Dynamic Stability Improvement of a Power System Based on a PSO-Tuned H_2 Controller

M. Mohseni Mirabadi, N. R. Abjadi, S. Hoghoughi-Isfahani, and S. Shojaeian

Abstract—**To supply power demands reliably, power system should cope with various disturbances and faults and its stability should be retained. A power system may be failed due insufficient damping of synchronizing torque. In this paper, to improve the dynamic stability of a power system a feedback control based on H2 method is designed. To formulate the problem appropriately, linear matrix inequality (LMI) theory is employed. To optimize the overall closed-loop system response, the parameters of controller is optimized using particle swarm optimization (PSO) algorithm. Simulation results represent the effectiveness and validity of the proposed controller and its superiority over conventional power system stabilizer (PSS).**

Index Terms—Dynamic Stability, Robust Control, Linear Matrix Inequality (LMI), Single Machine Infinite Bus (SMIB), Power System Stabilizer (PSS), H_2Control.

I. Introduction

WITH the growth of power networks, low frequency oscillations appear in power system. Small and sudden disturbances cause such oscillations. In more cases, these oscillations are damped quickly and the amplitude of the oscillation is under a certain value; but depending on the operating point conditions and system parameters values, these oscillations may become continuing for a long time and in the worst case, their amplitudes are increased. The dynamic stability of the power system is an important factor in development power networks. In [1], using fuzzy logic laws, a controller is designed for STATCOM and the improvement of power system dynamic stability is studied. In [2], a robust controller is proposed for SVC control to improve the damping of synchronous machine oscillations. The achieved results in this work are compared to the ones from a conventional power system stabilizer (PSS). In [3], to increase the dynamic stability a UPFC is employed and two control methods are proposed. In this work the effect of UPFC capacitance value on dynamic stability is investigated. There are various PSS structures; but conventional PSS is still interesting because of its simple structure and good flexibility and feasibility. However the performance of conventional PSS is sensitive to operating point of the system which is changed by load variation; thus the conventional PSS may be failed capability [4]. In [5], the effect of the injected reactive power of STATCOM on grid voltage and the damping of synchronous machine oscillations is investigated. Most of the controllers proposed for this purpose need a perfect model of the power system with good precision. It is worthwhile to note the power system is a nonlinear coupled system. Most of the models used in controller design are a linear approximation around the operating point. Usually the design of the controller is based on the worst operating point and simply the damping torque is increased. With a change in load or system parameters, the good performance of the system is not guaranteed. In this paper, a robust H2 state feedback control to improve dynamic stability of power system in the presence of parametric uncertainties is introduced. This controller overcomes the mentioned difficultly in power system. To achieve the best controller tuning, the particle swarm optimization (PSO) is employed. The obtained results are compared to the results with a conventional PSS.

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II. Selected Power System and it's Modeling

The power system under study in this paper is presented in Fig. 1. In this figure, V_t and V_o are terminal voltage and infinite bus voltage respectively. A local load with Y=G+jB admittance is on generator bus and the transmission line is presented with Z=R+jX total impedance [6].

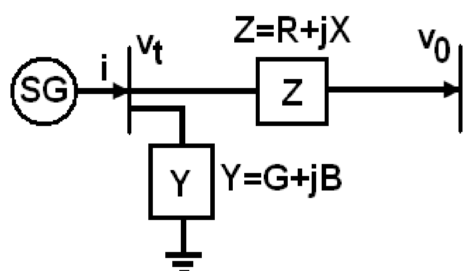

Fig. 1. Selected power system

Considering Heffron-Philips model for a synchronous generator, the model of the system is given by the following equations:

$$\dot{\delta} = \omega_0 \omega \quad (1)$$

$$\dot{\omega} = \frac{1}{M}(T_m - T_e - D\omega) \tag{2}$$

$$\dot{E}'_q = \frac{1}{T'_{d0}}(E_{fd} - E'_q - (X_d - X'_d)i_d) \tag{3}$$

$$T_e = C_3 E'_q \sin\delta + C_4 \sin 2\delta \tag{4}$$

$$i_d = \frac{E'_q - V_o \cos\delta}{X'_d} \tag{5}$$

$$C_3 = \frac{V_o}{X'_d} \tag{6}$$

$$C_4 = \frac{V_o^2}{2}\left(\frac{1}{X_q} - \frac{1}{X'_d}\right) \tag{7}$$

After linearization, considering state variables as $X_1 = \delta$, $X_2 = \omega$, $X_3 = E'_q$ and input variables as $u_1 = E_{fd}$ and $u_2 = T_m$ these equations can be written as:

$$\Delta\dot{X}_1 = \omega_0 \Delta X_2 \tag{8}$$

$$\Delta\dot{X}_2 = \frac{1}{M}(\Delta u_1 - \Delta T_e - D\Delta X_2) \tag{9}$$

$$\Delta X_3 = \frac{1}{T'_{d0}}(\Delta u_2 - \Delta X_3 - (X_d - X'_d)\Delta i_d) \tag{10}$$

$$\Delta i_d = \frac{\Delta X_3}{X'_d} + \frac{V_o \sin X_{10} \Delta X_2}{X'_d} = Y_d \Delta X_3 + F_d \Delta X_1 \tag{11}$$

$$\begin{aligned} \Delta T_e &= (C_3 \sin X_{10})\Delta X_3 \\ &+ (C_3 X_{30} \cos X_{10} + 2C_4 \cos 2X_{10})\Delta X_1 \end{aligned} \tag{12}$$

Substituting (11) and (12) in (9) and (10) the following linear state equation is obtained.

$$\begin{bmatrix} \Delta\dot{X}_1 \\ \Delta\dot{X}_2 \\ \Delta\dot{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 \\ \frac{-k_1}{M} & \frac{-D}{M} & \frac{-k_2}{M} \\ \frac{-k_4}{T'_{d0}} & 0 & \frac{-1}{k_3 T'_{d0}} \end{bmatrix} . \begin{bmatrix} \Delta X_1 \\ \Delta X_2 \\ \Delta X_3 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{M} & 0 \\ 0 & \frac{1}{T'_{d0}} \end{bmatrix} . \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{13}$$

Where

$$k_1 = C_3 X_{30} \cos X_{10} + 2C_4 \cos 2X_{10}$$

$$k_2 = C_3 \sin X_{10}$$

$$k_3 = \frac{1}{1 + (X_d - X'_d)Y_d}$$

$$k_4 = (X_d - X'_d)F_d$$

$$Y_d = \frac{1}{X'_d}$$

$$F_d = \frac{V_o \sin X_{10}}{X'_d}$$

T_m is mechanical input torque; T_e is electromagnetic torque of machine; M and D are inertia constant and damping coefficient of machine respectively; ω_0 is synchronous speed; E_{fd} is excitation voltage; X_d and X'_d are synchronous and transient d-axis machine reactance respectively; X_q is synchronous q-axis machine reactance; δ is power angle; T'_{d0} is open circuit time constant of the machine and X_{10} is the initial value of power angle.

III. ROBUST CONTROL

Using a suitable robust control, the closed-loop system remains stable even in the presence of system uncertainties. Most of these uncertainties are due the approximation in modeling the system. Usually in system modeling small time constants and some nonlinear and time varying terms are neglected. To retain the good performance of the closed-loop system despite these approximations, a robust controller is design for introduced power system [6].

Considering model uncertainties, the state equation

$$\dot{X}(t) = AX(t) + BU(t) \tag{14}$$

Is written as

$$\dot{X}(t) = (A + D\Delta(t)E_1)X(t) + (B + D\Delta(t)E_2)U(t) \tag{15}$$

Where $\Delta(t)$ represents an scalar or matrix including uncertainties which is satisfied $\Delta^T(t)\Delta(t) \le I$, D, E_1 and E_2 are scalars or matrices relating to uncertainties coefficients.

In control theory, the main aim is the obtaining of a stabilizing

Feedback gain (state feedback) as follow:

$$U = KX \tag{16}$$

To solve this control problem the following matrix inequalities are used:

$$\begin{bmatrix} G_1 & G_2^T & QR_1^{1/2} & Y^T R_2^{1/2} \\ G_2 & -\varepsilon I & 0 & 0 \\ R_1^{1/2} Q^T & 0 & -I & 0 \\ R_2^{1/2} Y & 0 & 0 & -I \end{bmatrix} < 0 \tag{17}$$

$$G_1 = QA^T + AQ + BY + Y^T B^T + DMD$$

$$G_2 = E_1 Q + E_2 Y$$

Where:

$$\varepsilon > 0 \tag{18}$$

$$Q > 0 \tag{19}$$

In these LMIs, Y is a variable without sign; R_1 and R_2 are positive definite constants relating to the following H_2 cost function:

$$J = \int_0^{\infty} (X^T R_1 X + U^T R_2 U) dt$$

Using MATLAB coding the following state feedback gain can be obtained:

$$K = YQ^{-1} \tag{20}$$

IV. Tuning by particle swarm optimization

Particle swarm optimization (PSO) was introduced in 1995 by Kennedy and Eberhart [7].

In PSO algorithm, a random population of points is generated. Each point represents a member of the population. In PSO algorithm there is no sudden jump or confusion; each point is a solution. Considering X and V as particle position and velocity respectively, the position of n[th] particle in a space with m dime is represented with $X_n = [X_{n1}, X_{n2}, ..., X_{nm}]$.

The position of each particle is changed in next stage and it reaches a new position. The best position of n[th] particle which is corresponding with the lowest cost function for that particle is saved in P_{best_n} .In addition, P_{best} of all particles are compared and the position of particle which has the lowest cost function is saved in G_{best} . The next vector of each particle is depending on its position and its distance to its P_{best} and its distance to G_{best} .The relations of particles movements are as follow:

$$V_{nm}^{i+1} = w \times V_{nm}^{i} + C_1 \times rand() \times (P_{best_{nm}} - X_{nm}^{i} + C_2 \times rand() \times (G_{best} - X_{nm}^{i})) \tag{21}$$

$$X_{nm}^{i+1} = X_{nm}^{i} + CV_{nm}^{i+1} \tag{22}$$

$$\left|V_{nm}^{i+1}\right| \le V_{\max} \tag{23}$$

Where $V_{\max}$ is a parameter that prevents to go out of suitable search space which causes the solution to be in acceptable region; C_1 and C_2 are constants which represent the speed of learning or pulling to P_{best} and G_{best} ; the weighing function w is given by:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \tag{24}$$

Here $w_{\min}$ and $w_{\max}$ are minimum and maximum of weighing function; $iter$ is the number of iterations.

In order to optimize the parameters of the controller with PSO, the following cost function is used

$$CostFunction = \int_0^{t_1} t_s \left|e(t)\right| dt \tag{25}$$

Where t_1 is the final time of simulation; e is the error signal and t_s is the settling time of the system.

V. Simulation and results

To show the effectiveness of the proposed controller, simulation results are demonstrated in this section. The simulation results are obtained for two cases: without considering uncertainties and with considering uncertainties. Using the model and system parameters the following state space and control matrices are obtained,

$$A = \begin{bmatrix} 0 & 376.9911 & 0 \\ -0.0286 & 0 & -0.0748 \\ -0.1683 & 0 & -0.4371 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0.0893 & 0 \\ 0 & 0.1874 \end{bmatrix}$$

To obtain the coefficients and parameters of (15) two cases are considered.

A. *Without considering uncertainties*

In this case these coefficients and parameters are given by

$$E_1 = E_2 = 0$$

$$D = 0$$

The parameters of the proposed controller R_1 and R_2 should be positive definite. In first step, they selected as unitary matrices. Using these matrices, some machine input variables become out of reasonable range. With PSO algorithm the optimal matrices are obtained as

$$R_1 = \begin{bmatrix} 3.19 & 0 & 0 \\ 0 & 47.53 & 0 \\ 0 & 0 & 0.000001 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 58.81 & 0 \\ 0 & 142.1 \end{bmatrix}$$

With MATLAB coding the following state feedback gain is obtained

$$K = \begin{bmatrix} -0.0378 & -27.9272 & 0.165 \\ -0.0055 & 0.1430 & -0.0394 \end{bmatrix}$$

The obtained results for sudden change in load are represented as follow.

Assuming a 500MW load is omitted from the power grid at t=0.1sec and it is returned after t=1.1sec. This test illustrates the dynamic stability of the system clearly. The obtained results are shown in Figs. (2)-(4). As can be seen from these figures, again the oscillations are damped rapidly and the maximum overshoot is small. The machine power angle has little oscillations. After the load variations, machine return to steady-state conditions.

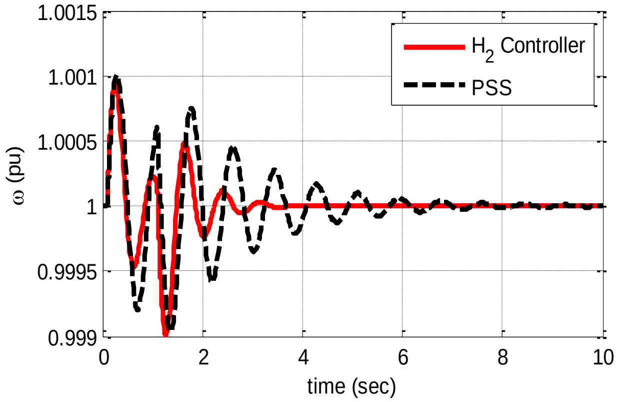

Fig. 2. Machine rotor speed for sudden variations of load

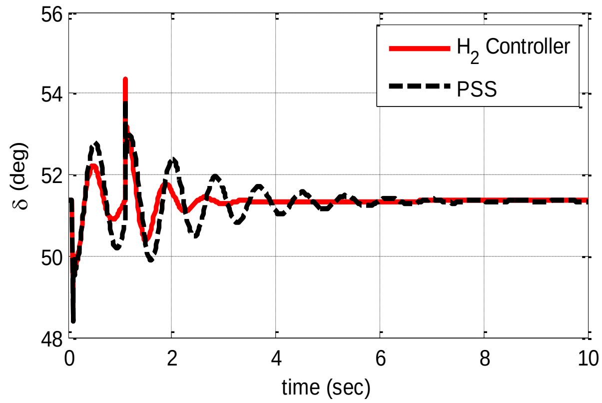

Fig. 3. Machine torque angle for sudden variations of load

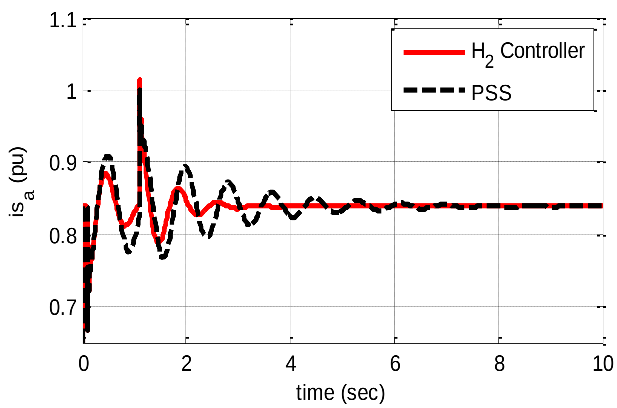

Fig. 4. Machine phase ‘a’ current for sudden variations of load

B. Power system with parametric uncertainties

In this section, it is assumed that there are uncertainties in damping coefficient (D) and inertia constant (H) of synchronous machine. The uncertainty in D is modeled as

$$\frac{D+\delta_D}{M}=\frac{D}{M}+\frac{\delta_D}{M} \tag{26}$$

Using the following geometric series

$$\frac{1}{1-a}=1+a+a^2+a^3+\ldots \tag{27}$$

The uncertainty in H is modeled as follow

$$\frac{-k_1}{2(H+\delta_H)}=\frac{-k_1}{2H(1+\frac{\delta_H}{H})}=\frac{-k_1}{2H}+\frac{k_1}{2H^2}\delta_H \tag{28}$$

In (28) and (30), δ_D and δ_H represent the uncertainties in D and H respectively.
The matrices of (17) is given by,

$$E_1=\begin{bmatrix} 0 & \frac{-1}{2H} & 0 \\ \frac{-k_1}{2H^2} & \frac{D}{2H} & \frac{-k_2}{2H^2} \end{bmatrix}$$

$$E_2=\begin{bmatrix} 0 & 0 \\ \frac{-1}{2H^2} & 0 \end{bmatrix}$$

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

The matrices R_1 and R_2 using PSO algorithm after 100 iterations are obtained as,

$$R_1=\begin{bmatrix} 6.6907 & 0 & 0 \\ 0 & 45.2011 & 0 \\ 0 & 0 & 0.1026 \end{bmatrix}$$

$$R_2=\begin{bmatrix} 78.0133 & 0 \\ 0 & 35.3664 \end{bmatrix}$$

Using MATLAB software, the state feedback gain is obtained as,

$$K=\begin{bmatrix} -0.1549 & -57.0393 & 0.0819 \\ -0.0781 & 1.0032 & -0.3686 \end{bmatrix}$$

Assuming a 500MW load is omitted from the power grid at t=0.1sec and it is returned after t=1.1sec in the presence of uncertainties. The obtained results are shown in Figs. (5)-(7). As can be seen from these figures, again the oscillations are damped rapidly and the maximum overshoot is small. The machine power angle has little oscillations. Conventional PSS operates very weak in this test.

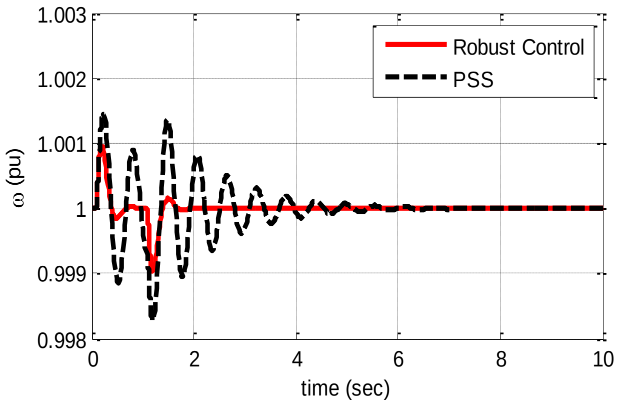

Fig. 5. Machine rotor speed for sudden variations of load

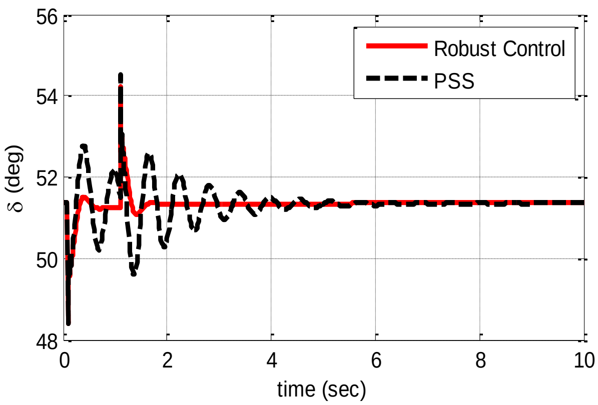

Fig. 6. Machine torque angle for sudden variations of load

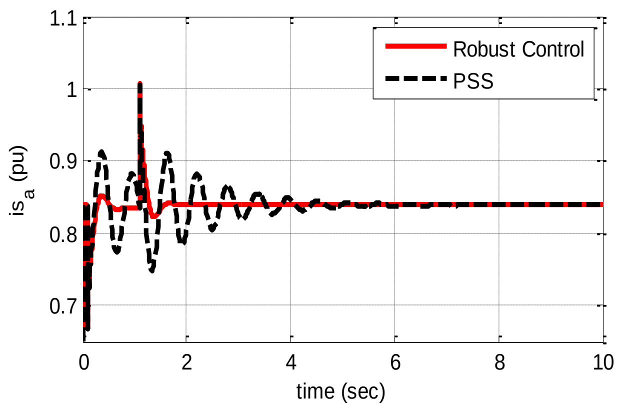

Fig. 7. Machine phase 'a' current for sudden variations of load

VI. CONCLUSION

Considering the capability of robust control in the presence of uncertainties, in this paper, a robust H_2 state feedback controller is designed for a power system. Parameters of the controller are tuned using PSO algorithm. The performance of the closed-loop system is investigated without and with uncertainties in the mechanical parameters with sudden load variation.

The obtained simulation results show the superiority of the proposed controller over conventional PSS. Using the proposed conventional the oscillations have a small amplitude and they are damped rapidly.

VII. APPENDIX

System data for single machine infinite bus power system Generator [8]:

$$H = 5.6 \;\; X_d = 1.8pu \;\; X_q = 1.8pu \;\; D = 1pu \;\; X'_d = 0.32pu$$
$$T'_{d0} = 5.3371\sec \;\; f = 60Hz$$

Transmission Line and Load:

$$R = 0.1273pu \;\; X = 0.85pu \;\; G = 0.27027pu$$
$$B = 0$$

Exciter (simplified IEEE type-ST1):

$$K_A = 10 \;\; T_A = 0.01\sec$$

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