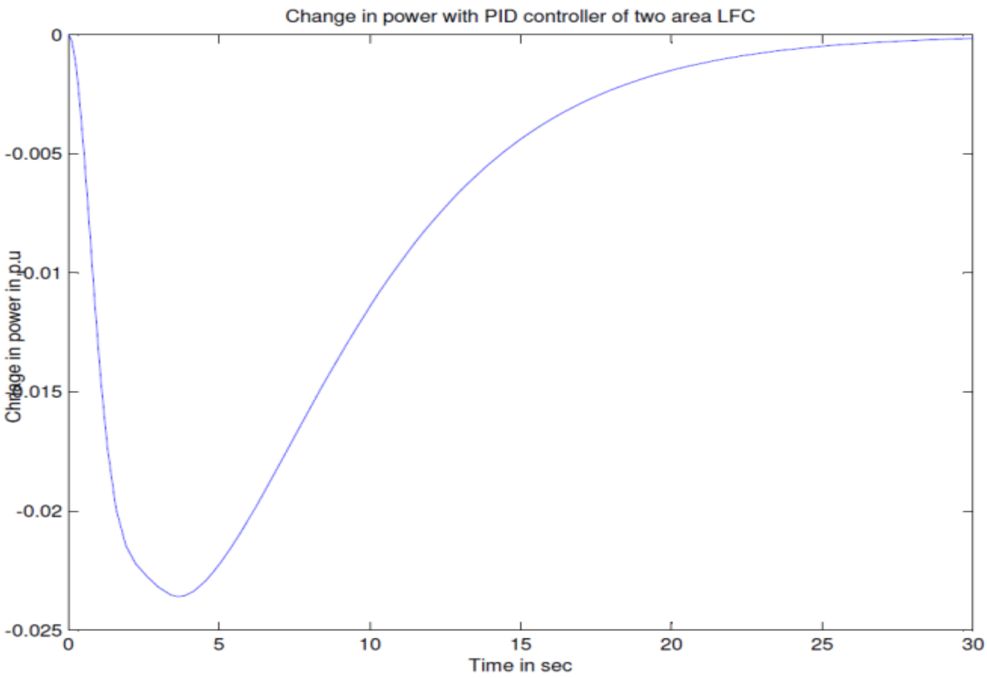

Fig.6. Change in tie-line power of the two area system with PID controller in the secondary LFC loop

The response of the LFC of the two-area system with only primary LFC loop following a step load change in area 1 (ΔP_{L1} = 0.2p.u., ΔP_{L2} =0*)* is shown in Fig.5. The response represents tie-line power deviation and frequency deviations in the two areas following the sudden load change. As the figure demonstrates, without a secondary LFC loop the response is accompanied by considerable steady-state errors in ΔP_{12} , Δf_1 and Δf_2 , sluggish performance, and long settling time. The frequency deviations also exhibit large overshoots.

Deviations of area frequencies of the optimal PID controllers of the LFC with secondary loop are shown in Fig. 6. For the system under study, adding a secondary LFC loop utilizing PID controllers has been found that it does not improve the response significantly as related to overshoots and settling time but eliminated the steady state error as previously noticed in Fig.5

In this paper IOPID controllers shown Fig.4 are replaced by LQR controllers. Deviations of tie-line power and area frequencies of the two area system with LQR controller in LFC secondary loop are shown in Fig.7.

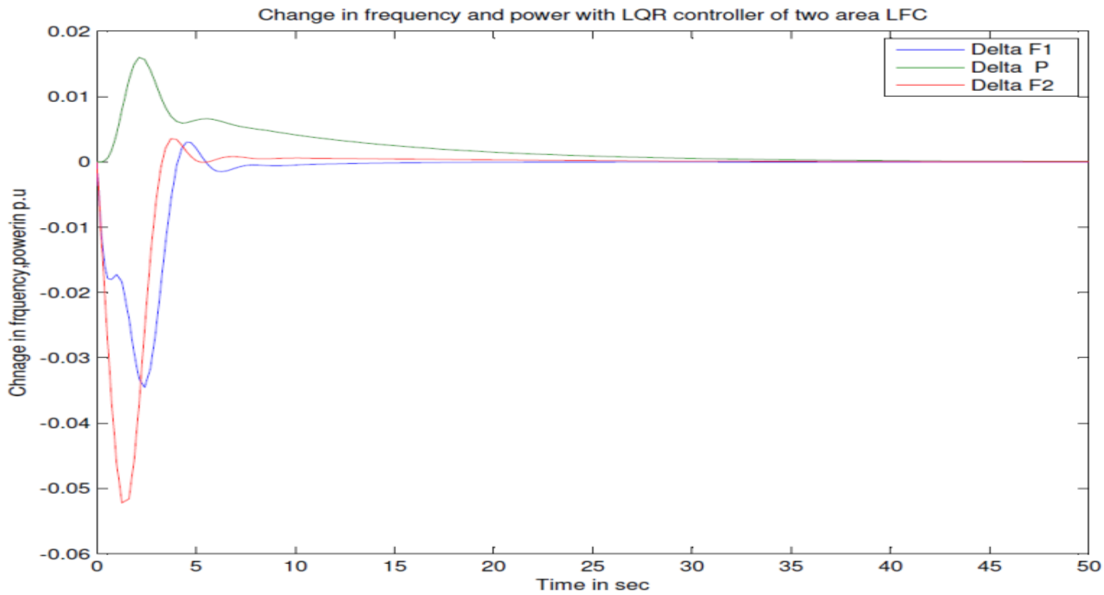

Fig.7. Change in the tie line power and frequency deviation of the two area system with LQR controller

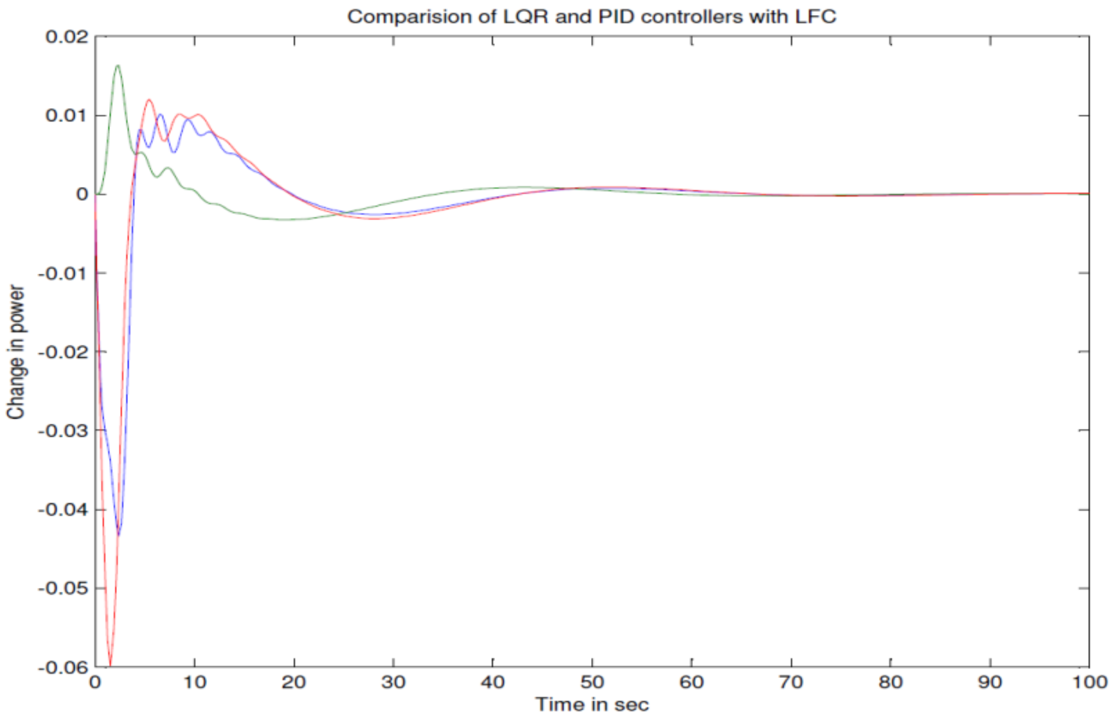

Fig.8. Change in the tie line power and frequency deviation of the two area system with LQR and PID controllers

As can be seen from this figure 8, the response obtained with LQR controllers is much better than the ones achieved with optimal PID controllers, i.e. adding a secondary LFC loop utilizing LQR controllers has been found that it has improved the response significantly as related to rise time, overshoots and settling time. Moreover, it has eliminated the steady state error.

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IV.CONCLUSION

The integer type PID controllers are well known and are widely used in power system, control systems to dampen system oscillations, increase stability and reduce steady state error as they are simple to realize and easily tuned. In LFC systems it is important to keep the power system frequency and the inter area tieline power as close as possible to the scheduled values, usually use simple integral controllers which are incapable of obtaining good dynamic performance. This paper has used the LQR controllers in place of the typical PID controllers for improving stability and response in feedback LFC system. The significant positive effects of applying LQR controllers to the LFC system are explored. The work presents a comparative analysis for PID and LQR. LFC of interconnected power systems, where in each case both LFC with primary loop and secondary loop have been considered. The results presented in this paper have shown that LFC system equipped with LQR controllers perform better than ones that have PID controllers. The simulation results show that the proposed LQR controllers are robust and competitive to PID controller.

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Bibliography

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