DESIGN OF A ROBUST SVC DAMPING CONTROLLER USING NONLINEAR H_∞ TECHNIQUE

Samir A. Al-Baiyat *

Electrical Engineering Department
King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

الخـلاصـــة:

يستعرض هذا البحث تصميم نظام تحكم غير خطي لمعوض متغيرات فولت – أمبير الساكن (SVC). وقد استـُخدم في هذا النوع من التصاميم غير الخطية الطرق الحديثة من نظام H_∞ غير الخطي. وللوصول لهذه الطريقة فقد تم الجمع بين استخدام طريقة التغذية المرجعة للحالات لتحويل النظام غير الخطي إلى نظام خطي مع تطبيق طريقة H_∞ للنظم الخطية. إن الطريقة المقترحة تتجنب الحل المعقد لمعادلة هاملتون – جاكوبي – إسحاق.

وقد تم تحليل الطريقة المقترحة - التي تم فيها إعادة نظم القوى إلى حالة الاسقرارية العابرة - من خلال المحاكاة لحالات عديدة من نظم القوى خلال تعرضها إلى اضطراب. كذلك لوحظ متانة الطريقة التي استخدمت في البحث من خلال المحاكاة لمجال كبير في تغير الاضطرابات.

* Address for correspondence KFUPM Box 1813
King Fahd University of Petroleum and Minerals
Dhahran 31261, Saudi Arabia
e-mail: sbaiyat@kfupm.edu.sa

ABSTRACT

This paper presents a nonlinear controller of Static Var Compensator (SVC). The nonlinear SVC controller is designed using the recently developed nonlinear H_∞ theory. The approach combined state feedback exact linearization with linear H_∞ principle, which avoids the difficulty solving the Hamilton–Jacoby–Issacs inequality. Simulation results with torque pulses and three phase faults on the generator show that the proposed controller can ensure transient stability of the power system in presence of major disturbances. The controller is also tested for a range of operating conditions considering a number of disturbances on the system. It is observed that the controller is very robust in providing good damping for a wide range of operation.

Keywords: SVC controller, nonlinear robust control, H_∞ control, global stabilization, power systems.

DESIGN OF A ROBUST SVC DAMPING CONTROLLER USING NONLINEAR H_∞ TECHNIQUE

1. INTRODUCTION

Recently, there has been a surge of interest in the development and use of Flexible AC Transmission Systems (FACTS) controllers in power transmission systems [1 – 6]. These controllers utilize power electronics devices to provide more flexibility to AC power systems. Flexibility is understood in the sense of the capability of a system to respond quickly to the control input and to change in its operating point. The most popular type of FACTS devices in terms of application is the SVC. These devices are well known to improve power system properties such as steady state stability limits, voltage regulation and var compensation, dynamic over-voltage and under voltage control, and damp power system oscillations. The SVC is an electronic generator that dynamically controls the flow of power through a variable reactive admittance to the transmission network.

A survey on power systems control shows that most existing controllers are designed with assumption that the power systems have fixed structure and parameters. However, in power systems uncertainties always exist due to sudden load shedding, generation tripping, occurrence of faults, change of parameters, and network configuration. In order to attenuate the influence of such disturbances to systems, it is essential to design robust controllers. The problem of designing robust controllers for uncertain nonlinear systems attracted the attention of many researchers during the past two decades [7 – 11].

The objective of this paper is to design a robust controller for a single machine infinite bus system with a SVC installed at the middle of the transmission line. The design principle of the robust controller is based on the nonlinear H_∞ control theory [7, 8]. The approach combined state feedback exact linearization with linear H_∞ principle, which avoids the difficulty from solving Hamilton–Jacoby–Issacs inequality. Simulation studies of the proposed controller showed the effectiveness of the controller in damping the electromechanical oscillations for a wide range of operating conditions.

2. NONLINEAR H_∞ CONTROL

In this section, we briefly review some background material about H_∞ control law that will be used in the paper.

Consider the nonlinear system given by the following equations:

$$\begin{aligned} \dot{x} &= f(x) + g_1(x)w + g_2(x)u \\ y &= h(x) \end{aligned} \tag{1}$$

where $x \in R^n$ is the state of the system, $u \in R^m$ is the control input, $w \in R^r$ is the disturbance signal, $y \in R^p$ is the system output and the functions f, g_1, g_2 are smooth vector fields with $f(0) = 0$, and $h(0) = 0$.

The nonlinear H_∞ optimal control problem of system (1) is to find the smallest $\gamma^* > 0$ and an associated control u^* such that for $\forall\, \gamma > \gamma^*$

$$\int_0^T (\|y\|^2 + \|u\|^2)dt \le \gamma^2 \int_0^T \|w\|^2 dt \qquad \forall\ T \ge 0 \tag{2}$$

holds and the closed loop system is stable.

In order to construct a nonlinear H_∞ controller, one needs to solve a partial differential inequality called Hamilton–Jacoby–Issacs (HJI). It is well known that an exact explicit solution for HJI is almost impossible [9, 10]. To overcome the difficulty, one can transform the nonlinear system (1) into a linear system by feedback linearization [12–14], which reduce the problem into solving a well–known Riccati inequality [15]. An important concept in feedback linearization is relative degree which is given by the following definition.

Definition : System (1) is said to have a relative degree r, if

$$\begin{aligned} &L_{g2} L_f^k h(x) = 0 \qquad 0 \le k < r-1 \\ &L_{g2} L_f^{r-1} h(x) \ne 0 \end{aligned} \tag{3}$$

where $L_f^r h(x)$ denotes the r^{th} order Lie derivative of $h(x)$ along $f(x)$.

Now consider system (1), assume $g_1(x) = [g_{11}(x)\ \ g_{12}(x), \ldots, g_{1s}(x)]$ and $w = [w_1, \ldots, w_s]^T$. Let us also assume that the relative degree r of the system from the control u to the output y is equal to n, and the relative degree related to disturbance $w_1, \ldots, w_s$ are $\rho_1, \ldots, \rho_s$ respectively, and denote ρ the minimum of $\rho_1, \ldots, \rho_s$, with $\rho \le n$.

Let

$$z_1 = h(x),\ z_2 = L_f h(x),\ \cdots,\ z_n = L_f^{n-1} h(x), \tag{4}$$

or write to be $z = T(x)$, and a state feedback

$$v = \alpha(x) + \beta(x) u \tag{5}$$

where $\alpha(x) = L_f^{n-1} h(x)$, and $\beta(x) = L_{g2} L_f^{n-1} h(x)$, then system (1) can be transformed to the following system [11],

$$\begin{aligned} \dot{z} &= Az + B_2 v + \frac{\partial T(x)}{\partial x} g_1(x) w \\ y &= Cz \end{aligned} \tag{6}$$

where A, B_2, and C are matrices of dimensions $n \times n$, $n \times 1$ and $1 \times n$ respectively. They are of the form

$$A = \begin{bmatrix} 0 & 1 & 0 & . & . & . & 0 \\ 0 & 0 & 1 & . & . & . & 0 \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & . & . & 1 \\ 0 & 0 & 0 & . & . & . & 0 \end{bmatrix}, \qquad B_2 = \begin{bmatrix} 0 \\ 0 \\ . \\ 0 \\ 1 \end{bmatrix}, \qquad \mathrm{C} = \begin{bmatrix} 1 & 0 & 0 & . & . & . & 0 \end{bmatrix}. \tag{7}$$

Further simplification for system (6) will be achieved by setting

$$\bar{w} = \frac{\partial T(x)}{\partial x} g_1(x) w = \begin{bmatrix} L_{g11} h(x) & . \ . & L_{g1s} h(x) \\ . & . \ . & . \\ L_{g11} L_f^{\rho_1 - 2} h(x) & . \ . & L_{g1s} L_f^{\rho_s - 2} h(x) \\ L_{g11} L_f^{\rho_1 - 1} h(x) & . \ . & L_{g1s} L_f^{\rho_s - 1} h(x) \\ L_{g11} L_f^{\rho_1} h(x) & . \ . & L_{g1s} L_f^{\rho_s} h(x) \\ . & . \ . & . \\ L_{g11} L_f^{n-1} h(x) & . \ . & L_{g1s} L_f^{n-1} h(x) \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ w_s \end{bmatrix}. \tag{8}$$

By using the relative degree, Equation (8) becomes

$$\bar{w} = \frac{\partial T(x)}{\partial x} g_1(x) w = \begin{bmatrix} 0 & . \ . & 0 \\ . & . \ . & . \\ 0 & . \ . & 0 \\ L_{g11} L_f^{\rho - 1} h(x) & . \ . & L_{g1s} L_f^{\rho - 1} h(x) \\ L_{g11} L_f^{\rho} h(x) & . \ . & L_{g1s} L_f^{\rho} h(x) \\ . & . \ . & . \\ L_{g11} L_f^{n-1} h(x) & . \ . & L_{g1s} L_f^{n-1} h(x) \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ w_s \end{bmatrix}. \tag{9}$$

Then system (6) can be written as

$$\begin{aligned} \dot{z} &= Az + B_2 v + B_1 \bar{w} \\ y &= Cz \end{aligned} \tag{10}$$

where

$$B_1 = \begin{bmatrix} 0_{(\rho-1)\times(\rho-1)} & 0_{(\rho-1)\times(n-\rho+1)} \\ 0_{(n-\rho+1)\times(\rho-1)} & I_{(n-\rho+1)\times(n-\rho+1)} \end{bmatrix} \tag{11}$$

Now designing a nonlinear robust control law u to stabilize the nonlinear system (1) is equivalent to designing a robust control v to stabilize the linear system (10). Solution of the robust control for the linear system (10) involves finding a nonnegative matrix P^* as a solution for the following Riccati equation [15]:

$$A^T P + PA + P(\frac{1}{\gamma^2} B_1 B_1^T - B_2 B_2^T)P + C^T C = 0 \ . \tag{12}$$

Then, the optimal control v^* is given by

$$v^* = -B_2^T P^* z \ . \tag{13}$$

Using Equations (13) and (5) the control law u^* for the nonlinear system (1) is give by

$$u^* = -\beta^{-1}(x)(\alpha(x) + B_2^T P^* T(x)) \ . \tag{14}$$

3. POWER SYSTEM MODEL

In this paper, a single machine infinite bus system (SMIB) with a SVC is shown Figure 1. The SVC is placed at the middle of the transmission line which is generally considered to be the ideal site. The synchronous generator is represented by the classical second order model. The SVC is considered as a shunt controllable reactive susceptance with time delay as shown in Figure 2. The system dynamics is described by the following Equations [3]:

$$\begin{aligned} \dot{\delta} &= \omega - \omega_o \\ \dot{\omega} &= \frac{\omega_o}{2H}(P_m - P_e) - \frac{D}{2H}(\omega\text{-}\omega_o) \\ \dot{B}_L &= \frac{K}{T}[-B_L + B_{Lo} + K_c u] \end{aligned} \tag{15}$$

where

$$P_e = \frac{E' V_t}{x_{l1} + x_{l2} + x_{11} x_{l2}(B_L - B_c)} \sin\delta \ . \tag{16}$$

In Equations (15) and (16),

δ power angle of the generator (in radian)

ω relative speed (in radian)

P_m mechanical input power (in p.u.)

P_e electric power of generator (in p.u.)

D damping constant (in p.u.)

H inertia constant of generator (in sec.)

x_{l1}, x_{12} reactances (in p.u.)

E' transient EMF of generator (in p.u.)

V_t infinite bus voltage (in p.u.)

B_C susceptance of the equivalent capacitor (in p.u.)

B_L susceptance of the inductor in SVC (in p.u.)

B_{LO} initial value of the B_L (in p.u.)

K control gain of SVC (in p.u.)

T time constant of SVC

K_c gain in the control loop (in p.u.).

The values of these parameters are listed in the appendix. The mid-bus voltage V_m can be written as

$$V_m = \sqrt{(x_{l2}E'\cos\delta + x_{l1}V_t)^2 + (x_{l2}E'\sin\delta)^2} \Big/ \Sigma \quad (17)$$

where $\Sigma = x_{l1} + x_{l2} + x_{l1}\, x_{l2}\,(B_L - B_C)$

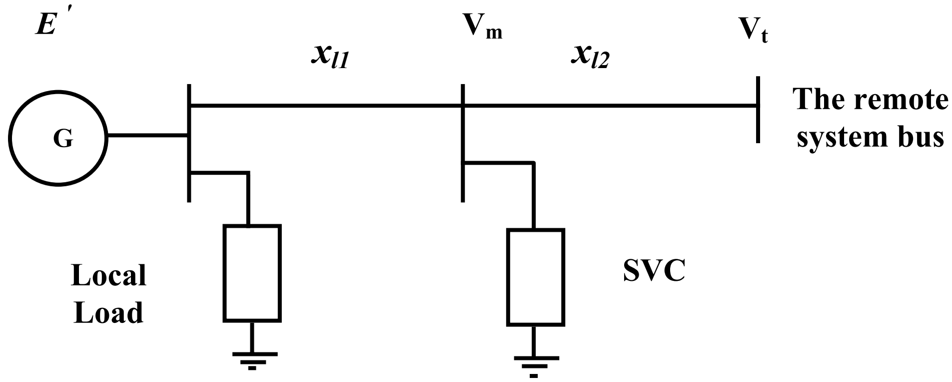

Figure 1. Single machine system with SVC

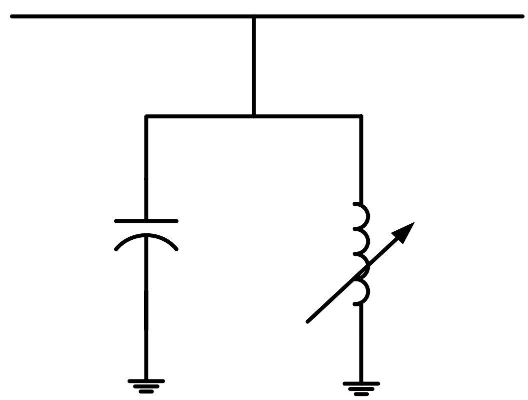

Figure 2. The SVC Model

The dynamic of a synchronous generator, based on (15) and (16), can be written in a state space as

$$\begin{aligned} \dot{x}(t) &= f(x) + g_2(x)u \\ y(x) &= h(x) \end{aligned} \quad (18)$$

where

$$x = \begin{bmatrix} \delta & \omega & B_L \end{bmatrix}^T \quad (19)$$

$$g_2 = \begin{bmatrix} 0 & 0 & c_7 \end{bmatrix}^T \quad (20)$$

$$h(x) = \delta \quad (21)$$

$$f(x) = \begin{bmatrix} \omega - \omega_o \\ c_1 p_m - c_3(\omega - \omega_o) - \dfrac{c_1 c_2 \sin\delta}{c_4 + c_5(B_L - B_c)} \\ c_6(-B_L + B_{Lo}) \end{bmatrix} = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{bmatrix} \quad (22)$$

and

$c_1 = \omega_o/2H$, $c_2 = E'\ V_t$, $c_3 = D/2H$, $c_4 = x_{l1} + x_{l2}$, $c_5 = x_{l1}x_{l2}$, $c_6 = 1/T$, and $c_7 = K_c/T$, .

4. FEEDBACK LINEARIZATION DESIGN APPROACH

The development of the feedback linearization techniques provides a powerful tool for the design of controllers for nonlinear systems. Since it avoids the local nature of approximate linearization and transforms the nonlinear systems to linear ones over a wide range, it has been applied to power systems by many researchers in recent years [16 – 18]. In this section we will discuss the design principle based on feedback linearization. The first step in the design procedure is the establishment of the linearizability condition for the SMIB system given in the preceding section. The Lie derivatives needed to check the linearizability condition are

$$\begin{aligned} &L_g h(x) = 0 \\ &L_g L_f h(x) = 0 \\ &L_g L_f^2 h(x) = \frac{c_1 c_2 c_5 c_7 \sin x_1}{[c_4 + c_5(x_3 - B_c)]^2}. \end{aligned} \tag{23}$$

Hence the SMIB system has relative degree $r = 3$, which is equal to the system order. It was shown in [11] that if a nonlinear system of the form given in (15) has relative degree $r = n$ where n is the system order, then the nonlinear system can be transferred into a linear system of the form

$$\begin{aligned} \dot{z} &= Az + B_2 v \\ y &= Cz \end{aligned} \tag{24}$$

where the matrices A, B_2, and C are given in (7). Clearly the single machine system given in preceding section can be transformed into a linear system. One such a transformation is given by

$$\begin{aligned} z_1 &= T_1(x) = \delta = x_1 \\ z_2 &= T_2(x) = \omega - \omega_o = x_2 \\ z_3 &= T_3(x) = c_1 P_m - c_3 x_2 - \frac{c_1 c_2 \sin x_1}{c_4 + c_5(x_3 - B_c)} \end{aligned} \tag{25}$$

and the associated linearizing control law is given by

$$v = \alpha(x) + \beta(x) u \tag{26}$$

where

$$\beta(x) = \frac{c_1 c_2 c_5 c_7 \sin x_1}{[c_4 + c_5(x_3 - B_c)]^2} \tag{27}$$

and

$$\alpha(x) = \left[-\frac{c_1 c_2 \cos x_1}{c_4 + c_5(x_3 - B_c)} f_1(x) - c_3 f_2(x) - \frac{c_1 c_2 c_5 \sin x_1}{[c_4 + c_5(x_3 - B_c)]^2} f_3 \right] \tag{28}$$

The transformed system dynamics, in the new state space coordinate, are given by

$$\begin{aligned} \dot{z} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} z + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v \\ y &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} z. \end{aligned} \tag{29}$$

Having transformed the SMIB (15) into a linear system, a controller can now be designed via any linear design technique. An important point to be noticed is that the linear system in (29) is independent of the operating point of the system. This is of great importance in power system design. Figure 3 shows the block diagram for the transformed system.

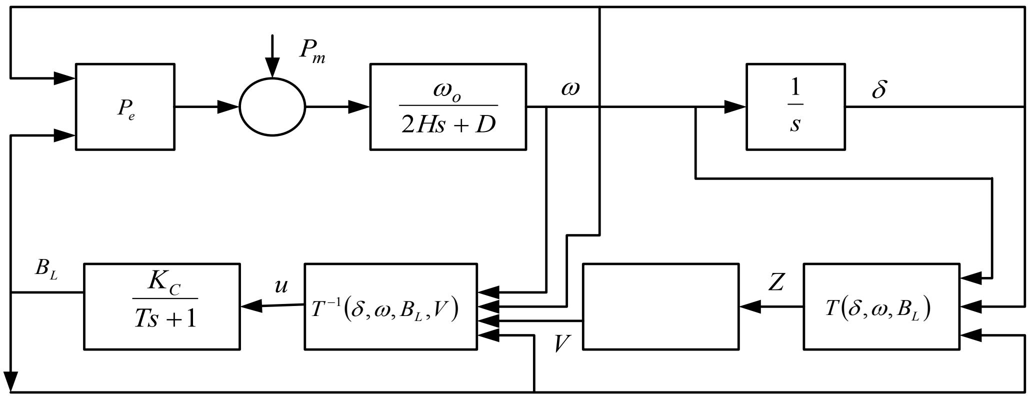

Figure 3. Block diagram of the transformed power system model

5. ROBUST CONTROLLER DESIGN

Many dynamical systems encountered in practice may not be adequately described by differential equations, because of the existence of uncertainties such as parameter variation and exogenous disturbances. Power systems are no special of dynamical systems where uncertainties always exist. Causes for uncertainties may attribute to sudden load changes, generation tripping, occurrence of faults, change of parameters, and network configuration, *etc*. In order to attenuate the influence of such disturbances to systems, it is essential to design a robust controller.

In the SMIB system with SVC given in Equations (15) and (16), two types of disturbances will be considered. The first disturbance is w_1 which represents torque disturbance acting on the rotating shaft of the generator, while the second disturbance w_2 represents the output current of the SVC. Therefore, the robust control of the SMIB system with SVC can be rewritten as

$$\begin{aligned}\dot{\delta}&=\omega-\omega_o\\ \dot{\omega}&=\frac{\omega_o}{2H}(P_m-P_e)-\frac{D}{2H}(\omega-\omega_o)+\frac{\omega_o}{2H}w_1\\ \dot{B}_L&=\frac{\mathrm{K}}{\mathrm{T}}[-B_L+B_{Lo}+K_c u]+\frac{K}{T}w_2\end{aligned} \tag{30}$$

$$P_e=\frac{E'\,V_t}{x_{l1}+x_{l2}+x_{l1}\,x_{l2}(B_L-B_c)}\sin\delta\quad. \tag{31}$$

System (30) can be written as,

$$\dot{x}=f(x)+g_2(x)u+g_1(x)w \tag{32}$$

where $g_2(x)$ and $f(x)$ are given in (20) and (22) respectively while $g_1(x)$ is given as

$$g_1(x)=\begin{bmatrix}0 & 0\\ c_1 & 0\\ 0 & c_5\end{bmatrix}\quad. \tag{33}$$

Choose the output,

$$y=h(x)=\delta \tag{34}$$

and since the relative degree of the system from u to y was obtained in the preceding section to be 3, from Section 2 we have

$$\bar{w} = \frac{\partial T(x)}{\partial x}\begin{bmatrix} g_{11}(x) & g_{12} \end{bmatrix} w = \begin{bmatrix} L_{g_{11}} h(x) & L_{g_{12}} h(x) \\ L_{g_{11}} L_f h(x) & L_{g_{12}} L_f h(x) \\ L_{g_{11}} L_f^2 h(x) & L_{g_{12}} L_f^2 h(x) \end{bmatrix} \quad . \tag{35}$$

Calculating the elements of the above matrix yields

$$\begin{aligned} & L_{g_{11}} h(x) = L_{g_{12}} h(x) = L_{g_{12}} L_f h(x) = 0 \\ & L_{g_{11}} L_f h(x) = c_1 \qquad\qquad L_{g_{11}} L_f^2 h(x) = -c_1 c_3 \quad . \\ & L_{g_{12}} L_f^2 h(x) = \frac{c_2 c_5 c_7 \sin x_1}{[c_4 + c_5(x_3 - B_c)]^2} \end{aligned} \tag{36}$$

Clearly from (36) the relative degrees ρ_1 and ρ_2 from w_1 and w_2 to y are 2 and 3 respectively. By taking ρ to be the minimum of the two relative degrees, then the matrix B_1 in (11) is given by

$$B_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad . \tag{37}$$

Through coordinate transformation of system (25) and state feedback control law (26), the system in (30) can be transformed into,

$$\begin{aligned} \dot{z} &= Az + B_2 v + B_1 \bar{w} \\ y &= Cz \end{aligned} \tag{38}$$

where

$$\begin{aligned} & A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \qquad B_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad B_2 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\ & C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}. \end{aligned} \tag{39}$$

Designing a nonlinear robust control law u to stabilize the power system with uncertainties in (30) is equivalent to designing a robust control law v for the linear system in (38). The optimal control law then is given by,

$$v^* = -B_2^T P^* z \tag{40}$$

where the positive definite matrix P^* is a solution to the Riccati Equation (12). Once v^* is determined, then the nonlinear control u is computed using (26).

6. SIMULATION RESULTS

In order to show the validity of the approach described in this paper, several simulations were performed for SMIB system with a SVC given in Figure 1. The system data is given in the Appendix. The control was tested for cases given below.

In the first case the disturbance is assumed to be a self-clearing three-phase fault for 0.1 second on the remote bus for loading condition of 0.8pu output power, load angle, angular speed and the mid-bus voltage are shown in Figures 4, 5 and 6 respectively. In the second case the system was driven to more sever condition by applying a 50% input torque pulse to the generator for 0.1 second and a pulse disturbance of 50% to the SVC for the same period in addition to the three phase fault. The responses are given in Figures 7, 8, and 9. The simulation results indicate that the proposed controller is quite effective in damping the transient oscillations and in managing stronger disturbances. Finally the system was simulated for a number of operating conditions as shown in the plot of the rotor power angle in Figure 10. It can be observed that the robust controller provides very good overall damping over a wide range of operating conditions.

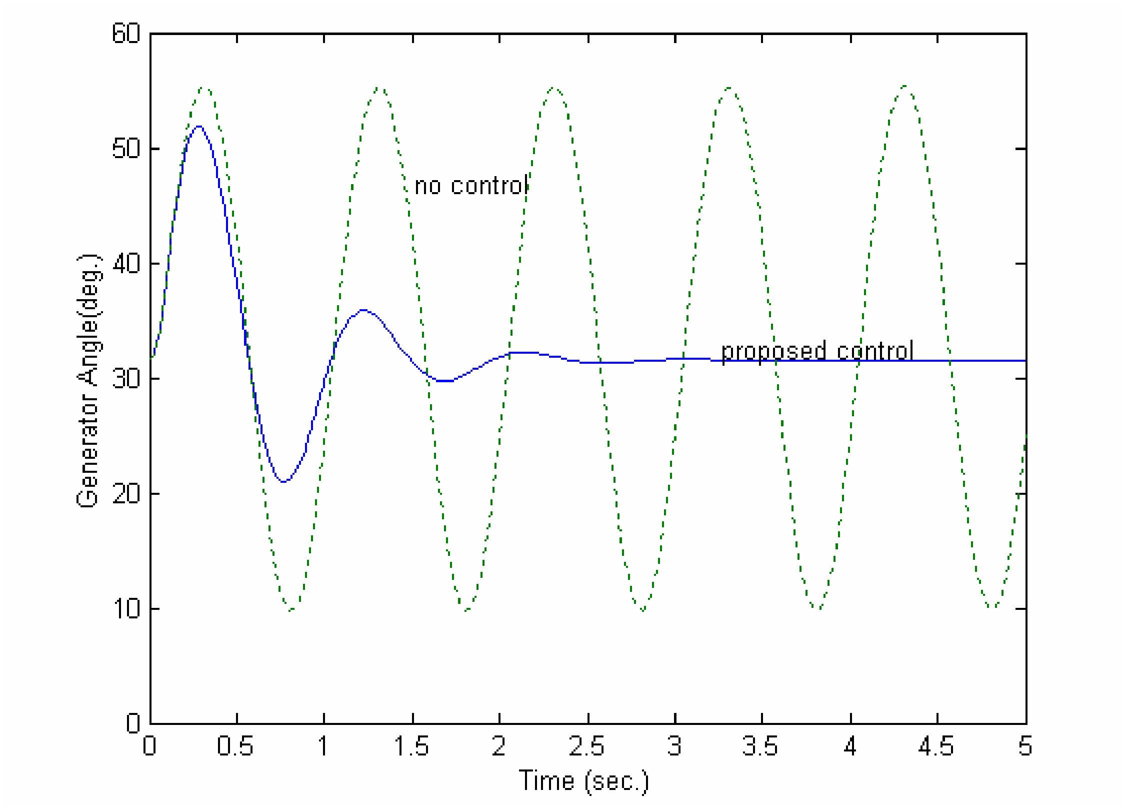

Figure 4. Variation of rotor power angle following three-phase fault cleared in 0.1 The generator was loaded to $P_o = 0.8$ p.u.

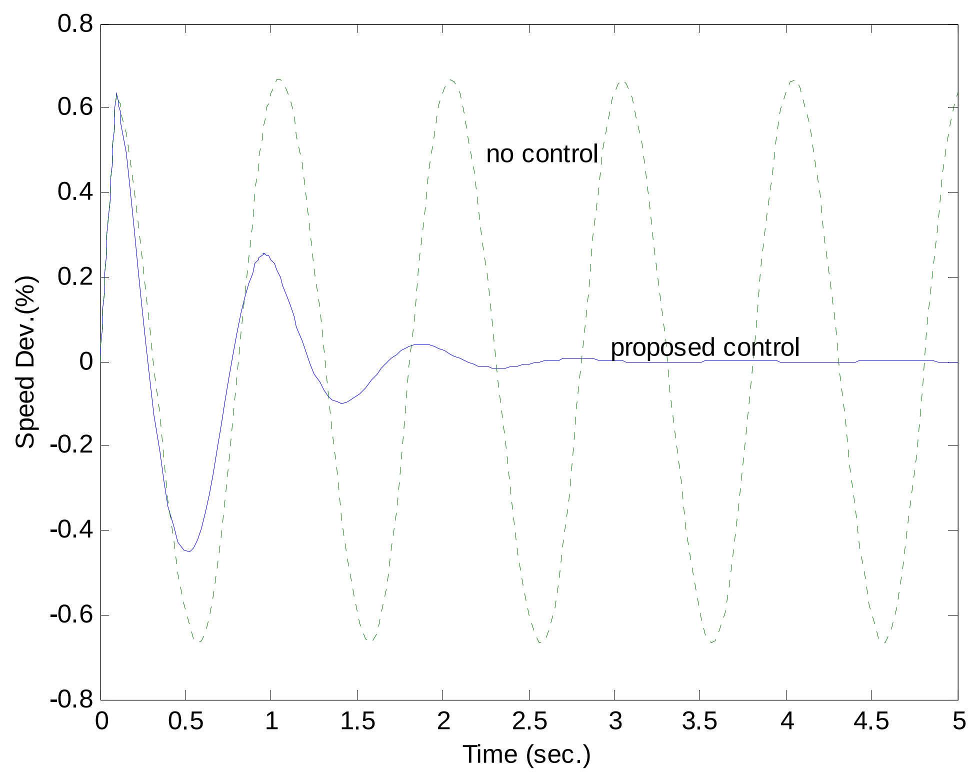

Figure 5. Variation of rotor speed following three-phase fault cleared in 0.1 The generator was loaded to $P_o = 0.8$ p.u.

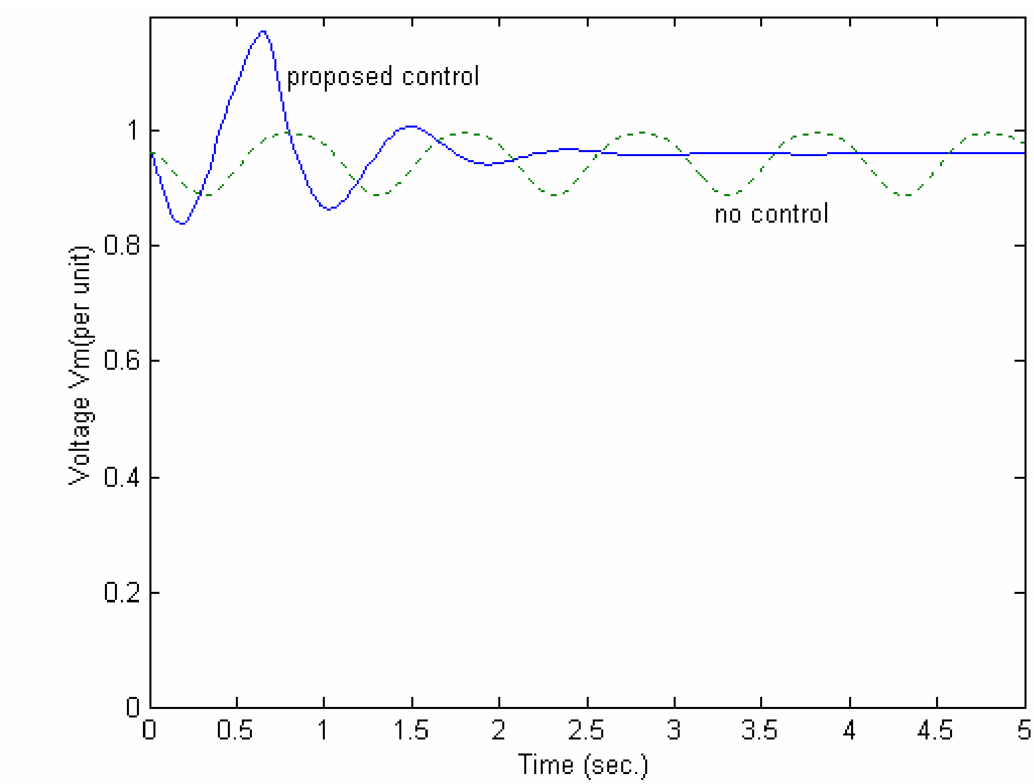

Figure 6. Variation of mid-bus voltage following three-phase fault cleared in 0.1 The generator was loaded to P_o = 0.8 p.u.

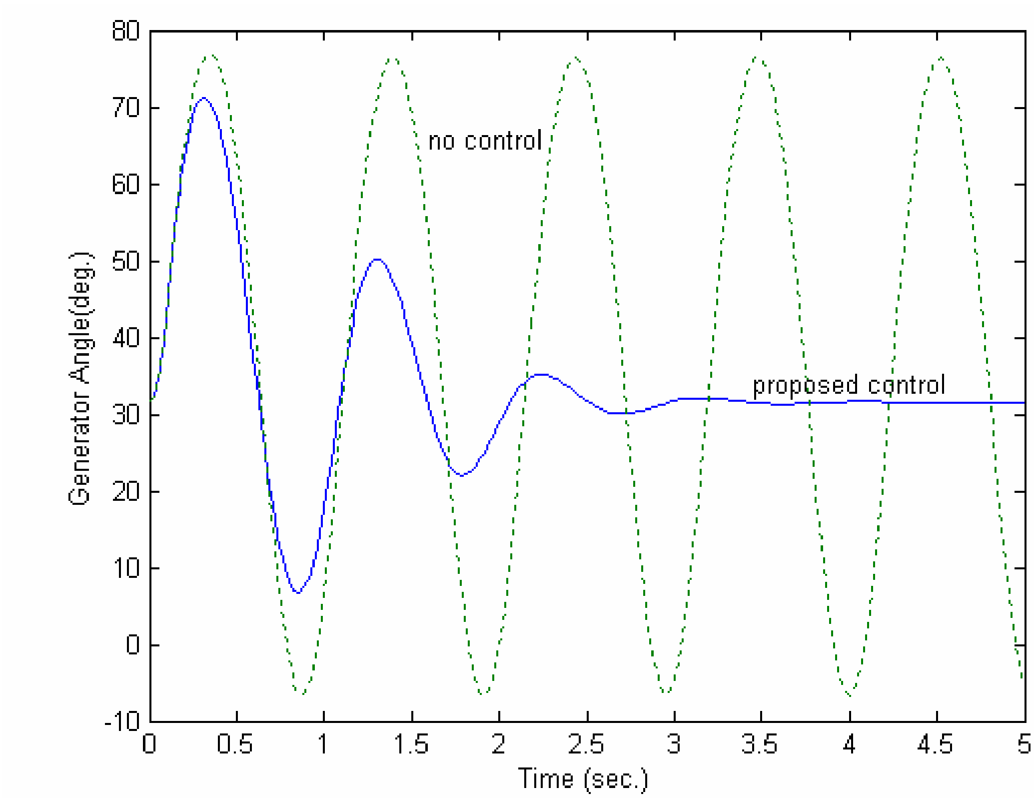

Figure 7. Variation of rotor angle following three-phase fault cleared in 0.1 and 50% input torque pulse to the generator for 0.1 and a pulse disturbance of 50% to the SVC. The generator was loaded to P_o = 0.8 p.u.

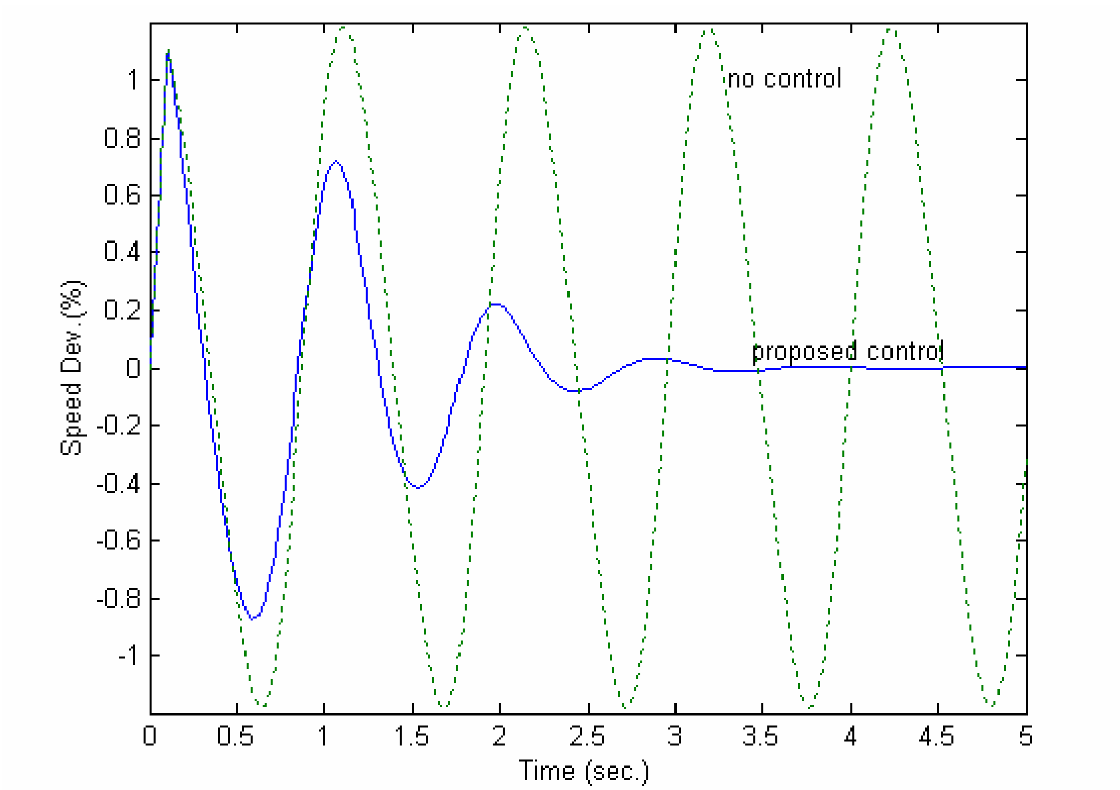

Figure 8. Variation of rotor speed following three-phase fault cleared in 0.1 and 50% input torque pulse to the generator for 0.1 and a pulse disturbance of 50% to the SVC. The generator was loaded to $P_o = 0.8$ p.u.

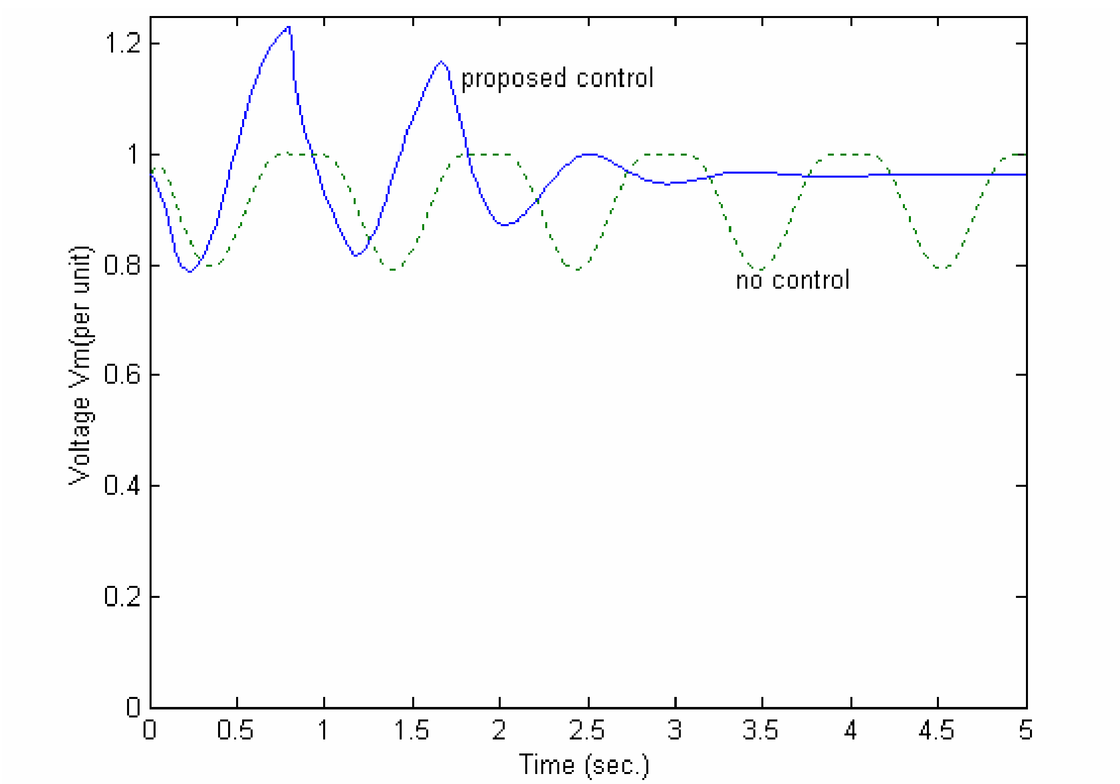

Figure 9. Variation of mid-bus voltage following three-phase fault cleared in 0.1 and 50% input torque pulse to the generator for 0.1 and a pulse disturbance of 50% to the SVC. The generator was loaded to $P_o = 0.8$ p.u.

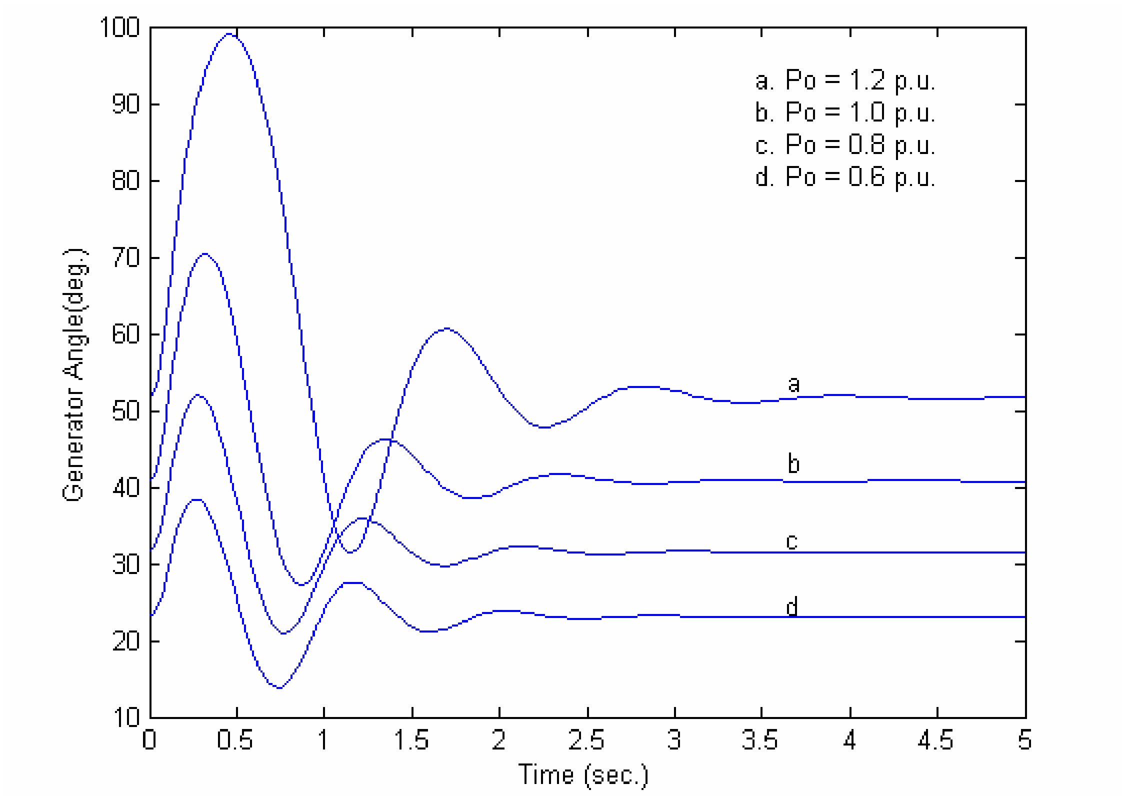

Figure 10. Variation of rotor power angle for various loading conditions following three-phase fault cleared in 0.1.

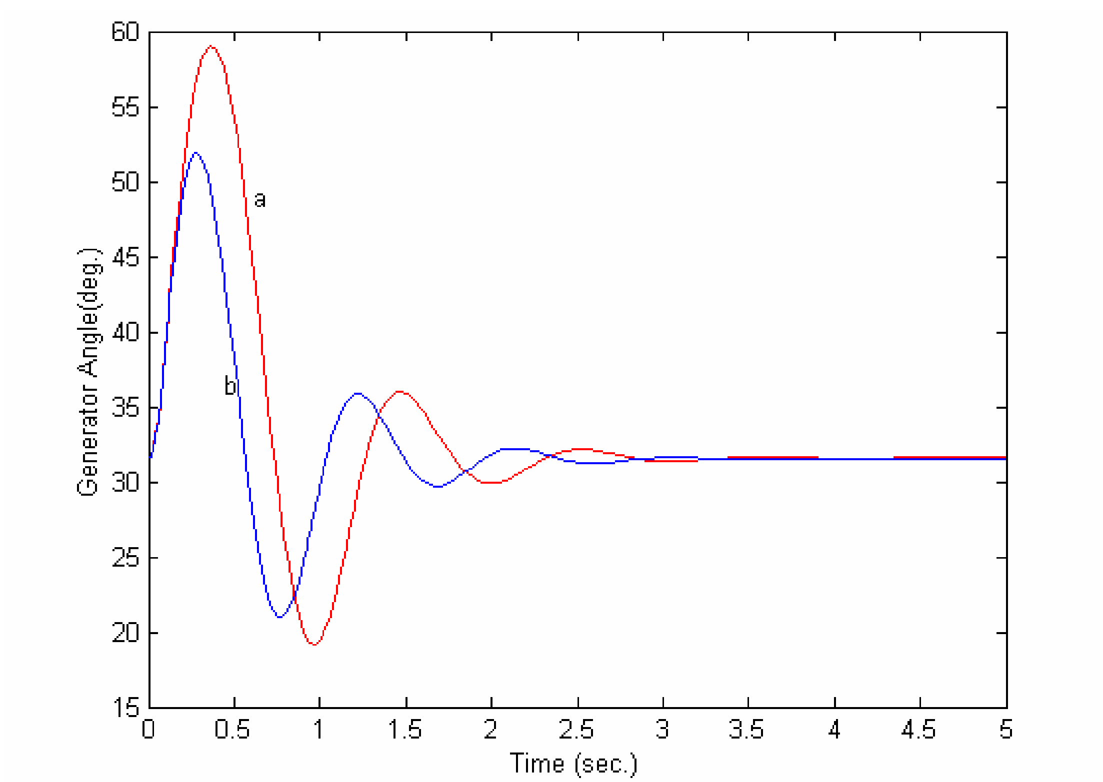

Figure 11. Comparison of rotor angle characteristics with PI and proposed controllers following three-phase fault cleared in 0.1 – at a nominal loading of 0.8 (a) PI control; (b) proposed control

7. EVALUATION OF THE ROBUST CONTROLLER DESIGN

The effectiveness of the proposed robust controller in damping power system oscillations is evaluated through a comparison with a conventional PI controller. The gains of controller were selected based on a pole-placement technique [19]. The method produces an optimum control function for linear system designed for a specific operating point. The transfer function of a PI controller is given as,

$$G_{PID}(s) = K_P + \frac{K_I}{s} \quad . \tag{41}$$

Here, K_P, and K_I are the gains in the proportional and integral loops. Often a washout is added in cascade to the controller to eliminate any unwanted steady state signal. The controller transfer function than can be written as

$$G_c(s) = \frac{sT_w}{1+sT_w}(K_P + \frac{K_I}{s}) \tag{42}$$

where, T_w is the washout time constant.

The PI gains were determined so as to provide the closed-loop compensated system a damping ratio of 0.35 corresponding to the dominant eigenvalues $-1.9 \pm j\,5.1$. The damping ratio is large for normal power system operation, and was intentionally chosen to give a worse scenario for the proposed robust controller. The washout time constant was selected to be 1 sec. The gains at a nominal operating point corresponding to power output of 0.8 pu were obtained as,

$$K_P = -\,0.1128$$

$$K_I = 5.648 \tag{43}$$

Figure 11 gives comparison of the rotor angle variations following a self-clearing type three-phase fault on the remote bus for duration of 0.1 second. Curves '*a*' and '*b*' show the responses with the PI and the robust controllers, respectively. Though the PI controller has been designed to perform optimally at this loading, it is apparent from the curves that the response with the robust control design is superior to the PI control design. Figure 12 shows a comparison of the response with the PI and proposed robust controller for an off-nominal loading of 1 pu. It can be observed that response with PI control is deteriorated. For loadings beyond 1.1 pu, the PI controller gives unstable response. The robust controller, however, performs well for ranges of operating points which are quite far from the nominal one.

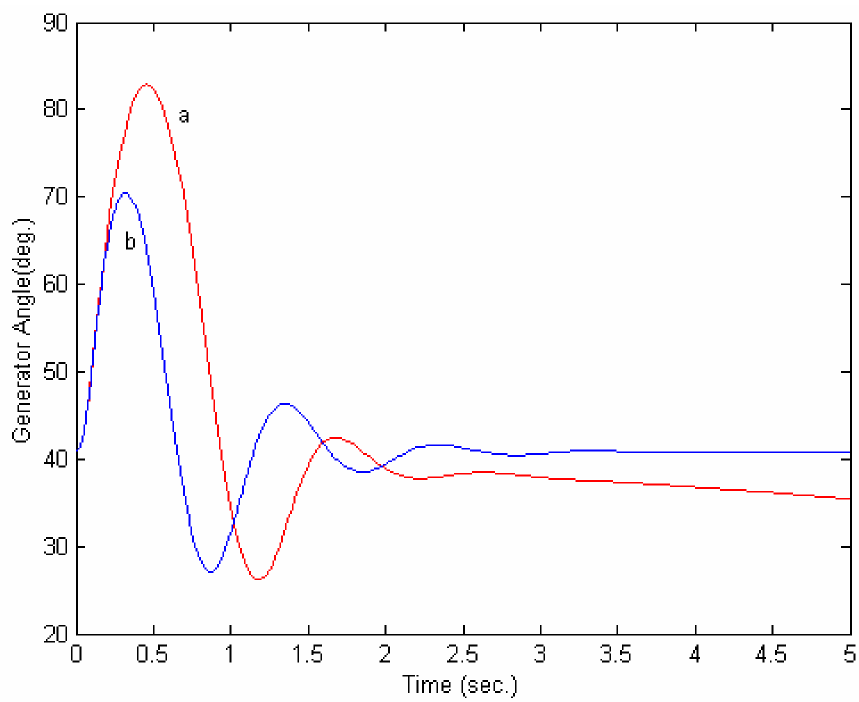

Figure 12. Comparison of rotor angle characteristics with PI and proposed controllers following three-phase fault cleared in 0.1– at loading of 1.0 (a) PI control; (b) proposed control

CONCLUSIONS

Robust stabilizing controller for a single machine infinite-bus system with a SVC has been developed. A more realistic power system model has been used. The model has the advantages that it takes into account the uncertainties in the system. The controller was designed using the H_∞ technique. The proposed controller is shown to be effective and robust in suppressing large disturbances, as well as enhancing the system stability. It is also very effective for a range of operating conditions of the power system.

ACKNOWLEDGMENT

The author would like to acknowledge the support and encouragement of King Fahd University of Petroleum and Minerals.

REFERENCES

[1] C. A. Canizares, M. P. Sandro Corsi, and E. Uzunovic, "STATCOM Modeling for Voltage and Angle Stability Studies," *Electrical Power & Energy Systems*, **25** (2003), pp. 1 – 20.

[2] A. H. M. A. Rahim, S. S. AL-Baiyat, and H. M. Al-Maghrabi, "Robust Damping Controller Design for a Static Compensator," *IEE Proceedings Generation Transmission Distribution*, **149** (**4**) (2002), pp. 491 – 496.

[3] Y. Ma, S. Chen, and B. Zhang, "A Study on Nonlinear SVC Control for Improving Power System Stability," *TENCON'93, Proceedings, Computer, Communication, Control and Power Engineering, 1993 IEEE Region 10 Conference*, Vol. 5, pp. 166 – 169.

[4] Y. Wang, Y.L. Tan, and G. Guo, "Robust Nonlinear Co-Ordinated Excitation and TCSC Control for Power Systems," *IEE Proc. Genr. Transm. Distrib*., **149** (**3**) (2002), pp. 367 – 372.

[5] H. F. Wang and F. Li, "Design of STATCOM Multivariable Sampled Regulator," *Int. Conf. Electric Utility Deregulation and Power Technology 2000, City University London*, April 2000.

[6] H. F. Wang, " Philips–Heffron Model of Power Systems Installed with STATCOM and Applications," *IEE Proc. Genr. Transm. Distrib*., **146** (**5**) (1999), pp. 521 – 527.

[7] A. Isidori and A. Astolfi, "Disturbance Attenuation and H_∞ -Control Via Measurement Feedback in Nonlinear Systems," *IEEE Trans. on Automatic Control*, **37** (**9**) (1993), pp. 1283 – 1293.

[8] A. J. van der Schaft, "L_2-Gain Analysis of Nonlinear Systems and Nonlinear State Feedback H_∞ Control," *IEEE Trans. on Automatic Control*, **37** (**6**) (1993), pp. 770 – 784.

[9] C. C. Cheah, S. Kawamura, S. Arimoto, and K. Lee, " H_∞ Tuning for Task-Space Feedback Control of Robot with Uncertain Jacobian Matrix," *IEEE Trans. on Automatic Control*, **46** (**8**) (2001), pp. 1313 – 1318.

[10] Shr-Shing Hu, Pao-Hwa Yang, and B.C. Chang, "Modified Nonlinear H_∞ Controller Formulas and the H_∞ I/O Linearization Problem," *Proceedings of the 37th IEEE Conference on Decision & Control*, *Tampa, Florida, USA*, December 1998, pp. 3500 – 3505.

[11] Qiang Lu, Yuanzhang Sun, and Shengwei Mei, *Nonlinear Control Systems and Power System Dynamics*, Norwell, Massachusetts, Kluwer Academic Publishers, 2001.

[12] L. R. Hunt, R. Su, and G. Mayer, "Global Transformation of Nonlinear Systems," *IEEE Trans. on Automatic Control*, **28** (**1**) (1983), pp. 24 – 31.

[13] A. Isidori , *Nonlinear Control Systems*. Berlin: Springer Verlag, 1989.

[14] H. K Khalil, *Nonlinear Systems*, Upper Saddle River, New Jersey: Prentice Hall, 1996.

[15] J. Doyle, K Glover, P. Khargonekar, and B. A. Francis, "State-Space Solution to Standard H_2 and H_∞ Control Problem," *IEEE Trans. on Automatic Control*, **34** (**8**) (1989), pp. 831 – 842, August 1989.

[16] S. A. AL-Baiyat and A. Rahim, "Dynamic Braking Resistor-Reactor Switching Strategies Through a Novel Linear Transformation Technique", *Electric Machines and Power Systems*, **21** (1993), pp. 543 – 555.

[17] A. F. Okou, O. Akhrif, and L. A. Dessaint, "Nonlinear Control of Non-Minimum Phase Systems: Application to the Voltage and Speed Regulation of Power Systems," *Proceedings of the 1999 IEEE International Conference on Control Applications*, *Hawaii, USA*, August 1999, pp. 609 – 615.

[18] Yi Guo, David J. Hill, and Youyi Wang, "Global Transient Stability and Voltage Regulation for Power Systems," *IEEE Trans. on Power Systems*, **16** (**4**) (2001), pp. 678 – 688.

[19] Y. Hsu, and C. Chen, "Tuning of Power System Stabilizers Using an Artificial Neural Network," *IEEE Trans. Energy Conversion*, **6** (**4**) (1991), pp. 612 – 619.

APPENDIX

The power system data are as follows:

H=6.0 sec, D=.0055, K=1.2, T = 0.2, x1 = 0.45 p.u, x2 = 0.3 p.u, ω_o = 377.0, E'= 1.1, V_t =1, B_{lo} = 0.58, B_c = 0.8. In the robust control γ is set to be 0.1.

Paper Received 16 February 2004; Revised 19 May 2004; Accepted 1 June 2004.