POWER SYSTEM CONTROLLER DESIGN BASED ON ROBUSTH_2THEORY

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ABSTRACT

This paper proposes a robust H_2 feedback controller design for damping power system oscillations over a wide range of operating conditions. Robust H_2 control technique based power system controller is developed for both excitation system and speed governor control. The effectiveness of the proposed power system controller is validated by a simple power system composed of a synchronous generator connected to an infinite bus through a transmission line. A comparison between power system responses at variety of operating conditions using the proposed H2 controller and Linear Quadratic Regulator LQR control is obtained. The digital simulation results prove the powerful of the proposed power system controller based on H_2theory in terms of fast power system mechanical oscillation damping over a wide range of operating conditions with system uncertainty and parameters change.

Keywords: H_2 control Theory, LQR control, synchronous generator.

1. Introduction

Early machines and equipment had controls which were predominantly of a manual nature, and the adjustments had to be reset frequently to maintain the desired output or performance. The design of newer equipment with greater usefulness and capabilities is bringing about an ever-increasing growth in the development of control equipment. There are two reasons. First, automatic controls relieve people of many monotonous activities so that they can devote their abilities to other endeavors. Second, modern complex controls can perform functions which are beyond the physical abilities of people to duplicate such as fuzzy logic controller and neural network. For example, an elaborate automatic control system operates the engine of a modern jet air plane with only a minimum amount of the pilot's attention so that the pilot is free to maneuver and fly the airplane [1].

There were advanced search technique such as genetic algorithm (GA) has been implemented to design a power system controller. Genetic algorithms (GA) were developed as in [2] and are based on the principles of natural selection and genetic modification. GA are optimization methods, which operate on a population of points, designated as individuals. Each individual of the population represents a possible solution of the optimization problem. Individuals are evaluated depending upon their fitness. Fitness indicates how well an individual of the population solves the optimization problem. [2].

The modern trend in engineering systems is toward greater complexity, due mainly to the requirements of complex tasks and good accuracy. Complex systems may have multiple inputs and multiple outputs and may be time varying. Because of necessity of meeting increasingly stringent requirements on the performance of control systems, the increase in system complexity, and easy access to large scale computers, modern control theory, which is a new approach to the analysis and design of complex control systems, has been developed since around 1960.[3,4]

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The robust H2 filtering problem is often formulated in a kalman-stochastic context, where the uncertain dynamic system is subjected to white Gaussian disturbance. The objective of the design problem is to find the filter parameters such that the worst case mean square estimation error is minimized.[5-9]. Modern robust control theory such as H2 and H∞ theory can be used to damp power system oscillations with system uncertainty,[10-15]. There are many robust control methods say H_2, H_∞ and LQG control …etc...

In this study, H2 power system controller has been designed and applied to synchronous machine connected to infinite bus through transmission line.

2. Power system mathematical model

Figure 1shows the Block diagram of the power system model which consists mainly a synchronous machine connected to an infinite bus through transmission line. The linear differential equations of the power system under study described as follow [12,13]:

$$\Delta\dot{\delta} = \Delta\omega \tag{1}$$

$$\Delta\dot{\omega} = -\left(\frac{K_1}{M}\right)\Delta\delta - \left(\frac{D}{M}\right)\Delta\omega - \left(\frac{K_2}{M}\right)\Delta E'_q + \left(\frac{1}{M}\right)\Delta T_m - \left(\frac{1}{M}\right)\Delta P_d \tag{2}$$

$$\Delta\dot{E}_q = -\left(\frac{K_4}{T'_{d0}}\right)\Delta\delta - \left(\frac{1}{K_3 T'_{d0}}\right)\Delta E'_q + \left(\frac{1}{T'_{d0}}\right)\Delta E_{fd} \tag{3}$$

$$\Delta\dot{T}_m = -\left(\frac{1}{T_t}\right)\Delta T_m + \left(\frac{1}{T_t}\right)\Delta P_g \tag{4}$$

$$\Delta\dot{P}_g = -\left(\frac{1}{RT_g}\right)\Delta\omega - \left(\frac{1}{T_g}\right)\Delta P_g + \left(\frac{1}{T_g}\right)U_2 \tag{5}$$

$$\Delta\dot{E}_{fd} = -\left(\frac{1}{T_A}\right)\Delta E_{fd} - \left(\frac{K_A K_5}{T_A}\right)\Delta\delta - \left(\frac{K_A K_6}{T_A}\right)\Delta E_q' + \left(\frac{K_A}{T_A}\right)\Delta U_1 \tag{6}$$

The state spaceform of the above equations is:

$\dot{X} = AX + BU$, where:

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & \frac{1}{M} & 0 & 0 \\ -\frac{K_4}{T'_{d0}} & 0 & \frac{-1}{(K_3 T'_{d0})} & 0 & 0 & \frac{1}{T'_{d0}} \\ 0 & 0 & 0 & \frac{-1}{Tt} & \frac{1}{Tt} & 0 \\ 0 & -\frac{1}{(RT_g)} & 0 & 0 & \frac{-1}{T_g} & 0 \\ -\left(\frac{K_4 K_5}{T_A}\right) & 0 & -\left(\frac{K_A K_6}{T_A}\right) & 0 & 0 & \frac{-1}{T_A} \end{bmatrix}$$; system matrix.

$$X = \begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \\ \dot{\Delta E'_q} \\ \dot{\Delta T_m} \\ \dot{\Delta P_g} \\ \dot{\Delta E_{fd}} \end{bmatrix} \text{; state vector.} \qquad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1/Tg \\ \dfrac{K_A}{T_A} & 0 \end{bmatrix} \text{, input matrix}$$

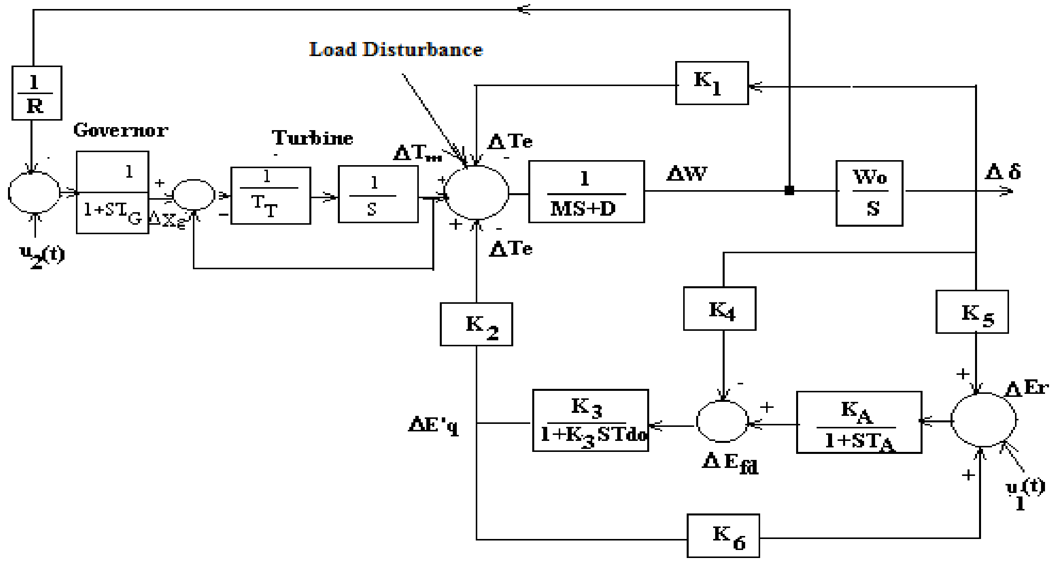

Fig.1. Block diagram of the power system model [12]

3. H_2 Power system controller design

The robustness can be defined as the ability of the controller to maintain the stability of the system over a wide range of operating condition. One way of ensuring system robustness is to take into consideration at the design stage, the various uncertainties that arise in the system due to inaccuracy of the mathematical model, the system parameter variations, neglected dynamics etc. Modern robust controls theory such as H_2 theory can be used to damp power system oscillations with system uncertainty. One of the important in H_2 optimal control design is the choice of the weighting functions. Weighting function are necessary to achieve a trade-off between the conflicting design requirements such as small sensitivity and complementary sensitivity. However, there is no systematic procedure yet available for selecting these weighs. [10,11]

The H_2 formulation and solution procedures are explained on how to choose proper weighting functions that reflect the robustness and performance goals. Also, H_2 synthesis is carried out in two stages [9]. First, called the formulation procedure to robust for modeling errors and weighting. Second one, called the solution procedure; the weights are iteratively modified until an optimal controller. Time response simulations are used to validate the results obtained. The effectiveness of such controllers is examined at different extreme operating conditions. The present section uses robust H_2 approach to design a robust power system controller applied on synchronous machine with its control system connected to an infinite bus through a transmission line. The essential feature of the proposed H_2 power system controller is that it is simple, easy to implement, and it is not sensitive to the external disturbances and power system parameter variations. The illustration of the H_2 controlled system is shown in Fig. 2. The linear plant P with input u_2, disturbance u_1, and performance output y_1 and measurement signal y_2. The input is generated by dynamic output feedback, using the controller K. The signal y_1 is the performance associated with the H_2 criterion. Furthermore, u_1 represents an exogenous signal and $H_{y1u1}(s)$ denotes the closed loop transfer function from y_1 to u_1 (output to input). Then the following control objectives are equivalent [5].

1- The closed-loop system is asymptotically stable.

2- The performance function $\left\| H_{y1u1} \right\|_2$ is minimized.

Fig. 2 shows the stabilizing control K for a system plant P. The augmented system plant P can be calculated by calling MATLAB function "*augment*" as:

$$(A, B_1, B_2, C_1, C_2, D_{11}, D_{12}, D_{21}, D_{22}) = augment(sys, W_1, W_2, W_3) \quad (7)$$

Where; $P = \left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{array} \right]$

The compensation configuration depicted in Fig. 2 will be referred to as the standard compensator of robust H_2 controller. The objective is to design a controller K, for the plant P such that the input/output transfer characteristics from the external input vector u1 to the external output y_1 is desirable, according to some engineering specification. The weighting system W1, W2, W3 (state-space form) function were chosen to reflect desired robust H_2 and performance goals. The TSS_P system can be determined by using the MATLAB function *mksys* as follows:

$$Tss\_P = mksys(A \quad B_1 \quad B_2 \quad C_1 \quad C_2 \quad D_{11} \quad D_{12} \quad D_{21} \quad D_{22}) \quad (8)$$

Which compute the H_2 controller and the controller feedback K by using MATLAB function H_2as:

$$[SS\_Cp, SS - Cl) = H_2 syn(Tss\_P) \tag{9}$$

The output data is:
Controller matrix F(s)= SS_CP ,
Closed-Loop transfer matrix K= SS_CL
Referred to Fig.2 shows the general setup of the H_2 design problem where:
P(s): is the transfer function of the augmented plant (nominal plant G(s) plus the weighting functions that reflect the design specifications and goals),
u2: is the exogenous input vector, typically consists of command signals, disturbance, and measurement noises,
u1 : is the control signal,
y2 : is the output to be controlled, its components typically being tracking errors, filtered actuator signals,
y1: is the measured output.

Figure 3 shows the block diagram of the robust H_2 controller applied to the power system under study.
Fig.4 depicts the Schematic diagram of power system model with H2power system stabilizers.
W1, W_2, and W_3 is the weighting matrix and it is selecting to give good damping response [11]. Then, the following fundamental relations and fined as:

$$y(s) = \frac{G(s)K(s)}{1+G(s)K(s)} r(s) + \frac{1}{1+G(s)K(S)} d(s) - \frac{G(s)K(s)}{1+G(s)K(s)} n(s)$$

The complementary transfer function
$T(s) = \frac{G(s)K(s)}{1+G(s)K(s)}$Also, the sensitivity transfer function$S(s) = \frac{1}{1+G(s)K(s)}$

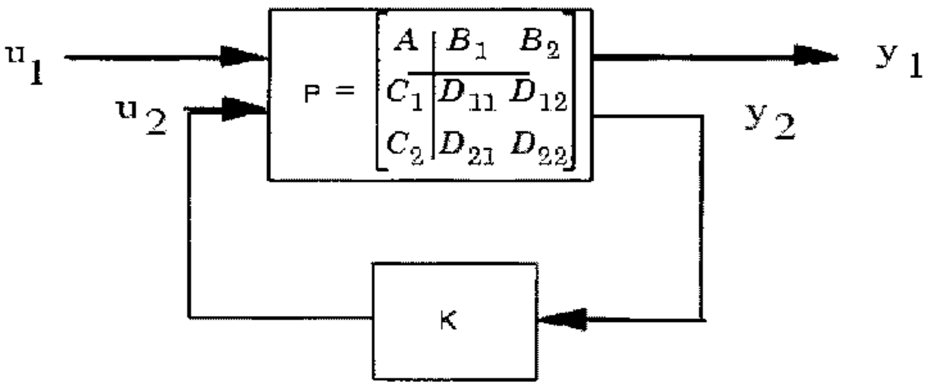

Fig. 2. Standard H_2 compensation configuration

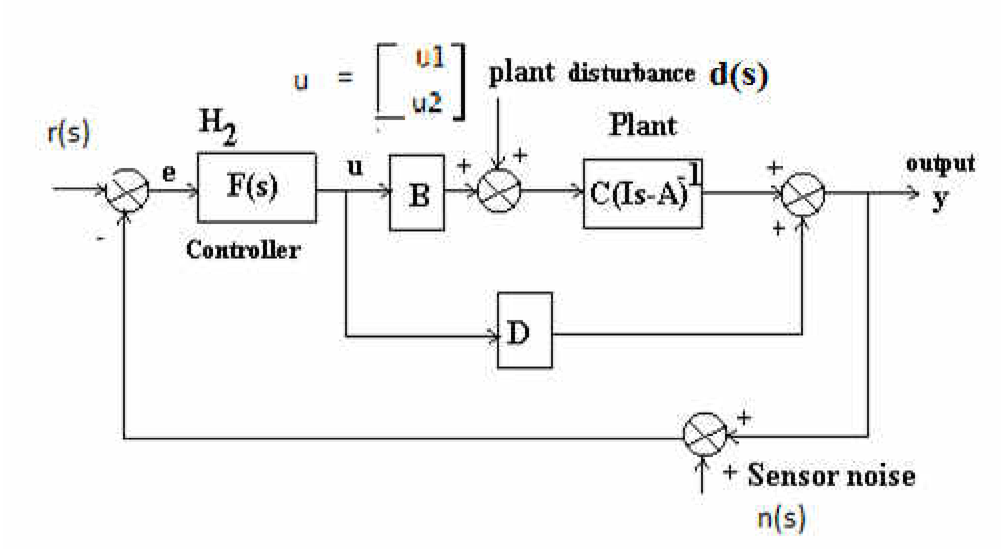

Fig. 3. block diagram of the H_2 controller for power system

4. LQR control method

The idea of the optimal control method linear quadratic regulator (LQR) is the iterations on the elements in a cost function, J. This method determines the feedback gain matrix that minimizes J in order to achieve some compromise between the use of control effort, the magnitude, and the speed of response that will guarantee a stable system.[3]

Design of power system controller based on Linear Quadratic Regulator (LQR) control for continuous –time system as follow.

- [K,S,E] =lqr(A,B,Q,R,N) (10)

Where; Q, R: choosing matrix

For a continuous time system, the state-feedback law $u = -Kx$ minimizes the quadratic cost function.

$$J(u) = \int_0^\infty (x^T Qx + u^T Ru + 2x^T Nu)dt \tag{11}$$

4.1. Limitations of LQR control

- The pair (A, B) is stabilizable.
- $R > 0$ and $Q - NR^{-1}N^T \geq 0$.
- $Q - NR^{-1}N^T, A - BR^{-1}N^T$ has no unobservable mode on the imaginary axis.

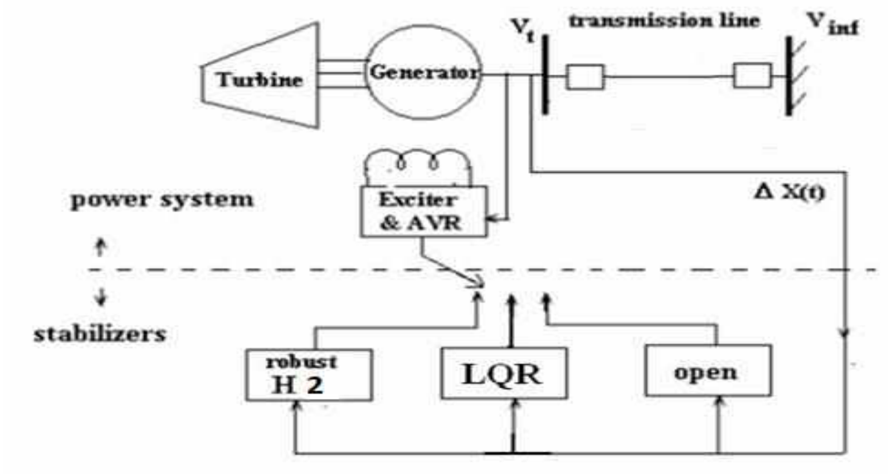

Fig. 4. Schematic diagram of power system model with and without controllers for comparison

5. Digital simulation results

The dynamic stability of linear power system subjected to step disturbances using the program in MATLAB is proposed and referred to Fig. 4. By choosing the machine parameters at nominal operating point as:
X_d=1.6; X_q=1.55 ; $X_{d'}$=0.32 ; X_e= 0.4p.u
M=10; T_{do}= 6; D=0; T_A=0.06 ; K_A=25;
; Tt=0.27 ;Tg= 0.08 ; R=1/(Tg*6.86) ;.$\omega_\circ$ = 377
A,B,C,D matrices are calculated at (P=1, Q=0.25pu) as follows:-

$$A=\begin{bmatrix} 0 & 377.0000 & 0 & 0 & 0 & 0 \\ -0.1317 & 0 & -0.1104 & 0.1000 & 0 & 0 \\ -0.2356 & 0 & -0.4630 & 0 & 0 & 0.1667 \\ 0 & 0 & 0 & -3.7037 & 3.7037 & 0 \\ 0 & -6.8600 & 0 & 0 & -12.5000 & 0 \\ 15.4703 & 0 & -194.8383 & 0 & 0 & -16.6667 \end{bmatrix}$$

$$B=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 12.5000 \\ 416.6667 & 0 \end{bmatrix}$$

$$C=\begin{bmatrix}1&0&0&0&0&0\\0&1&0&0&0&0\end{bmatrix},\qquad D=\begin{bmatrix}O&O\\O&O\end{bmatrix}$$

By choosing the Q,R,N matrices as follows:

$$Q=0.1*\begin{bmatrix}1&0&0&0&0&0\\0&1&0&0&0&0\\0&0&1&0&0&0\\0&0&0&1&0&0\\0&0&0&0&1&0\\0&0&0&0&0&1\end{bmatrix}$$

$$R=900*\begin{bmatrix}1&1\\0&1\end{bmatrix}$$

$$N=\begin{bmatrix}0&0&0&0&0&0\\0&0&0&0&0&0\end{bmatrix}$$

The matrix S is calculated from equation (10) as follow:

$$S=\begin{bmatrix}0.1877&0.0266&0.1065&0.0041&-0.1054&0.0295\\0.0266&571.7086&-15.5510&-0.0603&4.2984&-0.3341\\0.1065&-15.5510&3.3821&-0.0012&-0.2918&0.0660\\0.0041&-0.0603&-0.0012&0.0030&-0.0025&0.0007\\-0.1054&4.2984&-0.2918&-0.0025&0.1132&-0.0248\\0.0295&-0.3341&0.0660&0.0007&-0.0248&0.0105\end{bmatrix}$$

Where S is a positive definite symmetrical and stable matrix
The optimal gain matrix K can be calculated from Eq.(10) as:

$$K=\begin{bmatrix}0.0137&-0.1547&0.0306&0.0003&-0.0115&0.0049\\-0.0015&0.0597&-0.0041&-0.0000&0.0016&-0.0003\end{bmatrix}$$

The weights W_1, W_2 and W_3 to give best performance after 22 iteration of MATLAB program under the tolerance 0.01 are executed and their values are given by:

$$W_1(s)=\begin{bmatrix}\frac{100S+0.63}{0.1S+30}&0\\0&\frac{100S+0.63}{S+300}\end{bmatrix},\qquad W_2(s)=\begin{bmatrix}\frac{50S^2+0.3S+6}{1106S^2+166S+1106}&0\\0&\frac{1.5S^2+2S+7}{5S^2+S+4}\end{bmatrix}$$

$$W_3(s)=\begin{bmatrix}\frac{0.1S^2+0.107S+4}{100S^2+5000S+4500}&0\\0&\frac{0.01S^2+0.072S+3}{0.1S^2+40S+60}\end{bmatrix}$$

The following graphs show the responses of power system model with and without controller due to 0.05 load disturbance. Figure 5 shows the rotor speed deviation response with and without H_2controller at operating conditions (P=0.2,Q=0pu). Fig. 6 displays the rotor speed deviation response at operating conditions (P=1,Q=0.25pu). Fig. 7 depicts the rotor speed deviation response at heavy load (P=1.2,Q=0.8pu). Fig. 8shows the rotor speed deviation response at lead power factor load (P=1,Q=-0.25pu). Fig. 9 manifest the rotor speed deviation response at heavy lead power factor load (P=0.8,Q=-0.6pu). Robustness of the proposed H_2 controller due to uncertainty of the system parameters in terms of T_t and T_g is studied .The rotor speed deviation response due to 0.05 pu load disturbance at (P=1, Q= 0.25pu) and 50% increase in T_t and T_g.is shown in Fig. 10. Tables 1,2 show the eigenvalues of power system model with and without (LQR &H_2) controllers at different operating conditions. Table 3 depicts the Settling time calculation with and without controller.

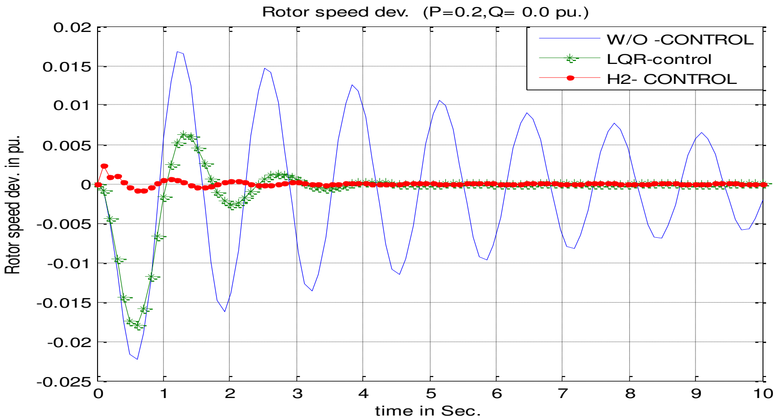

Fig. 5. Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR &H_2) controllers at (P=0.2, Q=0 pu)

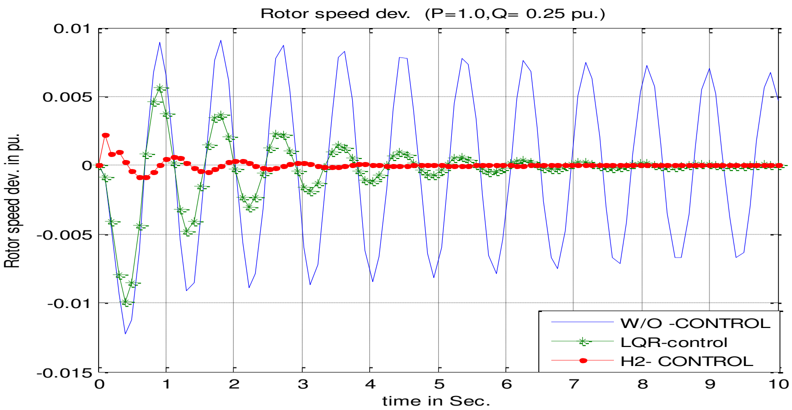

Fig. 6. Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR &H_2) controllers at (P=1, Q=0.25pu)

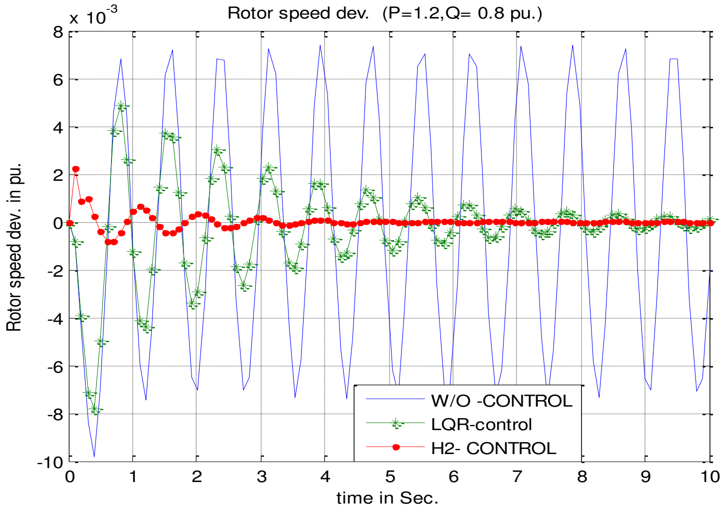

Fig. 7. Rotor speed dev. Response due to 0.05 puload disturbance with and without (LQR &H_2) controllers at (P=1.2, Q=0.8 pu)

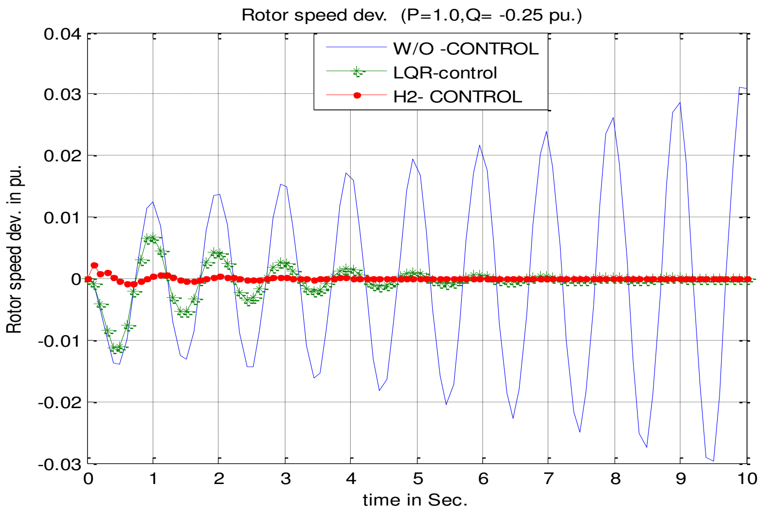

Fig. 8. Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR &H_2) controllers at (P=1, Q=-.25 pu)

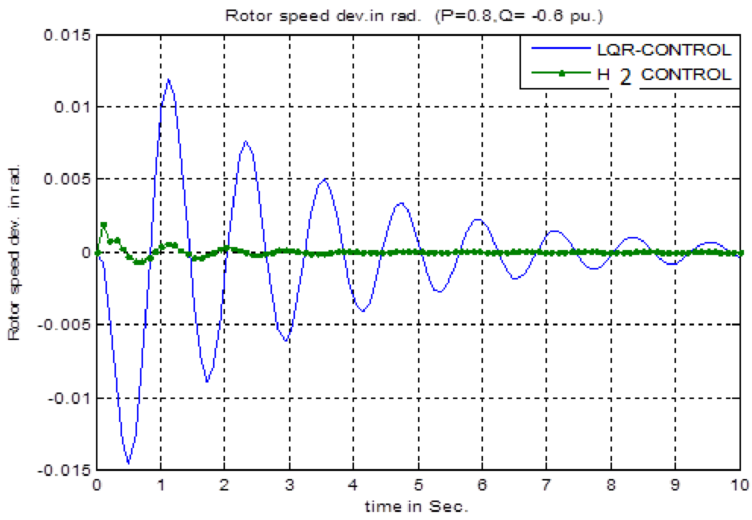

Fig. 9. Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR &H_2) controllers at (P=0.8, Q=-.6 pu)

0

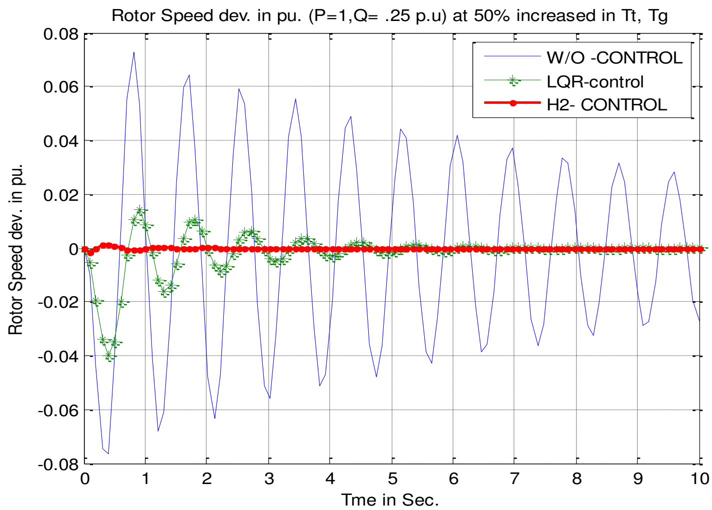

Fig.10. Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR &H_2) controllers at (P=1, Q= 0.25pu) and 50% increase in Tt and Tg

Table 1.

Eigenvalues calculation of power system model at different operating conditions.

operating condition	Without control	With LQR control	With H_2control
P=1 , Q=0.25	-0.0367 + 6.9961i -0.0367 - 6.9961i -14.2953 -12.4821 -2.7625 -3.7201	-0.5150 + 7.0572i -0.5150 - 7.0572i -14.3045 -13.1712 -4.0526 -2.8368	1.0e+002 * -3.9849 -3.0000 -3.0000 -0.1300 + 0.3090i -0.1300 - 0.3090i -0.4908 -0.3135 + 0.1269i -0.3135 - 0.1269i -0.1432 -0.0067 + 0.0680i -0.0067 - 0.0680i -0.0281 -0.0008 + 0.0100i -0.0008 - 0.0100i -0.0092 -0.0151
P=0.2 ,Q=0	-0.1273 + 4.8103i -0.1273 - 4.8103i -13.9563 -12.4806 -2.9194 -3.7225	-13.8650 -13.3919 -1.1628 + 4.5001i -1.1628 - 4.5001i -2.9062 + 1.4571i -2.9062 - 1.4571i	1.0e+002 * -3.9849 -3.0000 -3.0000 -0.1308 + 0.3072i -0.1308 - 0.3072i -0.4908 -0.3153 + 0.1263i -0.3153 - 0.1263i -0.1392 -0.0067 + 0.0680i -0.0067 - 0.0680i -0.0321 -0.0008 + 0.0100i -0.0008 - 0.0100i -0.0092 -0.0151
P=1.2 ,Q=0.8	+0.0005 + 7.9973i + 0.0005 - 7.9973i -14.0016 -12.4831 -3.1312 -3.7186 Unstable	-0.3542 + 8.0952i -0.3542 - 8.0952i -14.0297 -13.1032 -4.5194 -3.0344	1.0e+002 * -3.9849 -3.0000 -3.0000 -0.1295 + 0.3100i -0.1295 - 0.3100i -0.4908 -0.3125 + 0.1273i -0.3125 - 0.1273i -0.1404 -0.0067 + 0.0680i -0.0067 - 0.0680i -0.0309 -0.0008 + 0.0100i -0.0008 - 0.0100i -0.0092 -0.0151

Table 2.
Eigenvalues calculation of power system model at different operating conditions (continue).

operating condition	Withoutcontrol	With LQRcontrol	With H_2control
P=1 ,Q=-0.25	+0.1033 + 6.3047i +0.1033 - 6.3047i -14.9008 -12.4804 -2.4303 -3.7285 Unstable	-14.9060 -13.1803 -0.4950 + 6.3372i -0.4950 - 6.3372i -2.2020 -4.1167	1.0e+002 * -3.9849 -3.0000 -3.0000 -0.1303 + 0.3084i -0.1303 - 0.3084i -0.4908 -0.3141 + 0.1267i -0.3141 - 0.1267i -0.1501 -0.0067 + 0.0680i -0.0067 - 0.0680i -0.0008 + 0.0100i -0.0008 - 0.0100i -0.0212 -0.0092 -0.0151
P=0.8 ,Q=-0.6	+0.4782 + 5.3406i + 0.4782 - 5.3406i -15.7727 -12.4784 -2.2925 -3.7461 Unstable	-15.7666 -13.2084 -0.3335 + 5.2332i -0.3335 - 5.2332i -3.8501 -1.9029	1.0e+002 * -3.9849 -3.0000 -3.0000 -0.1307 + 0.3075i -0.1307 - 0.3075i -0.3149 + 0.1265i -0.3149 - 0.1265i -0.4908 -0.1595 -0.0067 + 0.0680i -0.0067 - 0.0680i -0.0008 + 0.0100i -0.0008 - 0.0100i -0.0118 -0.0092 -0.0151

Table 3.
Settling time calculation with and without controller.

operating condition	Without control	With LQR control	With H_2 control
P=0.2 ,Q=0	T_s>10 Sec	T_s=5 Sec	T_s=2.5 Sec
P=1 , Q=0.25	T_s>10 Sec	T_s=8 Sec	T_s=3 Sec
P=1.2 ,Q=0.8	Un-stable	T_s=10 Sec	T_s=3.5 Sec
P=1 ,Q= -0.25	Un-stable	T_s=7 Sec	T_s=1.7 Sec
P=0.8 ,Q= -0.6	Un-stable	T_s=5 Sec	T_s=1 Sec

6 . Discussion

From the previous figures, it is noted that the system is more damping with LQR control at different operating conditions. This means that the system have less overshoot and less settling time, but the oscillation is increasing with increase the loads until the system become unstable, which means that the system does not has settling time and infinity peak overshoot as shown in Figs.7, 8 and Table2 . Moreover, the system is more damping with

H_2 control at all operating conditions. This means that the system has less overshoot and less settling time. H_2controller is the better than LQR controller in sense of fast damping oscillation with the system uncertainty.

7. Conclusions

The present paper aims to design and application of power system controller based on robust H_2 theory. Moreover, the H_2 control design problem was described and formulated in the standard form with emphasis on the selection of the weighting functions that assured optimal robustness and fast oscillation damping. The investigated power system is subjected to disturbances such as load disturbances over wide range of operating conditions and system uncertainty . Power system states deviation responses due to the above disturbances with the change of operating conditions are obtained for both with and without proposed H_2 controller. The digital simulation results validate the effectiveness and power of the proposed H_2 compared with LQR controllers in terms of fast power system mechanical oscillation damping over a wide range of operating conditions. The time settling with the proposed H_2controller is smaller than with and without LQR control. The maximum over and under shoot with the proposed H_2controller is less than the LQR controller.

8. References

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“ تصميم متحكم قوى كهربائية يعتمد على نظرية أتش 2

الملخص العربى

تقترح هذه الورقة تصميم التحكم المتين المعتمد على نظرية اتش 2 لتقليل الاهتزازات على نطاق واسع من نقاط التشغيل, أيضا تم تصميم هذا التحكم للتحكم فى جهد الإثارة و التحكم فى سرعة التربينة للماكينة, لمعرفة كفاءة و قوة التحكم المقترح تم اختباره على مولد متزامن متصل بنظام لا نهائى عبر خط نقل, تم عمل مقارنة بين المتحكم المقترح و متحكم خطى تربيعى, نتائج التمثيل الرقمى اثبت قوة التحكم المقترح بنظرية اتش 2 من ناحية سرعة تخميد الاهتزاز الميكانيكى على نطاق واسع من نقاط التشغيل مع تغيير باراميترات النظام.