International Journal of Engineering Works
Kambohwell Publisher Enterprises
ISSN: 2409-2770 Vol. 5, Issue 3, PP. 40-49, March 2018
www.kwpublisher.com

Design of Optimal Linear Quadratic Gaussian (LQG) Controller for Load Frequency Control (LFC) using Genetic Algorithm (G.A) in Power System

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***Abstract*—**Nowadays power demand is increasing continuously and the biggest challenge for the power system is to provide good quality of power to the consumer under changing load conditions. When real power changes, system frequency gets affected while reactive power is dependent on variation in voltage value. For satisfactory operation the frequency of power system should be kept near constant value. Many techniques have been proposed to obtain constant value of frequency and to overcome any deviations. The Load Frequency Control (LFC) is used to restore the balance between load and generation by means of speed control. The main goal of LFC is to minimize the frequency deviations to zero. LFC incorporates an appropriate control system which is having the capability to bring the frequency of the Power system back to original set point values or very near to set point values effectively after the load change. This can be achieved by using a conventional controller like PID but the conventional controller is very slow in operation. Modern and optimal controllers are much faster and they also give better output response than conventional controllers. Linear Quadratic Regulator (LQR) is an advanced control technique in feedback control systems. It's a control strategy based on minimizing a quadratic performance index. In despite of good results obtained from this method, the control design is not a straight forward task due to the trial and error involved in the selection of weight matrices Q and R. In this case, it may be hard to tune the controller parameters to obtain the optimal behaviour of the system. The difficulty to determine the weight matrices Q and R in LQR controller is solved using Genetic Algorithm (G.A). In this research Paper, G.A based LQG controller which is the combination of LQR and Kalman Filter is feedback in LFC using MATLAB/SIMULINK software package. Reduction in frequency deviations and settling time was successfully achieved by using LQG Controller with LFC based on G.A.

***Keywords*—** Load Frequency Control, Linear Quadratic Regulator, Linear Quadratic Gaussian, Kalman Filter, Genetic Algorithm.

I. INTRODUCTION

Natural energy is converted into electrical energy using electrical power system. It is necessary to guarantee the quality of electrical power for the optimization of electrical equipment. The active and reactive power balance must be maintained during transmission, generation and utilization. The demand for a good quality electrical power system is to maintain the voltage and frequency at the desired value regardless of the changes in loads that occurs randomly. It is impossible to maintain the active and reactive power at desired values without use of control system, which results in variations of voltage and frequency levels. Active and reactive powers have a combined effect on frequency and voltage. The frequency depends largely on the active power and the voltage on reactive power. To overcome the effects of load variation and maintain frequency and constant voltage level, a control system is required. Frequency deviation can affect the stability of the system so, in order to maintain system stability imbalances between load and generation must be corrected in seconds to avoid frequency deviation. The problem of controlling the frequency in large power systems is by adjusting the production of generating units in response to changes in the load which is called Load Frequency Control (LFC). LFC is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. The electric power system becomes more and more complicated with an increasing demand. The power system is subjected to local variations of load in random magnitude and duration. As the load varies, the frequency related to that area is affected. Frequency transients should be removed as soon as possible. Generators working in that control area always vary their speed (accelerate or decelerate) to maintain the frequency and relative power angle to the predefined values with tolerance limit in static and dynamic conditions [1]. Electrical Power is generated by converting mechanical into electrical energy. The rotor which consists of turbine and generator units stored kinetic energy due to its rotation. This stored kinetic energy accounts for sudden increase in the load. Now consider the

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input of mechanical torque by Tm and the electric output torque by Te. Disregarding the rotational losses, a generating unit is operating in steady state at constant speed. The difference between these two elements of torque is zero. In this case we say that the accelerating torque is zero.

$$Ta = Tm - Te \tag{1}$$

When power demand increases suddenly, the electric torque increases. However, Tm remains constant without any feedback control mechanism to alter mechanical torque. Therefore, as a result, the accelerating torque becomes negative causing a deceleration of the mass of rotor. As the rotor decelerates kinetic energy is released to supply the increase in load. During this time the frequency of the system, which is proportional to the rotor speed also decreases. The deviations of the frequency form its nominal value of 50 or 60 Hz is indicative of the imbalance between Tm and Te. The frequency decreases when Tm < Te and rises when Tm > Te. The frequency must remain almost constant for satisfactory operation of the power system. Frequency deviations can directly impact power system performance, system reliability and efficiency [5]. Large frequency deviations can damage equipments and degrade load performance. Overloading can ultimately lead to a system collapse. Variation in frequency adversely affects the operation and speed control of induction and synchronous motors. Several control strategies have been proposed and investigated by several researchers for the design of LFC in power systems. Many classical approaches have been used to provide a supplementary control that will drive the frequency to the normal operating value within a very short time [9]. This extensive research is due to the fact that LFC is an important function of the power system, where the main objective is to maintain frequency fluctuations within preset limits. LFC incorporates an appropriate control system that has the ability to re-adjust the power system frequency to original set point values or very close to set point values effectively after the load change [2].

II. Brief Literature Review

Pradipkumar Prajapati has presented various conventional controllers for Multi-Area LFC in the power system. A comparison was made between PID controller and PI controller with battery storage system in terms of frequency deviations and settling time for 2-area LFC. Simulation results showed that the PID controller with battery outperformed the PI controller in terms of less frequency deviation and settling time [1]. Gajendra Singh Thakur used PI and PID controller to solve the LFC problem of single area power system. The simulation results show that the PID controller performs better than the PI controller because it reduces settling time with less overshoot. PID with a simple focus can provide better performance compared to the conventional PI controller. The results of the simulation show the superior performance of the system using the Z-N tuned PID controller. [2].

Mohinder Pal used the PI controller for LFC in the power system. It is seen that PI Controller results in a stable frequency. With appropriate choice of control parameters, frequency deviations can be effectively controlled. Due to disturbances in the power system frequency deviates. To overcome this problem PI controller is used [3]. Mohammed Wadi presents the analysis of an optimal LQR controller and the Legendre Wavelet function. A comparison was made between an optimal LQR controller and an optimal controller based on the Legendre Wavelet function in terms of performance in single area power systems. The results of the simulation showed that the optimal controller based on the method of approximation of the Legendre wavelet function surpassed the LQR controller in terms of less frequency deviation and steady state error, while both had the same settling time. A numerical example demonstrated the effectiveness of the optimal control proposed through the Legendre Wavelets Function over the LQR controller [4]. Divya has presented the hydro-power system simulation model. He has taken an assumption of same frequencies of all areas, to overcome the difficulties of extending the traditional approach. His model was obtained by ignoring the difference in frequencies between the control areas [11]. The concept of optimal control for LFC of in power system was first started by Elgerd. [17] R. K. Green discussed a new formulation of the principles of LFC. He has given a concept of LFC, directly controlling the set point frequency of each unit [18]. Fosha and Elgerd [17] were first presented their work on LFC using optimal process. A power system of two areas was considered for investigation. R. K. Cavin has considered the problem of LFC using optimal stochastic system point of view. An algorithm based on control strategy was developed which gives improvised performance of power system. The special attractive feature of the control scheme was that it required the recently used variables [20].

III. Load Frequency Control

In large electrical power systems, nominal frequency depends significantly on the balance of produced and consumed active power. Peak demands do not have any certain time so, they can occur in power system at any random time of the day. When the active power imbalance occurs in any part of the system this will result in changes in the overall system frequency. If there is an abrupt change in load in control area of the power system then there will be a frequency deviation. The generators in a control area always vary their speed together (accelerate or slow) to maintain the frequency at predefined values with a tolerance limit under both static and dynamic conditions. The main LFC is to keep the frequency constant by means of the speed control. The industrial loads connected to the power supply system are very sensitive to the quality of electrical energy mainly the frequency component. Thus, the steady-state frequency error in the system must remain within acceptable values in order to maintain the equilibrium. Possible increase in load reduces the nominal frequency of the system. This frequency alternation is detected by a regulator in the primary control loop. Thereafter, the speed of rotation of the turbine increases, resulting in an increase in the power produced. Frequency deviations can directly impact power system operation, system reliability and efficiency [6]. Large frequency deviations can damage equipments, overload transmission lines, degrade load performance and adversely affect the performance of system protection schemes.

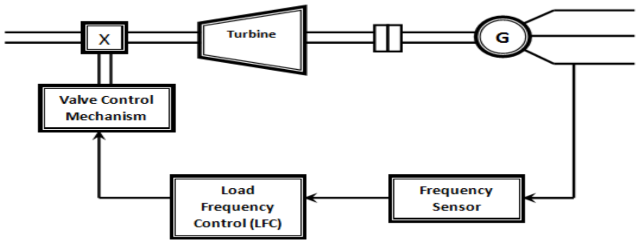

Figure 1. Example Block Diagram of LFC in Power system [8].

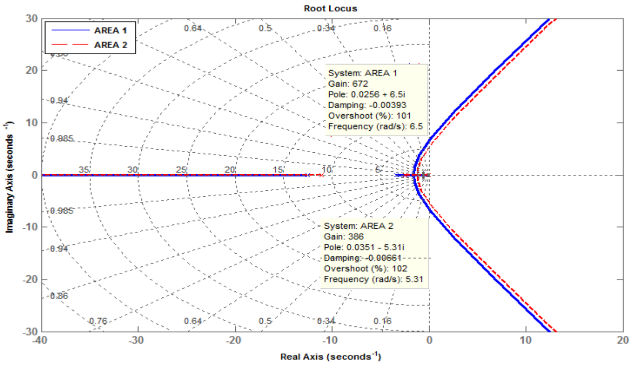

Figure 2. Root Locus of LFC in Power System

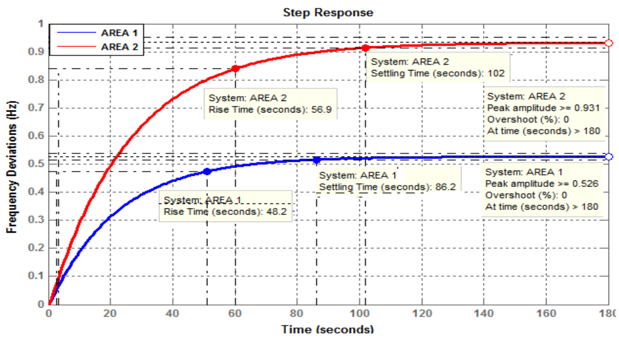

Figure 3. Open Loop Step Response of LFC in Power system

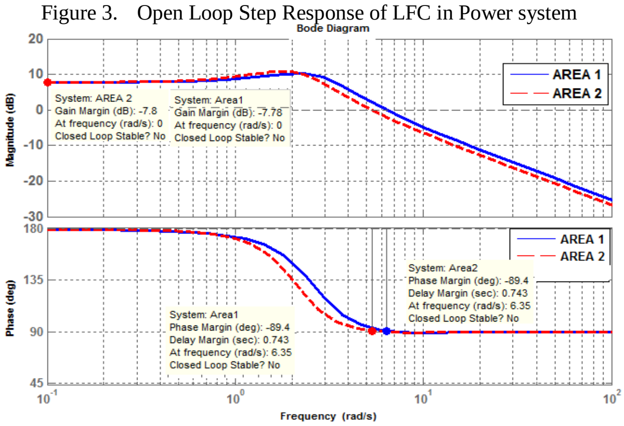

Figure 4. Bode Plot of LFC in Power system

These large-frequency deviation events can ultimately lead to a system collapse. The frequency variation adversely affects the operation and speed control of induction and synchronous motors. In household appliances refrigerator‘s efficiency decreases, reactive power consumption of television and air conditioners increases considerably with reduction in power supply frequency. It is very important to keep the frequency within an acceptable range. Due to the dynamic nature of the load, the continuous load change cannot be avoided but the system frequency can be maintained within sufficiently small tolerance levels by continuously adjusting the generation using LFC [4].

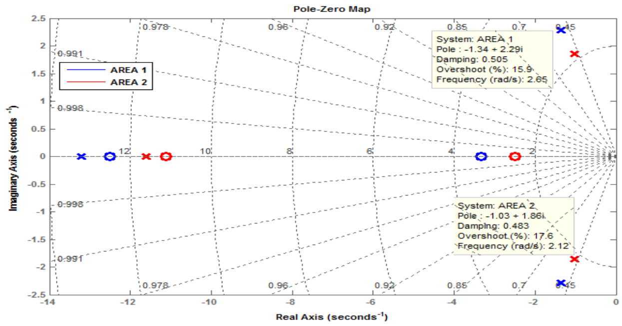

Figure 5. Pole Zero Mapping of LFC in Power system

IV. LINEAR QUADRATIC REGULATOR

This is a technique applied in the design of the control system that is implemented by minimizing the performance index of the system variables. Here, we discussed the design of optimal controllers for linear systems with quadratic performance index, also called LQR controller. The aim of the optimal regulator design is to obtain a control law u*(x, t) which can move the system from its initial state to the final state by minimizing the Performance Index. The Performance Index is selected to give a best trade-off between performance and cost of control. The Performance Index which is widely used is the Quadratic Performance Index and is based on minimum error and minimum energy criteria [9].

Consider a plant:

$$X(t) = Ax(t) + Bu(t) \tag{2}$$

The aim is to find the Vector K of the control law,

$$U(t) = -K x(t) \tag{3}$$

It minimizes the value of the Quadratic Performance Index J of the form,

$$J = \int_{to}^{t} (x^T Q x + u^T R u) dt \tag{4}$$

Where Q is a positive semi definite matrix and R is real symmetric matrix. The choice of the elements of Q and R allows the relative weighting of individual state variables and individual control inputs.

To obtain the solution we make use of the method of Langrange Multipliers. The problem reduces to the minimization of the following unconstrained equation, [9]

$$L[x, \lambda, u, t] = [x^T Q x + u^T R u] + \lambda^T [Ax + Bu - \dot{X}] \tag{5}$$

The optimal values are found by equating the partial derivative to zero.

$$\frac{dL}{d\lambda} = AX^{*}+BU^{*}-\dot{X}^{*}= 0 \quad , \quad X^{*} = AX^{*}+ BU^{*} \tag{6}$$

$$\frac{dL}{du} = 2RU^{*} + \lambda^{T} B =0 \quad , \quad U^{*} = \frac{-1}{2} R^{-1} \lambda^{T} B \tag{7}$$

$$\frac{dL}{dx} =2x^{T}Q+ \lambda^{T} + \lambda^{T}A =0 , \quad \dot{\lambda} = -2Q\dot{X}^{*}-A^{T} \lambda \tag{8}$$

Assume that there exists a symmetric, time varying positive definite matrix P(t) satisfying,

$$\lambda =2P (t) X^{*} \tag{9}$$

Substituting (3) into (7) gives the optimal closed-loop control law,

$$U^{*}(t) = - R^{-1}B^{T}P(t) X^{*} \tag{10}$$

Where,

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

Obtaining the derivative of (9),

$$\dot{\lambda}=2(\dot{P} X^{*}+P\dot{X}^{*}) \tag{11}$$

From (8) and (11), we obtained

$$P (t) = - P (t) A – A^{T}P (t) – Q + P (t) B R^{-1}B^{T} P \tag{12}$$

The above equation is referred to as Matrix Riccati Equation. For linear time invariant systems, since $\dot{P}$=0, when the process is of infinite duration tf =∞ (12) becomes,

$$PA + A^{T}P + Q - P B R^{-1}B^{T} P = 0 \tag{13}$$

One approach to find a controller that minimize the LQR cost function is based on finding the solution of above Algebraic Riccati Equation (ARE). The property of LQR controller is that it guarantees nominally stable closed-loop system. The MATLAB can be used for the solution of the Algebraic Riccati Equation. Choosing the weight matrices Q and R usually involves some kind of trial and error and they are usually chosen as diagonal matrices. In despite of the good results obtained from this method, the control design is not a straight forward task due to the trial and error method involved in the definition of weight matrices Q and R [8].

The solution of LQR results in an asymptotically stable closed-loop system if,

The system (A, B) is controllable.

R>0

$Q=C^{T} C$ Where (C, A) is observable.

The LQR design procedure is in stark contrast to classical control design, where the gain matrix K is selected directly. To design the optimal LQR, the design engineer first selects the design parameters weight matrices Q and R. Then, the loop time response is found by simulation. If this response is unsuitable, new values of Q and R are selected and design is repeated [9]

Classically the weight matrices Q & R can be written as, [9]

$$Q=C^{T}C \quad , \quad R=1 \tag{14}$$

The MATLAB code is written in MATLAB-R2011. The MATLAB command to obtained feedback K-Matrix is given as, [8]

$$[K, P]=lqr2 (A, B, Q, R) \tag{15}$$

The optimal gain vector K for Area 1 & Area 2 in Power system for LFC is obtained by using (15),

Feedback K-Matrix for Area 1=K1=[-0.0861 -0.5078 -0.9094]

Feedback K-Matrix for Area 2=K2=[-0.0771 -0.5292 -0.9146]

V. KALMAN FILTER

To fully implement the advantage of state feedback, all the states should be feedback. Typically the physical state of the system cannot be determined by direct observation. A state observer is a system that provides an estimate of the internal state of a system, from the measurements of the input and output of the system. If a system is observable then it is possible to design the system from its output measurements, using the state observer commonly known as Kalman Filter. It is based upon a measurement of the output given by (16) & (17) and known input U. This observer is guaranteed to be optimal in the presence of estimated states. The state estimation problem is given by [9].

$$\dot{X}(t) = A x (t) + B u (t) + \omega \tag{16}$$

$$Y (t) = C x (t) +D u (t) + v \tag{17}$$

Where,

A, B, C are the plant's state coefficient matrices.

ω is the input-process noise vector.

v is the output-measurement noise vector.

The optimal observer (Kalman Filter) is given by,

$$\hat{\dot{X}}(t) = A \hat{x}+Bu +L (Y-C\hat{x}) \tag{18}$$

Where $\hat{X}$ is the estimate of state x and L is the gain of Kalman Filter. The observer gain is computed as,

$$L=S C^{T}z^{-1} \tag{19}$$

Kalman filter is an optimal observer, the problem of Kalman filter is solved using Algebraic Riccati Equation as, [5]

$$AS+ SA^{T}-SC^{T}V^{-1}CS+B \omega B^{T} =0 \tag{20}$$

Eq. (20) is very similar to the LQR solution known as Riccati Equation. The ω and v represent the intensity of the process and sensor noise input and it can be selected by the user. These matrices are known as co-variance matrices. Their size is a measure of how strong the noise is; the larger the size, the more random or intense the noise hence it is called the noise intensity. Finally the mathematical condition for the design of Kalman Filter is that the matrices ω and v are positive semi definite and the system must be observable [9].

The Kalman gain matrix L is calculated with ω and v matrices as follows, [5]

$$\omega = 10\, B^T B \quad (21)$$

$$v = 0.01\, C\, C^T \quad (22)$$

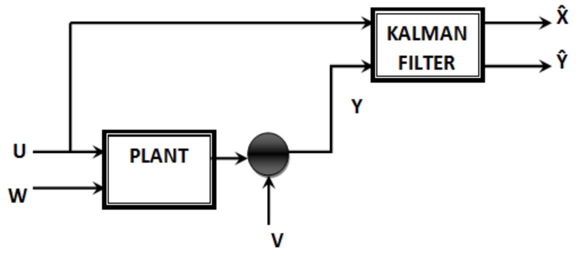

Figure 6. Block Diagram of Kalman Filter for LFC [9].

The MATLAB code is written in MATLAB-R2011. The Algebraic Riccati Equation can be solved using the specialized Kalman Filter MATLAB Command lqe. The MATLAB command to obtained observer gain L of Kalman Filter which is given by [5],

$$[L, S] = \text{lqe}\,(A, B, C, \omega, v) \quad (23)$$

Where,

L is the returned Kalman filter optimal gain.

S is the returned solution to the Algebraic Riccati Equation.

The observer gain L of Kalman Filter for Area 1 & Area 2 in Power system for LFC is obtained by using (23),

Observer L-Gain of Kalman Filter for $\text{Area}_1 = L_1 = \begin{bmatrix} -4.9329 \\ -0.0162 \\ 939.230 \end{bmatrix}$ (24)

Observer L-Gain of Kalman Filter for $\text{Area}_2 = L_2 = \begin{bmatrix} -4.366 \\ -0.0150 \\ 673.4705 \end{bmatrix}$ (25)

VI. Linear Quadratic Gaussian Controller

LQR controller and Kalman Filter were designed separately for LFC in the power system. First LQR controller is designed which is the cause of minimization of the quadratic objective function. Kalman Filter (State Estimator) is then introduced for LFC with presence of noise process ω and measurement noise v. The combination of LQR with the Kalman Filter forms an optimal compensator which is called as LQG Controller. The optimal compensator design process is the following, [5]

- Design an optimal regulator (LQR) for a linear plant using full-state feedback. The regulator is designed to generate a control input U (t), based upon the measured state-vector X.
- Design Kalman Filter for the plant assuming a known control input U (t) a measured output Y (t) including noises ω & v.
- Combine the separately designed LQR controller and Kalman Filter into an optimal compensator that generates the input vector U (t), based upon the estimated state-vector $\hat{X}$ rather than the actual state vector X, and the measured output Y (t).

The plant equation and the problem solution is now repeated,

$$\dot{X}(t) = A\,x(t) + B\,u(t) + \omega \quad (26)$$

$$Y(t) = C\,x(t) + v \quad (27)$$

The Control-Law of LQR is now given by,

$$U(t) = -K\,\hat{x}(t) \quad (28)$$

The state-space equation of Kalman Filter is given by,

$$\hat{X}(t) = A\,\hat{x} + Bu + L\,(Y - C\hat{x}) \quad (29)$$

By putting (28) of LQR controller in (29) of Kalman Filter, the state-space equation of LQG Controller is given by,

$$\hat{X}(t) = (A - B\,K - L\,C + L\,D\,K)\,\hat{x} + LY \quad (30)$$

Where,

K & L are the optimal regulator and Kalman Filter gain.

$\hat{X}$ Is the estimated state vector.

Fig. 7 shows the block diagram of Eq. (30) of optimal LQG-compensator,

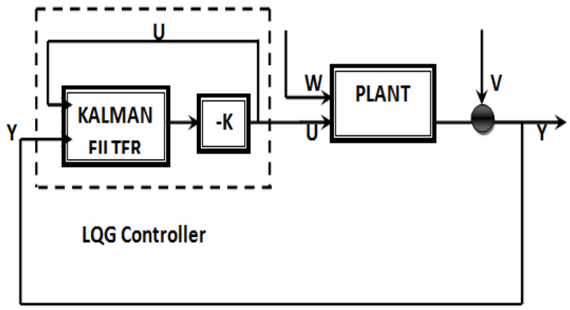

Figure 7. Block Diagram of LQG Controller for LFC [9]

Using MATLAB software, a state-space model of the closed-loop system can be constructed as follows, [5]

Sysp= ss(A,B,C,D); (31)

Sysc=ss(A-B*K-L*C+L*D*K ,L,K ,zeros (size (D'))); (32)

Syscl=feedback (sysp,sysc); (33)

Where,

Sysp = State-space model of the plant (LFC).

Sysc= State-space model of the LQG compensator.

Syscl = State-space model of the closed loop (Feedback) system.

VII. Genetic Algorithm

G.A is a search algorithms based on the mechanics of natural selection and natural genetics. It was invented in 1975 by John Holland at University of Michigan [23]. The G.A starts with no knowledge of the correct solution and depends

ISSN: 2409-2770

on response from its environment and evolution operators to arrive at the best solution. By starting at several independent points and searching in parallel, the algorithm avoids local minima and converging to optimal solutions. In this way, G.A has been shown to be capable of locating high performance areas in complex domains without experiencing the difficulties associated with high dimensionality. G.A is typically initialized with a random population. This population is usually represented by a real valued number or a binary string called a chromosome. The algorithm starts with a random population of individuals (chromosomes) and through genetic processes similar to those occurring in nature, evolve under specified rules in order to minimize a cost function. Since, the population is generated randomly the G.A is able to virtually search the entire solution space and provide simultaneous searches at different points in this space. During the algorithm execution the chromosomes that possess the best fitness (lowest cost) generate offspring and improving the average cost value of the population as a whole [12].

In LQG problem, the weighting matrices Q and R have profound effect on controller performance. On the other hand, finding the best Q and R needs many computer simulation and trial and errors, which are very time-consuming. Thus using intelligent optimization methods for finding Q and R is more effective [13]. The G.A objective here is to determine matrices Q and R so that LFC presents small overshoot and less settling time in the event of a load disturbance. For this, each chromosome is composed by the genetic structure defined in Table 1. The weight matrixes Q and R are generally used in the form of a diagonal matrix. They can be optimize by using the following representation, [21].

$$Q_w^{G.A} = \begin{bmatrix} q_{11} & 0 & 0 \\ 0 & q_{22} & 0 \\ 0 & 0 & q_{33} \end{bmatrix}, \quad R_w^{G.A} = q_{44} \qquad (34)$$

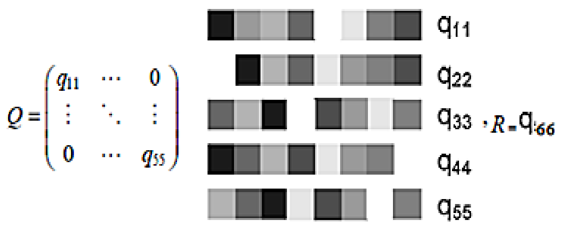

Figure 8. Chromosomal Representation of Q and R Matrices [13].

G.A is universally applicable, because they need only a good fitness function to work which is a requirement for any optimization technique so; objective function is the most important part of G.A [23]. An objective function is created to find a weight matrices Q and R for LQG controller that gives the smallest overshoot and quickest settling time. Each chromosome in the population is passed into the objective function one at a time The chromosome is then evaluated and assigned a number to represent its fitness, the bigger its number the better its fitness. The G.A uses the chromosome's fitness value to create a new population consisting of the fittest members.

TABLE I. GENETIC STRUCTURE FOR OPTIMAL Q AND R MATICES [21].

Gene	1	2	3	4
Parameters	q_{11}	q_{22}	q_{33}	r_{11}

The chromosome is formed by three values that correspond to the three gains of the weight matrix Q and R. The gains q_{11}, q_{22} and r_{11} are positive numbers and characterize the individual to be evaluated.

The objective fitness function to find the optimal values of weight matrices Q & R is, [12]

$$F(Q, R) = 1/(q_1x_1^2 + q_2x_2^2 + q_3x_3^2 + q_4u^3) \qquad (35)$$

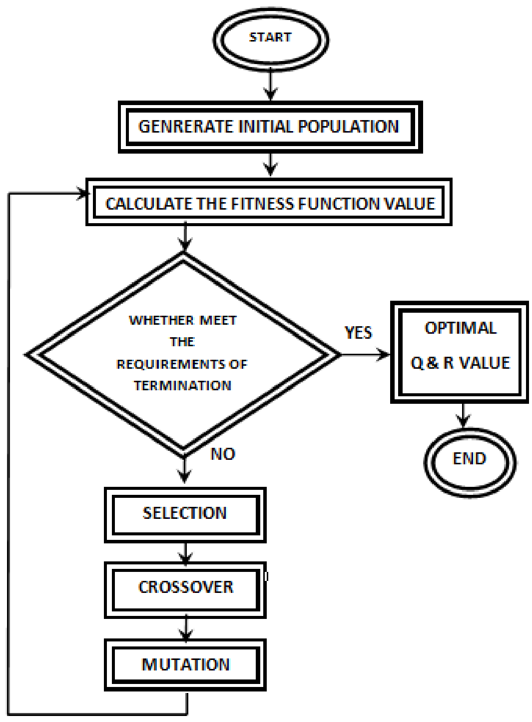

Figure 9. The Flowchart for Optimal Value of Q & R Matrices Using G.A [12].

The MATLAB is used to find the optimal weight matrices Q & R, which is found by using fitness values and current best individual using (35),

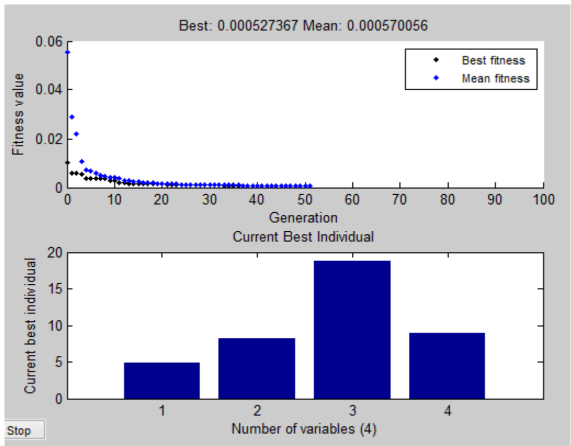

Figure 10. Matlab Simulation of G.A for Optimal Value of Q & R

After 51 Generations search the optimal solution is given by,

$$Q_w^{G.A} = \text{diag}\,(4.821,\ 8.139,\ 18.743)\ ,\ R_w^{G.A} = 8.904 \quad (36)$$

The MATLAB code is written in MATLAB-R2011. The MATLAB command to obtain feedback K-Matrix is, [5]

$$[K,\ P] = \text{lqr2}\ (A,\ B,\ Q,\ R) \quad (37)$$

The optimal gain K for Area 1 & Area 2 using G.A for LFC is obtained by using (37),

Feedback K-Matrix Using G.A for Area 1:

K1=[-0.0430 -0.5592 -1.4152]

Feedback K-Matrix Using G.A for Area 2 :

K2 = [-0.0361 -0.5738 -1.4185]

VIII. Simulation and Results

A comparison of LFC consists of six scenarios: the first one contains no controller (uncompensated LFC), the second scenario used PID Controller, the third scenario used LQR Controller, the fourth scenario used LQG Controller, the fifth scenario used LQR controller based on G.A and finally the last scenario used LQG Controller based on G.A has been observed. The comparison is made in terms of performance with respect to frequency deviations and settling time as shown in Table 4. The parameters of the numerical example of LFC are shown in Table 3. The simulation is carried out using MATLAB/SIMULINK software.

A. *LFC without any Controller*

In the first scenario, Simulink diagram of LFC is constructed using MATLAB and solved without using any controller. Fig. 11 and Fig. 12 show the Simulink diagram of LFC and the frequency deviations respectively,

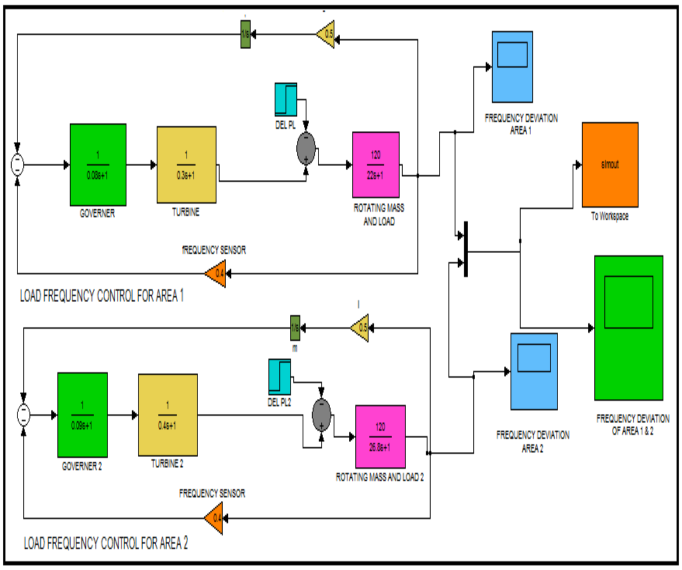

Figure 11. Simulink Model of First Scenario for LFC without any controller (uncompensated LFC)

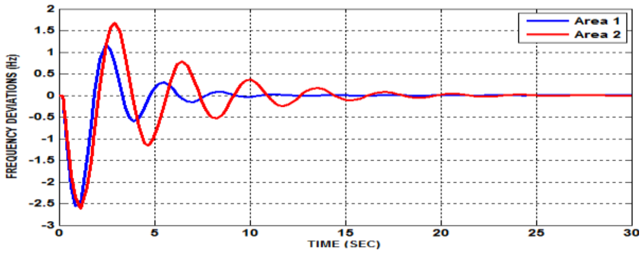

Figure 12. Frequency Deviation of First Scenario for LFC without any controller.

B. *LFC with PID Controller*

In the second scenario, MATLAB Simulation of LFC is constructed in which PID controller is designed to reduce the frequency deviations and settling time of the LFC in the power system. Fig. 13 and Fig. 14 show Simulink diagram and the frequency deviations respectively,

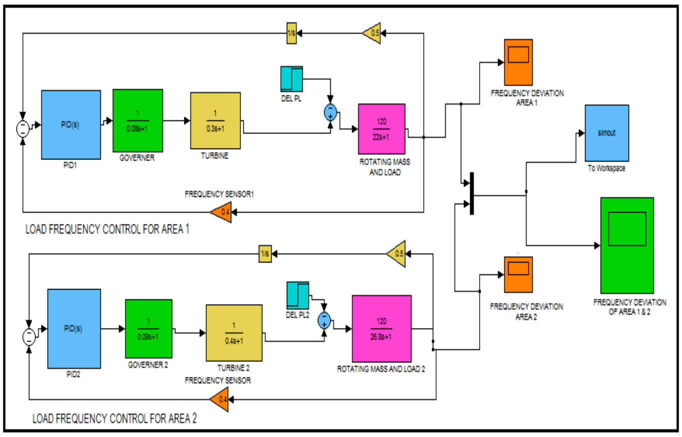

Figure 13. Simulink Model of Second Scenario for LFC using PID_controller.

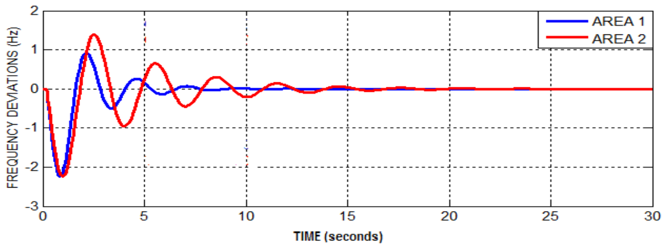

Figure 14. Frequency Deviation of Second Scenario for LFC using PID_controller.

C. *LFC with LQR Controller*

In the third scenario, LQR controller is designed in which K-gain vector is used as a feedback to reduce the frequency deviations and settling time of the LFC in the power system. The LQR controller is designed using (15) in M-file and MATLAB. The Simulink diagram and the frequency deviations are shown in Figs. 15 & 16 respectively,

ISSN: 2409-2770

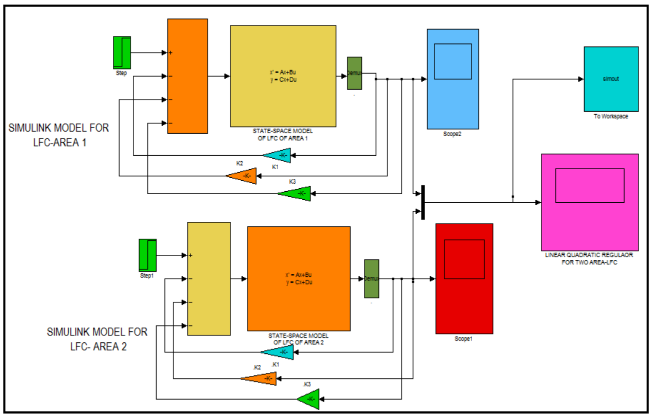

Figure 15. Simulink Model of Third Scenario for LFC with LQR_Controller.

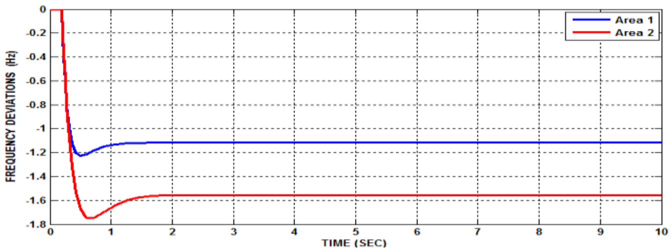

Figure 16. Frequency Deviation of Third Scenario for LFC with LQR Controller.

D. LFC with LQG Controller

In the fourth scenario, LQR controller is combined with Kalman Filter to form LQG controller, which is then used as feedback in LFC to reduce the frequency deviations and settling time in Power system. The LQG controller is designed using (31) to (35) in M-file using MATLAB. The frequency deviation is shown in Fig. 17,

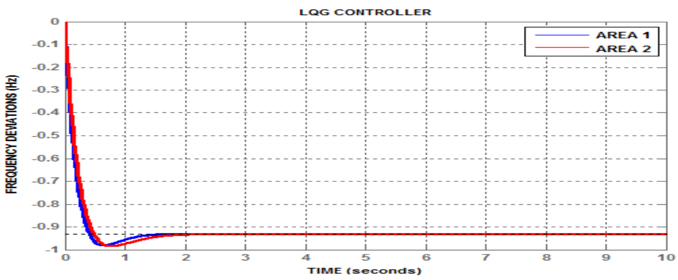

Figure 17. Frequency Deviation of Fourth Scenario for LFC with LQG Controller.

E. LFC with LQR Controller based on G.A.

In fifth scenario, LQR optimal controller is designed using G.A which is used to search the optimal value of Q & R. The K-gain vector is then used as a feedback to reduce the frequency deviations and settling time of the LFC in the power system. The LQR controller based on G.A is designed using (15) in M-file and MATLAB. The simulink diagram and the frequency deviations are shown in Figs. 18 & 19 respectively

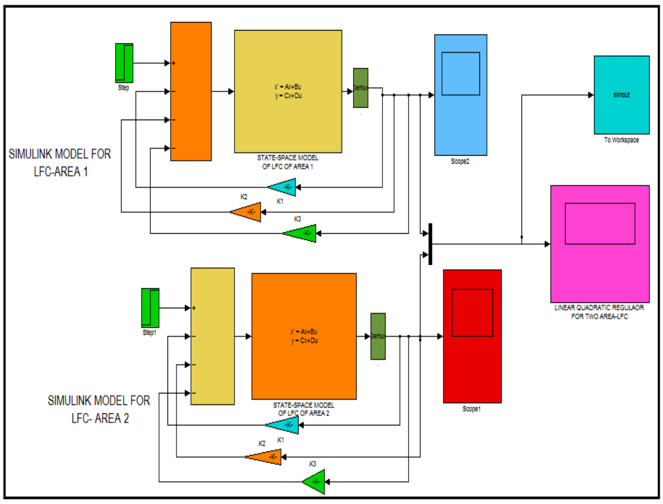

Figure 18. Simulink Model of Fifth Scenario for LFC with LQR_Controller based on G.A

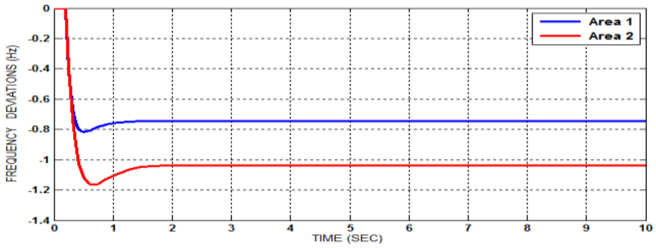

Figure 19. Frequency Deviation of Fifth Scenario for LFC with LQR_Controller based on G.A

F. LFC with LQG Controller based on G.A.

In the final scenario, G.A based LQR controller and Kalman Filter are combined with to form LQG controller, which is used as a feedback in LFC to reduce the frequency deviations and settling time in Power system. The LQG controller is designed using (31) to (35) in M-file using MATLAB. The frequency deviation is shown in Fig. 20,

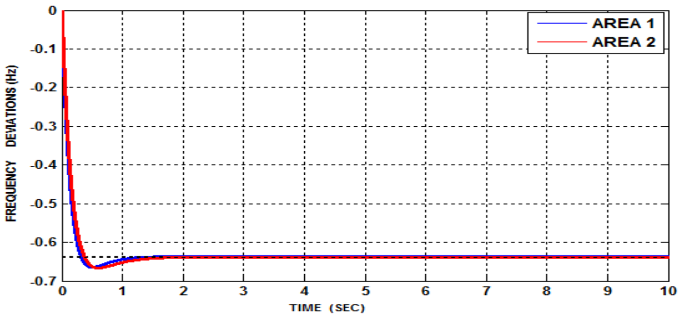

Figure 20. Frequency Deviation of Final Scenario for LFC with LQG Controller based on G.A.

G. Performance of LFC during different sudden load disturbance (ΔP_L)

For Area 1

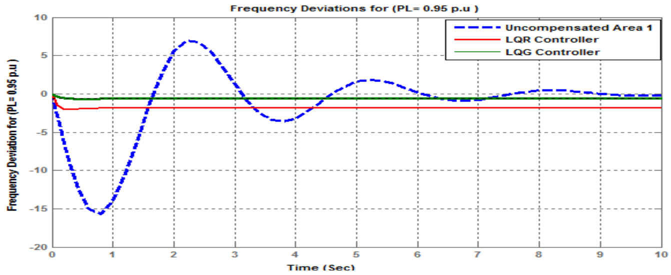

Figure 21. Frequency Deviations due to Load Disturbance with & without LQG & LQR controllers at ΔP_L = 0.95P.u

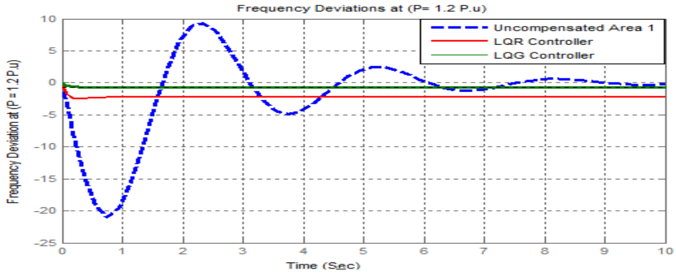

Figure 22. Frequency Deviations due to Load Disturbance with & without LQG & LQR controllers at ΔP_L = 1.2 P.u

For Area 2

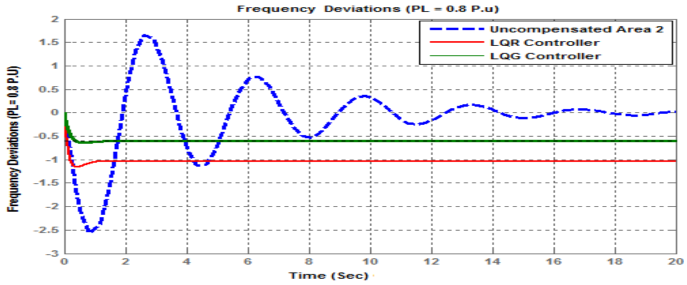

Figure 23. Frequency Deviations due to Load Disturbance with & without LQG & LQR controllers at ΔP_L = 0.8 P.u

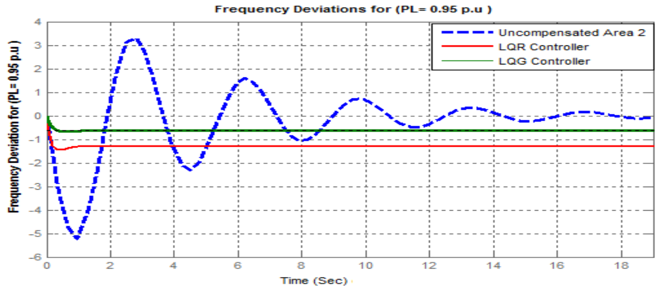

Figure 24. Frequency Deviations due to Load Disturbance with & without LQG & LQR controllers at ΔP_L = 0.95P.u

H. Comparative Analysis of Different Controllers with LFC

Fig. 25 & Fig. 26 show the performance of LFC for Area 1 & Area 2 by various controllers over frequency deviations and settling time in power system.

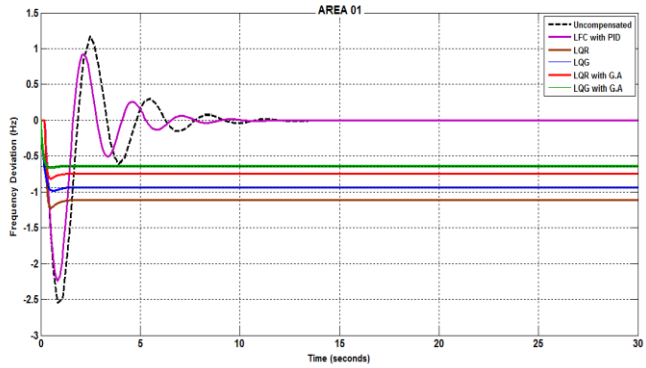

Figure 25. Comparative Analysis of different Controllers with LFC for Area 1

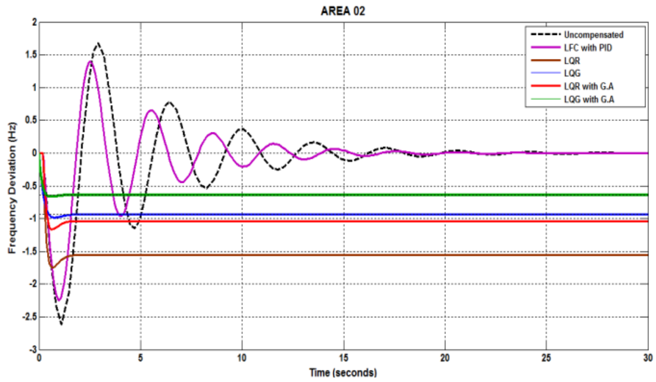

Figure 26. Comparative Analysis of different Controllers with LFC for Area 2

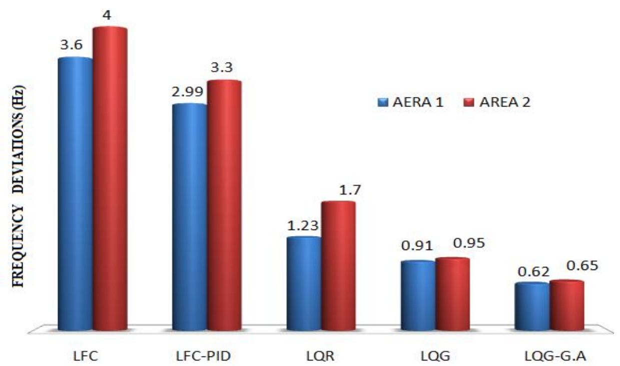

Figure 27. Frequency Deviations of LFC with Different Controllers

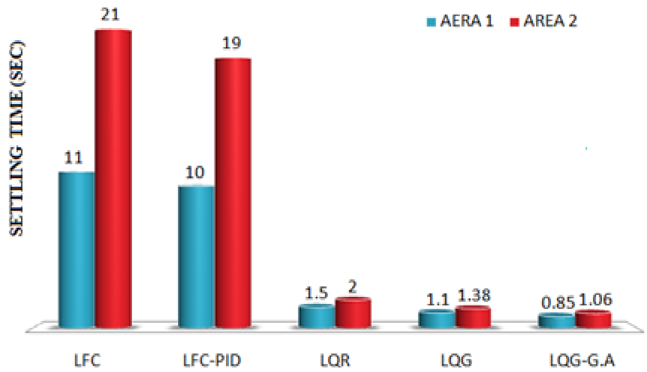

Figure 28. Settling Time of LFC with Different Controller

TABLE II. COMPARATIVE ANALYSIS OF DIFFERENT CONTROLLERS WITH LFC

Parameter	Area	LFC without any Controller	LFC with PID Controller	LFC with LQR Controller	LFC with LQG Controller	LFC with LQR Controller using G.A.	LFC with LQG Controller using G.A.
Overshoot	1	1.1	0.89	0	0	0	0
	2	1.5	1.20	0	0	0	0
Undershoot	1	2.5	2.1	1.23	0.91	0.8	0.62
	2	2.5	2.1	1.7	0.95	1.18	0.65
Settling Time	1	11	10	1.5	1.1	1.0	0.85

ACKNOWLEDGMENT

All Co-authors are thankful to Mr. Muddasar Ali, Lecturer & Researcher, Faculty of Electrical Engineering, Wah Engineering College (WEC), University of Wah, Pakistan for his valuable suggestions and necessary recommendations.

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