Robust Stabilization of a Steam Power Plant Oscillations

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Abstract*—the objective of this paper is to propose a new approach to robust stabilization of power system oscillations with unstable or lightly damped rotor modes taking into consideration the steam turbine and Governor response. A stabilizing robust controller using H∞ optimal control is designed for a steam turbine SMIB along with heffron phillip's K model. Also CPSS and FLC are designed for SMIB along with heffron phillip's K model. The simulation results show the best performance adjusts by robust H∞ control.
Keywords: power system (PS) - power system stabilizer (PSS) - Conventional power system stabilizer (CPSS) – single machine infinite bus system (SMIB) – Fuzzy logic controller (FLC) - High pass filter (HPF)-Automatic voltage regulator (AVR).

Nomenclature.

$\Delta\delta$	deviation of rotor angle
Δw	deviation of synchronization speed
ΔE_{fd}	deviation of field voltage
$\Delta E_q'$	deviation of internal quadrature voltage
M	damping
D	moment of inertia
$K_1 \vdots K_6$	Heffron – Phillips constants
V_{do}	direct axis voltage
V_{qo}	quadrature axis voltage
X_e	transmission line voltage
X_q	quadrature axis reactance
X_d	direct axis reactance
E_b	internal voltage
X_d'	transient direct axis reactance
ΔV_{ref}	deviation of reference voltage
I_{qo}	quadrature axis current
V_t	terminal voltage
K_A	amplifier gain
T_A	The amplifier time constant
T'_{do}	The generator time constant
ΔT_m	The deviation of mechanical torque
ΔT_e	The deviation of electromagnetic torque
d	The disturbance

I. Introduction

A steam turbine is a device that extracts thermal energy from pressurized steam and used it to do mechanical work on a rotating output shaft. Its modern manifestation was invented by Sir Charles Parsons in 1884 [4].

It is particularly suited to be used to drive an electrical generator about 90% of all electricity generation in the united states 1996 is by use of steam turbine [4].

Power system stability is a complicated subject that has challenged electrical power engineers. The stability of power systems was first recognized as an important problem in 1920 [1, 3]. The linear control for a linear model of the power system is used in the most PSSs.

The CPSS is used a lot in generation systems and give a shared in the increasing of the dynamic stability of power systems [1], [6], [7]. A linearized model of the power system is used to determine the CPSS parameters. As power systems are highly nonlinear systems, its parameters that change with time, the CPSS design cannot warranty its performance in a practical operating for power systems [1], [14], [17].

In recent years there has been an increasing interest for using developed control designs in PS like H∞ control, nonlinear control, FLC and neural control [1], [5], [8], [10], [12], [18-20].The goal of these studies is to achieve stability and performance robustness.

To include the model performance in a practical operating at the controller design stage, modern robust control methods have been used in recent years to design PSS [15], [16]. The resulting PSS can guarantee the stability for all operating points with respect to the nominal system and has good oscillation damping ability. The H∞ optimal controller design is relatively simpler in terms of the computational burden [11], [13].

In this paper make design for a robust controller to stabilize of a single machine infinite bus power system using The H∞ controller [9]. The proposed robust method is compared with the CPSS and FLC control methods. Simulation results show that the proposed method guarantees robust performance under a wide range of operating conditions [1].

The rest of the paper is organized as follows. Section 2 presents the dynamic model of a Steam turbine power plant. Section 3 provides the classical controller CPSS. In section 4 the controller is developed based on the FLC. A design of robust H∞ proposed controller is presented and the stability of the overall closed loop system is derived in section 5. Simulation results and discussion are given in section 6, and finally the conclusions.

II. DYNAMIC MODEL OF A STEAM TURBINE POWER SYSTEM

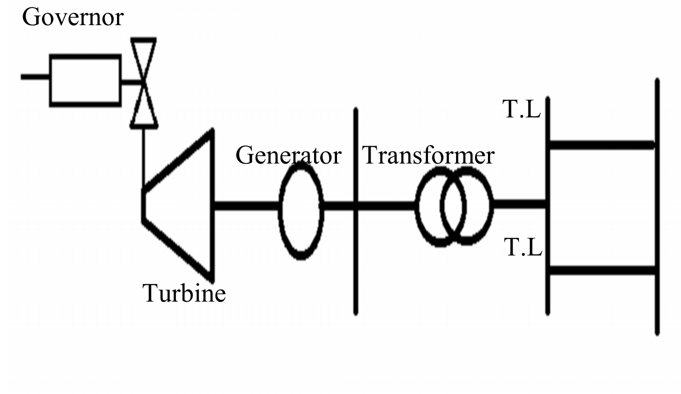


Figure 1. Steam Turbine Power System

A. DYNAMIC MODEL OF A STEAM TURBINE

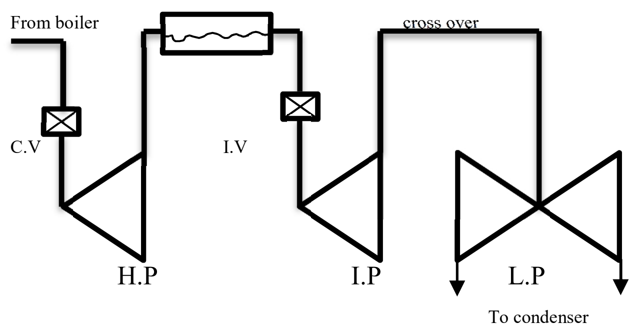


Figure 2. Single Re-heater Tandem compound steam turbine

Where C.V is control valve, I.V is intercept valve for re-heater.

The control valves modulate the steam flow through the turbine for load/frequency control during normal operation.

T_{CH} is the time constant for the response of steam flow to a change in control valve opening.

The intercept valve is normally used only for rapid control of turbine mechanical power in the event of an over speed.

T_{RH} is the time constant for the steam flow into the L.P section.

T_{CO} is the time constant for the steam flow into the crossover piping.

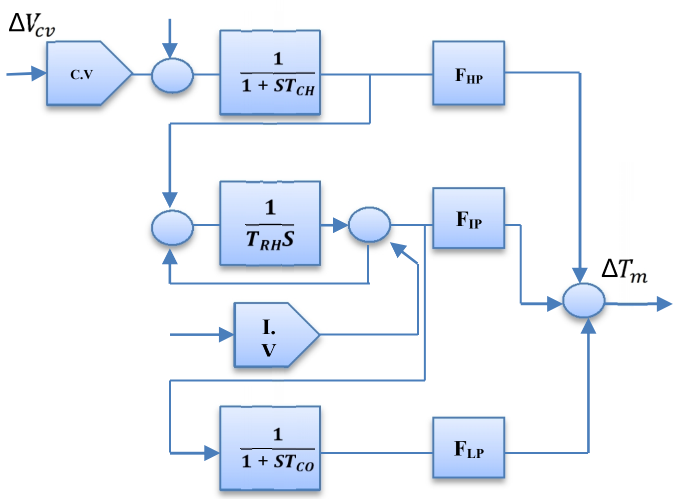


Figure 3. Block Diagram For A Steam Turbine

$$T.F = \frac{\Delta T_m}{\Delta V_{cv}} = \frac{1+SF_{HP}T_{RH}}{(1+ST_{CH})(1+ST_{RH})} \quad (1)$$

Typical values of parameters of the model:-

$F_{HP} = 0.3$ $F_{IP} = 0.3$ $F_{LP} = 0.4$
$T_{CH} = 0.3$ $T_{RH} = 7$ $T_{CO} = 0$

The control valve signal (Governor):-

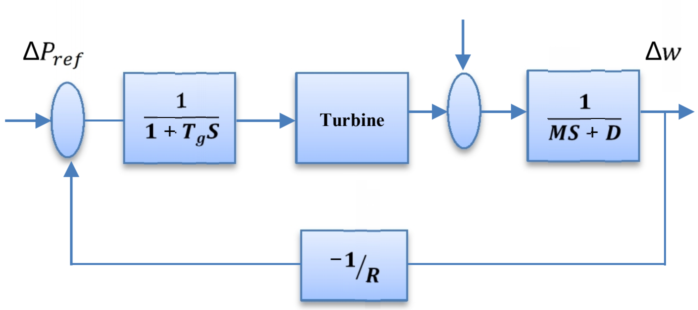


Figure 4. The Block Diagram for Governor

Where T_g is the time constant for governor response, in this study neglect it

B. DYNAMIC MODEL OF A SMIB

The SMIB system can be considered as a theoretical simple system that allows studying the electromechanical interaction between a single generator and the power system.

Figure.1 shows a SMIB power system (kundur, 1993) [4], A non-linear dynamic model of the system is calculated by neglecting the transients of generator, and the resistances of transformers and transmission lines (Kundur, 1993). The non-linear dynamic model of the system is given as eqs [1-4].

Non-linear dynamic model:

$$\dot{w} = (P_m - P_e - D\Delta w)/M \quad (2)$$

$$\dot{\delta} = w_o(w-1) \quad (3)$$

$$\dot{E_q}' = (-E_q + E_{fd})/T_{do}' \quad (4)$$

$$\dot{E_{fd}} = \frac{-E_{fd}+K_a(V_{ref}-V_t)}{T_a} \quad (5)$$

At per-unit $P_m = T_m$ and $P_0 = T_0$

Linearizing the non-linear dynamic model around the nominal operating condition to obtain the linear dynamic model

The linearized model of the system is obtained as eqs [5-8] (Kundur, 1993).

Linear dynamic model:

$$\Delta\dot{\delta} = w_o \Delta w \quad (6)$$

$$\Delta\dot{w} = \frac{\Delta T_m - \Delta T_e - D\Delta w}{M} \quad (7)$$

$$\Delta\dot{E_q}' = (-\Delta E_q + \Delta E_{fd})/T_{do}' \quad (8)$$

$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd}+K_a\Delta V_{ref}}{T_a} \quad (9)$$

So the full system (steam turbine power plant) state space is:

$$A = \begin{bmatrix} 0 & w_o & 0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & 0 & \frac{-K_2}{M} & 0 & 0 & \frac{1}{M} \\ \frac{-K_4}{T_{do}'} & 0 & \frac{-K_3}{T_{do}'} & \frac{1}{T_{do}'} & 0 & 0 \\ \frac{-K_a K_5}{T_a} & 0 & \frac{-K_a K_6}{T_a} & \frac{-1}{T_a} & 0 & 0 \\ 0 & \frac{-1}{RT_{CH}} & 0 & 0 & \frac{-1}{T_{CH}} & 0 \\ 0 & \frac{-F_{HP}}{RT_{CH}} & 0 & 0 & \frac{T_{CH}-F_{HP}T_{RH}}{T_{RH}T_{CH}} & \frac{-1}{T_{RH}} \end{bmatrix} \quad (10)$$

Where $, B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{K_a}{T_a} \\ \frac{1}{T_{CH}} & 0 \\ \frac{F_{HP}}{T_{CH}} & 0 \end{bmatrix} x = \begin{bmatrix} \Delta\delta \\ \Delta w \\ \Delta E_q' \\ \Delta E_{fd} \\ \Delta X_1 \\ \Delta T_m \end{bmatrix}, u = \begin{bmatrix} \Delta P_{ref} \\ \Delta V_{ref} \end{bmatrix}$

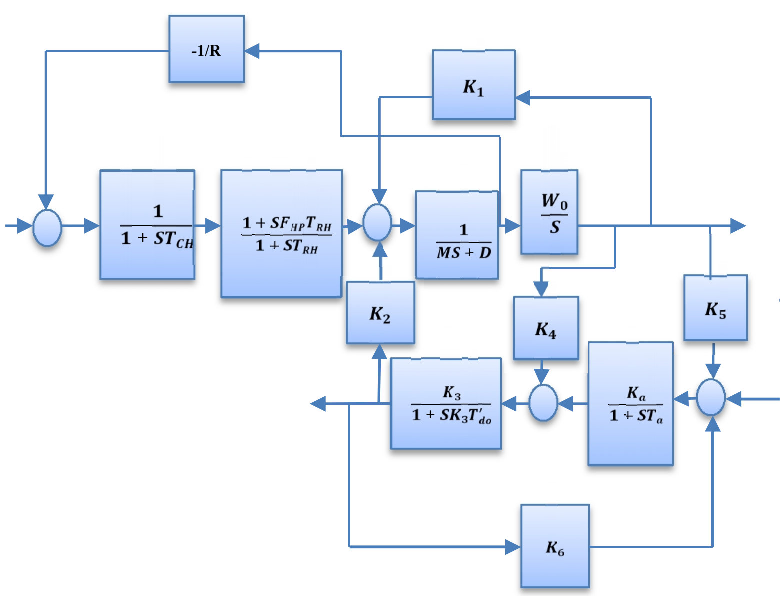


Figure 5. Block Diagram For A Steam Turbine Power System

III. CPSS TECHNIQUE

The CPSS structure is illustrated in figure 6.

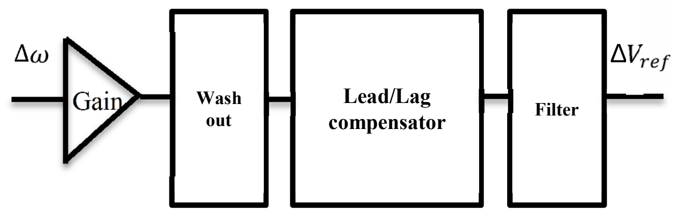


Figure 6. Structure of CPSS

The gain determines the amount of damping. The washout stage is HPF, and used to solve the oscillations in speed and block the dc offsets [1].

The compensation consists of two lead – lag compensators. The torsional filter is added to reduce the effect on the torsional dynamics of the machine while block the voltage errors [2, 3].The block diagram of HP model with CPSS as shown in figure 7.

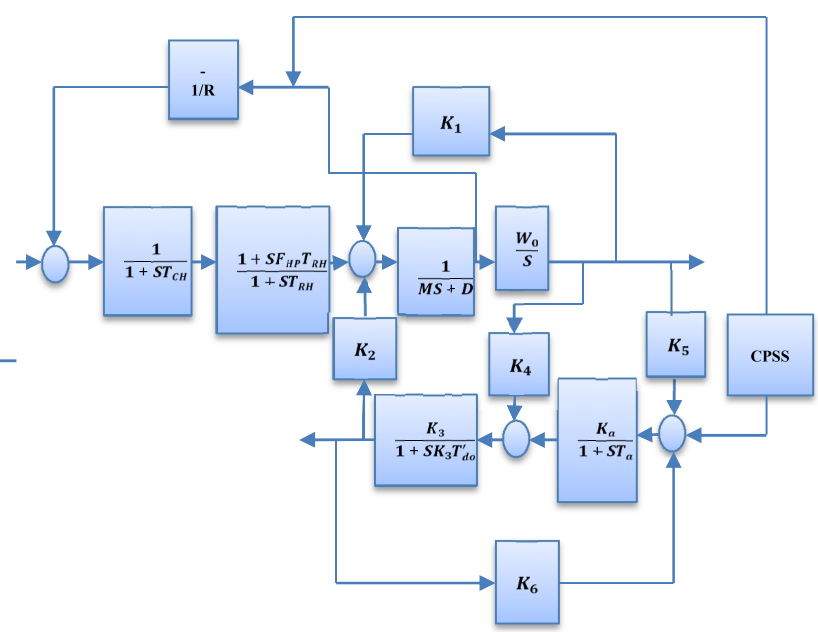


Figure 7. Heffron Phillips model with CPSS

IV. FLC TECHNIQUE

The speed and acceleration deviations are input variables and reference voltage is the output variable for FLC. The acceleration signal can be calculate from shaft speed signal [1].

$$\Delta w(k) = \frac{\Delta w(k)-\Delta w(k-1)}{\Delta T} \qquad (11)$$

All input and output variables are seven linguistic fuzzy: there are three types of negative LN- MN- SN (large – medium – small), ZE (Zero), and there are three types of positive SP -MP -LP (small-medium-Large) [1].

The membership functions are triangular. The variables multiply with gains K_{U1}, K_{U2}, K_{U3} so that their value lies between -1 and 1.

The speed and acceleration deviations results in 49rules for this model. All the rules shows in table 1.

The block diagram of HP model with FLC as shown in figure 8.

TABLE I. RULES BASE OF FUZZY LOGIC CONTROLLER:

Δw \ $\Delta\dot{w}$	LN	MN	SN	ZE	SP	MP	LP
LN	LN	LN	LN	LN	MN	SN	ZE
MN	LN	MN	MN	MN	SN	ZE	SP
SN	LN	MN	SN	SN	ZE	SP	MP
ZE	LN	MN	SN	ZE	SP	MP	LP
SP	MN	SN	ZE	SP	SP	MP	LP
MP	SN	ZE	SP	MP	MP	MP	LP
LP	ZE	SP	MP	LP	LP	LP	LP

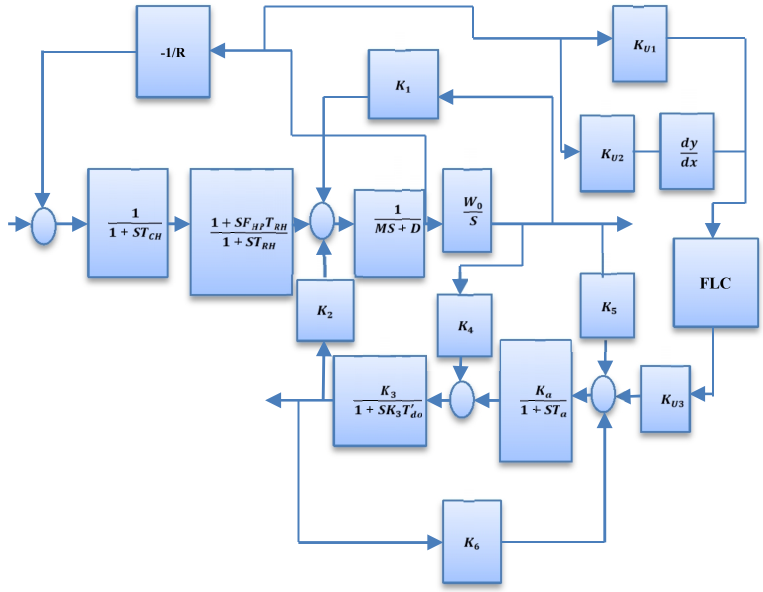
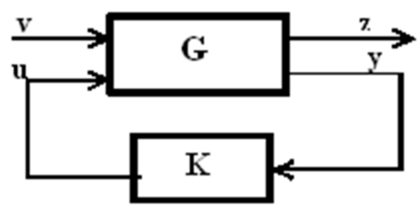


Figure 8. Heffron Phillips model with FLC

V. H_∞ FEEDBACK GAIN CONTROLLER

Consider the block diagram for SMIB system described by



V Indicate the signal that affects the system and cannot be impact by controller, v is called generalized disturbance, zdenote the signal that allows to describe whether a controller has certain in demand properties, z is called controlled variable, udenote the output signal of the controller, the so-called control input. y denotes the signal that enters the controller, the so-called measurement output [1].

The closed loop system:

$$z = f(G, K)v \qquad (12)$$

The transfer function $f(G, K)$ given by:

$$f(G, K) = G_{11} + G_{12}(I - KG_{22})^{-1}KG_{21} \tag{13}$$

Finding a controller K is the main problem of H_∞ control, K controller used to stabilize the plant G

$$J_\infty(K) = \|f(G, K)\|_\infty \tag{14}$$

Where $\|f(G, K)\|_\infty$ is the H_∞norm. The control problem is most comfortable solved in the time domain; The direct minimization of the cost $J_\infty(K)$ is a very hard problem.

$$J_\infty(K) < \gamma \tag{15}$$

For a given $\gamma > 0$. This condition used to determine a specific controller which achieves the bound (15). The conditions can be used for checking the capability of incidence for (15) for different values, to determine the minimum of $J_\infty(K)$. Such a procedure is called γ -iteration. In terms of the worst-case gain can be measure the performance of H_∞ in terms of L2-norm,

$$J_\infty(K) = \mathrm{Sup} \ \frac{\|Z\|_2}{\|v\|_2} \square \ v \neq 0 \tag{16}$$

The performance bound (15) is thus equivalent to

$$\frac{\|Z\|_2}{\|v\|_2} < \gamma \ all \ v \neq 0 \tag{17}$$

$$L(v, u) = \|z\|_2^2 - \gamma^2\|v\|_2^2 < 0 \qquad all \ v \neq 0 \tag{18}$$

By Parseval's theorem of the L2 – norm, the equivalent equation to (18)

$$L(v, u) = \int_0^\infty [z^T z - \gamma^2 v^T v]dt \ < 0 \ \text{all } v \neq 0 \tag{19}$$

In H_∞ full information feedback controller, the realizations of the transfer matrices G are taken to be of the form:

$$G = \begin{matrix} A & B_1 & B_2 \\ C & 0 & D \end{matrix} \tag{20}$$

The following assumptions must be satisfied:

(i) (A, B_2) are stabilizable

(ii) D are full column rank with [D 0] unitary.

(iii) $G = \begin{matrix} A - JwI & B_2 \\ C & D \end{matrix}$ have full column ranks for all v .

Theorem 1 [11].

Suppose G are given by (26) and satisfy (i), (ii) and (iii). Then the following two statements are equivalent [11]:

(a) For SMIB system a state feedback gain controllers K exist such that the resulting closed-loop systems, with transfer matrices T_{vz}, are internally stable and have H_∞ norm less than γ. i.e. $\|T_{vz}\|_\infty < \gamma$.

(b) There exist positive semi-definite real symmetric solutions G of the algebraic Riccati equation for system

$$A^TG + GA - (GB_2C^TD)(D^TD)^{-1}(B_2^TG + D^TC) + \gamma^{-2}GB_1B_1^TG + C^TC = 0 \tag{21}$$

Such that the following matrices are stability:

$$A - B_2(D^TD)^{-1}(B_2^TG + D^TC) + \gamma^{-2}B_1B_1^TG \tag{22}$$

If G satisfy the condition in part (a) exist, then the controller for SMIB system satisfying part (a) are given by:

$$K = -(D^TD)^{-1}(B_2^TG + D^TC) \tag{23}$$

The control is now

$$u = Kx \tag{24}$$

Which guarantees the stability of the system.
State space model of SMIB system as follow:

$$\dot{x} = Ax + B_1v + B_2u \tag{25}$$

$$z = Cx + Du \tag{26}$$

Where

$$x = \begin{bmatrix} \Delta\delta \\ \Delta w \\ \Delta E_q{'} \\ \Delta E_{fd} \\ \Delta X \\ \Delta T_m \end{bmatrix}, \quad v = \text{disturbance}, \qquad u = \begin{matrix} \Delta P_{ref} \\ \Delta V_{ref} \end{matrix}$$

And

$$A = \begin{bmatrix} 0 & w_o & 0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & 0 & \frac{-K_2}{M} & 0 & 0 & \frac{1}{M} \\ \frac{-K_4}{Td_o{'}} & 0 & \frac{-K_3}{T_{do}{'}} & \frac{1}{T_{do}{'}} & 0 & 0 \\ \frac{-K_aK_5}{T_a} & 0 & \frac{-K_aK_6}{T_a} & \frac{-1}{T_a} & 0 & 0 \\ 0 & \frac{-1}{RT_{CH}} & 0 & 0 & \frac{-1}{T_{CH}} & 0 \\ 0 & \frac{-F_{HP}}{RT_{CH}} & 0 & 0 & \frac{T_{CH} - F_{HP}T_{RH}}{T_{RH}T_{CH}} & \frac{-1}{T_{RH}} \end{bmatrix},$$

$$B_2 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{K_a}{T_a} \\ \frac{1}{T_{CH}} & 0 \\ \frac{F_{HP}}{T_{CH}} & 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

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

We calculate a H_∞ full information controller that achieves the infinity norm final γ for the interconnection structureG.The value achieved of γ is 866.4169 and the H_∞ full information controller K is

$$k = \begin{bmatrix} 54.5 & -6037.5 & 71.9 & 0 & -3.8 & -74.8 \\ -4.4 & 450.5 & -7.4 & -1.4 & -0.1 & 6.9 \end{bmatrix}$$

The block diagram of HP model with feedback H_∞controller as shown in figure 9.

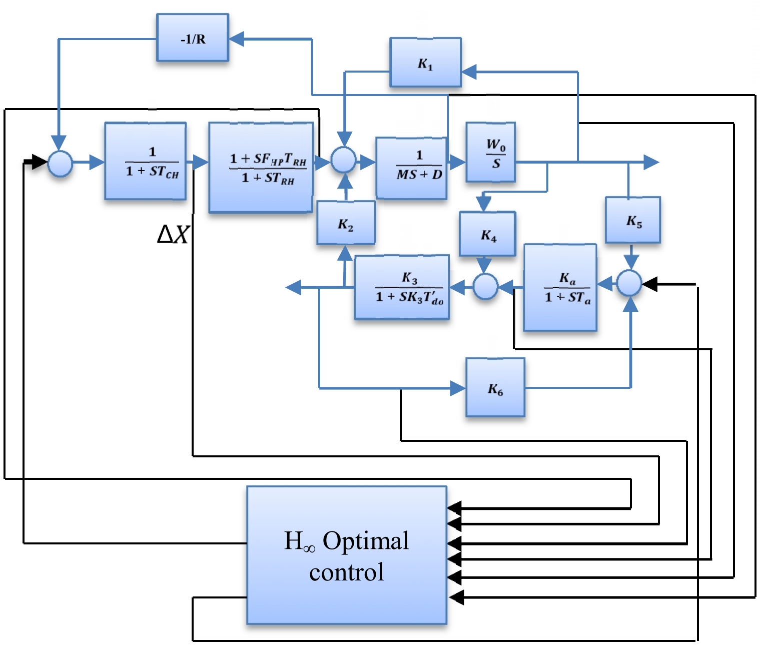


Figure 9. Heffron Phillips model with H_∞ optimal controller

VI. SIMULATION RESULTS AND DISCUSSIONS

In order to study the performance of the system with CPSS, FLC, and H_∞ control, at Nominal operating condition.

All these conditions are made with 10% step change in mechanical input ($\Delta w = 0.1$).

The CPSS has been designed and obtained as

$$\text{CPSS} = \frac{K(T_1 S+1)}{(T_2 S+1)} \tag{28}$$

Where $K = 35, T_1 = 0.3\ ,\ T_2 = 0.1$

Figures 10, 11, 12, 13 show the dynamic responses for speed, and angle deviations with controllers (CPSS, FLC, H∞ optimal controller).

From these figures, It notice that the least values for overshoot and settling time occurred in H∞ optimal controller.

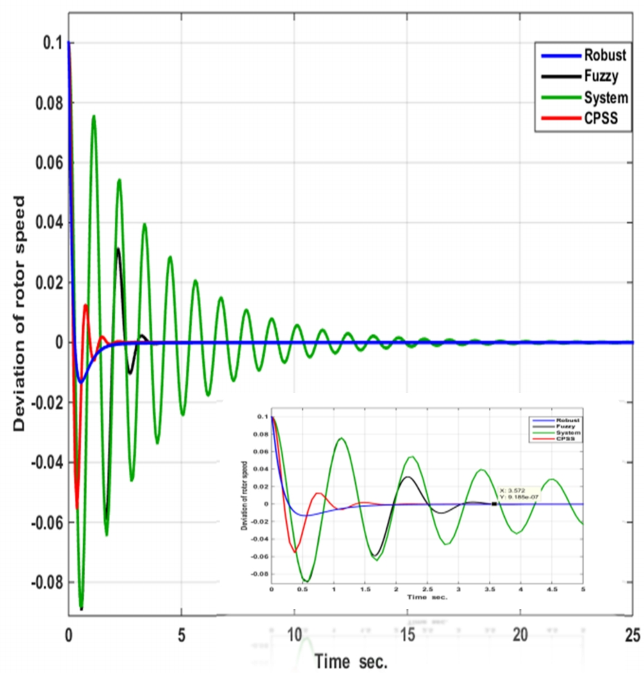


Figure 10. Dynamic responses for speed deviation

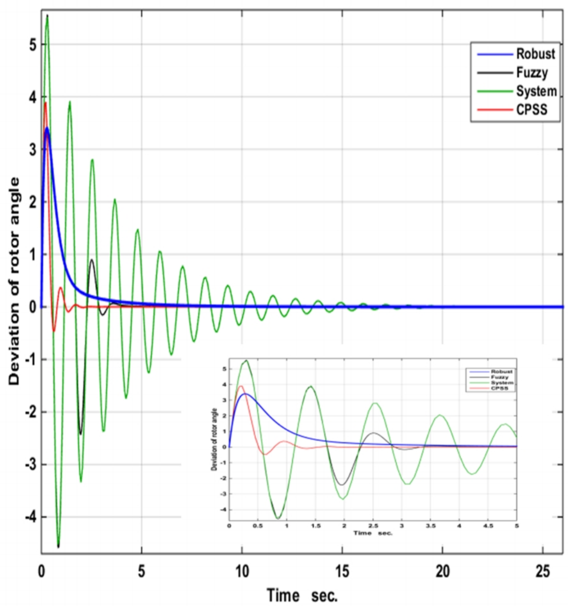


Figure 11. Dynamic responses for angle deviation

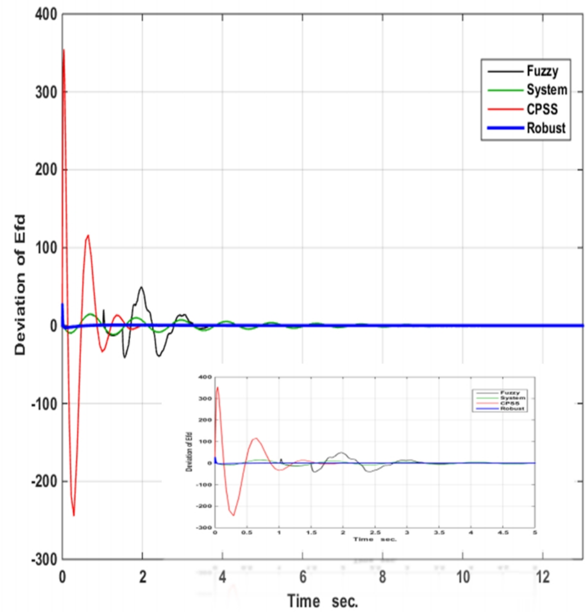


Figure 13. Dynamic responses for ΔE_{fd}

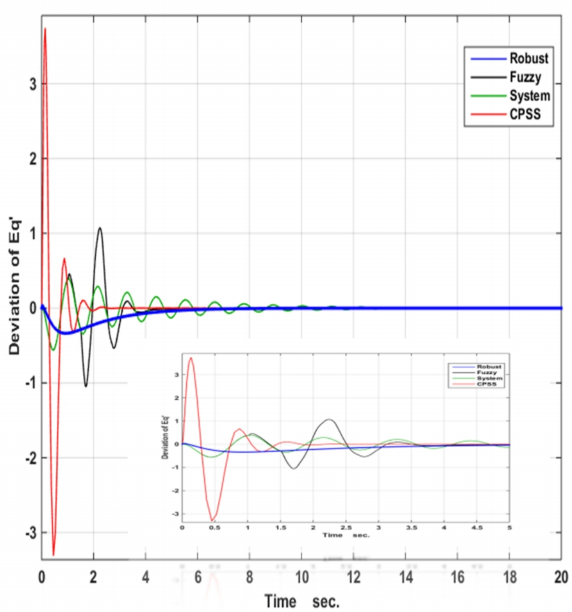


Figure 12. Dynamic responses for $\Delta E_q'$

TABLE II. Comparison The result for Speed Deviation

Design method	Settling time	Overshoot
CPSS	1.8	-0.0556
H∞	1.75	-0.01327
FLC	3.57	-0.08937
System	16.5	-0.08798

TABLE III. Comparison The result for Angle Deviation

Design method	Settling time	Overshoot
CPSS	2.333	3.899
H∞	10	3.405
FLC	5	5.467
System	20	5.52

TABLE IV. Comparison The result for E_q' Deviation

Design method	Settling time	Overshoot
CPSS	2.47	3.746
H∞	7.1	-0.3372
FLC	5	1.073
System	15	-0.5609

TABLE V. Comparison The result for E_{fd} Deviation

Design method	Settling time	Overshoot
CPSS	150<	354.6
H∞	7.6	28.68
FLC	9	49.32
System	150<	14.73

VII. CONCLUSIONS

The robust linear state feedback controller, fuzzy controller and power system stabilizer have been designed to globally asymptotically stabilize for single machine infinite bus power system. The most fast recovery for this change in the speed without a lot of effect in the induce voltage, field voltage, and the angle appear in the H_∞ optimal controller, so the effectiveness of the proposed technique (H∞ optimal controller) than other techniques.

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Appendix

The nominal parameters of the system are listed in Table 5.

TABLE VI. the nominal parameters of the system

Generator	$M = 10\ MJ/MVA$	$T'_{do} = 7.5\ sec$	$X_d = 1.68\ p.u$
	$X_q = 1.6\ p.u$	$X'_d = 0.3\ p.u$	$D = 0$
Excitation system		$K_a = 50$	$T_a = 0.02\ sec$
Transformer		$X_{tr} = 0.1\ p.u$	
Transmission lines	$X_{te}1 = 0.5\ p.u$	$X_{te}2 = 0.9\ p.u$	
Operation condition	$V_t = 1.05$	$P = 1.0\ p.u$	$Q = 0.2\ p.u$

BUPT