01 Aug 2004

Feedback Linearization Based Power System Stabilizer Design with Control Limits

Wenxin Liu

Ganesh K. Venayagamoorthy
Missouri University of Science and Technology

Donald C. Wunsch
Missouri University of Science and Technology, dwunsch@mst.edu

Jagannathan Sarangapani
Missouri University of Science and Technology, sarangap@mst.edu

Feedback Linearization based Power System Stabilizer Design with Control Limits

Wenxin Liu, *Student Member*, *IEEE*, Sarangapani Jagannathan, *Senior Member*, *IEEE*,
Ganesh K Venayagamoorthy, *Senior Member*, *IEEE* and Donald C Wunsch II, *Senior Member*, *IEEE*

***Abstract* — In power system controls, simplified analytical models are used to represent the dynamics of power system and controller designs are not rigorous with no stability analysis. One reason is because the power systems are complex nonlinear systems which pose difficulty for analysis. This paper presents a feedback linearization based power system stabilizer design for a single machine infinite bus power system. Since practical operating conditions require the magnitude of control signal to be within certain limits, the stability of the control system under control limits is also analyzed. Simulation results under different kinds of operating conditions show that the controller design not only can damp the power system oscillations very well but can also minimize the impact on the terminal voltage. In addition, the Brunovsky Canonical form of the power system model presented in this paper can be used for other forms of controller design.**

***Index Terms*—Power system, nonlinear systems, power system stabilizer, feedback linearization**

I. Introduction

Currently most of the generators are equipped with voltage regulators to control terminal voltage. It is known that the voltage regulator has a detrimental impact upon the dynamic stability of the power system. During changes of operating conditions, oscillations of small magnitude and low frequency often persist for long period of time and in some cases even present limitations on power transfer capability. Power system stabilizer (PSS) is designed to damp the low frequency oscillations of power systems. The issues of power system stabilizing control have received a great deal of attention since 1960's.

Earlier researches on stabilizing control are based on linear system model. For example, the widely used conventional power system stabilizer (CPSS) is designed using the theory of phase compensation and introduced as a lead-lag compensator. The parameters of CPSS are determined based on linearized models of power system around some nominal operating point. To have the CPSS provide robust damping, its parameters need to be fine tuned for different operating points and different types of oscillations. To overcome this problem, there are techniques based using intelligent optimization algorithms (such as simulated annealing, genetic algorithm, and tabu search) to get the "optimal parameters" of CPSS by optimizing an eigenvalue based cost function. In addition, fuzzy logics and neural networks are also applied to adjust the parameters of CPSS online after some initial offline training. Since power systems are highly nonlinear systems, with configurations and parameters changing with time, the designs based on linearized model cannot guarantee its performance in practical operating environment. Thus, adaptive stabilizing control schemes based on nonlinear model of the power systems are preferred [1].

Recently, different kinds of techniques have been reported for the design of adaptive stabilizing controllers or PSS, such as adaptive fuzzy logic control, direct and indirect adaptive neural network control, adaptive critic designs [2] and other nonlinear control techniques. Most of which only demonstrated the effectiveness of the controller design through simulation while not showing the stability analysis. One reason maybe the power systems are large complex nonlinear systems which are difficult for analysis. But industry will be reluctant to accept such a controller design if the stability cannot be guaranteed. Furthermore, since the implementation of the controller lacks the guidance of stability analysis, the controller parameters have to be adjusted by trial and error which is a time consuming job and limits the applications of such controller design. Therefore, stable PSS designs are necessary.

In the past decade, there appear some stabilizing controller designs based on the analysis of the control system [3–10], most of which are based on feedback linearization. In those papers, controls are implemented through either the turbine governor or the excitation system; the controlled variables are selected to be either rotor/power angle or the speed; the control systems are either single machine or multi-machine systems. If the stabilizing control is implemented in the excitation system together with the controls of the terminal voltage, these two kinds of control may interact with each other. But few papers investigated the performance of the terminal voltage under the proposed PSS design. Since the change of operating condition is unknown, it is difficult to set the reference signal to the rotor angle. Furthermore, to simplify stability analysis, most controller designs are based on simplified model. While simplified model cannot reflect the actual complex dynamics of power system, accurate multi-machine model is desired for practical controller design. Though practical operating conditions require the magnitude of the control signal to be within certain limit, none of the above mentioned papers consider the control limit constraints.

In this paper, the control objective is selected to be the speed because the desired value of which is always a constant given by $2\pi f$. The control algorithm is developed based on a single machine infinite bus power system model. The design of

The authors are with the Department of Electrical and Computer Engineering, University of Missouri – Rolla, MO, 65401, USA. (the email addresses for the authors are wl3g3@umr.edu, sarangap@umr.edu, ganeshv@umr.edu and dwunsch@umr.edu respectively)

decentralized control algorithm for multi-machine power system is under development and results will be reported in the future. The stability of the control system when the control signals are subjected to magnitude constraints is also investigated. Simulations under different operating conditions show satisfactory performance for both stabilizing and voltage controls.

The organization of the paper is as follows. The mathematical model of the single machine infinite bus power system is described in section II. The design and stability analysis of the feedback linearization based power system stabilizer is shown in section III. Simulation results are provided in section IV, and finally the conclusion in Section V.

II. Single Machine Infinite Bus Power System Model

Fig. 1 shows the configuration of the single machine infinite bus power system. The system consists of a synchronous generator, an exciter, an automatic voltage regulator (AVR) and a transmission line which connects the generator bus to the infinite bus. The control signal (PSS) is added to the inputs of AVR.

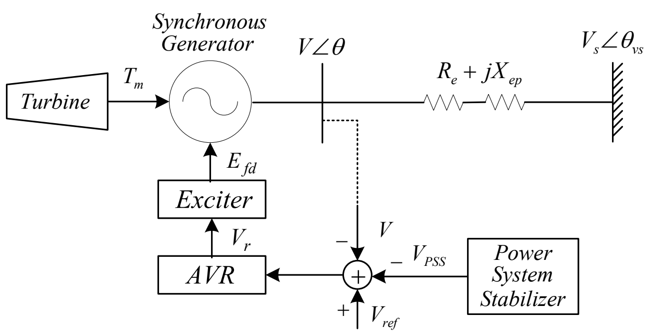

Fig. 1. Single machine infinite bus power system configuration

The dynamics of the single machine system is expressed using a Flux-Decay model as is shown in (1). The first three equations describe the dynamics of the synchronous generator, the fourth and fifth equations describe the dynamics of the exciter and AVR respectively [11].

$$\begin{aligned}
&\frac{d\delta}{dt} = \omega - \omega_s \\
&\frac{2H}{\omega_s}\frac{d\omega}{dt} = T_m - E_q^{'} I_q - (X_q - X_d^{'}) I_d I_q - D_{fw}(\omega - \omega_s) \\
&T_{d0}^{'}\frac{dE_q^{'}}{dt} = -E_q^{'} - (X_d - X_d^{'}) I_d + E_{fd} \\
&T_e \frac{dE_{fd}}{dt} = -E_{fd} + V_r \\
&T_a \frac{dV_r}{dt} = -V_r + K_a (V_{ref} - V_t - V_{pss})
\end{aligned} \tag{1}$$

where, I_d, I_q and V_t are subjected to the constraints of (2) and (3) respectively:

$$\begin{aligned}
&0 = R_e I_d - (X_q + X_{ep}) I_q + V_s \sin(\delta - \theta_{vs}) \\
&0 = R_e I_q + (X_d^{'} + X_{ep}) I_d - E_q^{'} + V_s \cos(\delta - \theta_{vs})
\end{aligned} \tag{2}$$

$$V_t = \sqrt{V_d^2 + V_q^2} \tag{3}$$

with,

$$\begin{aligned}
&V_d = R_e I_d - X_{ep} I_q + V_s \sin(\delta - \theta_{vs}) \\
&V_q = R_e I_q + X_{ep} I_d + V_s \cos(\delta - \theta_{vs})
\end{aligned} \tag{4}$$

In above equations, δ is the rotor angle, ω is the speed, E_{fd} is the field voltage, V_r is the output of the automatic voltage regulator (AVR), T_m is the mechanical torque, V is the terminal voltage at the generator bus, V_{ref} is reference used to control the terminal voltage, R_e and X_{ep} form the impedance of the transmission line between the generator and infinite bus, $V_s\angle\theta_{vs}$ are the voltage of the infinite bus, and V_{pss} is the control signal.

Table I shows the value of the parameters in the above model [11].

TABLE I
System Parameters

$T_{d0}^{'} = 6.0$	$X_d = 0.8958$	$X_d^{'} = 0.1198$	$X_q = 0.8645$
$H = 6.4$	$\omega_s = 377$	$D_{fw} = 0.0125$	$T_e = 0.314$
$T_a = 0.01$	$K_a = 20$	$R_e = 0.025$	$X_{ep} = 0.085$

III. Controller Design

Feedback linearization control is a nonlinear state feedback technique in which some of system outputs are constrained to behave as a linear system [12].

A. Model Transformation

Since in the model, the right hand side of the differential equations includes some variables (such as I_d, I_d and V_t) which are not the states, it is necessary to express these variables using the state variables. After that, the system model is transformed into:

$$\begin{aligned}
&\dot{\delta} = \omega - \omega_s \\
&\dot{\omega} = k_6 \sin^2(\delta - \theta_{vs}) + k_7 \cos^2(\delta - \theta_{vs}) + k_8 \sin(\delta - \theta_{vs})\cos(\delta - \theta_{vs}) \\
&+ k_9 \sin(\delta - \theta_{vs}) E_q^{'} + k_{10} \cos(\delta - \theta_{vs}) E_q^{'} + k_{11} E_q^{'2} + k_{12}\omega + k_{13} \\
&\dot{E}_q^{'} = -k_{14} E_q^{'} + k_{16} \sin(\delta - \theta_{vs}) + k_{17} E_q^{'} + k_{18} \cos(\delta - \theta_{vs}) + k_{14} E_{fd} \\
&\dot{E}_{fd} = k_{19} E_{fd} - k_{19} V_r \\
&\dot{V}_r = k_{27} V_r + k_{28} V_{ref} - k_{28} V_t + k_{28} V_{pss}
\end{aligned} \tag{5}$$

where,

$$V_t = \sqrt{\begin{aligned} &k_{21}\sin^2(\delta - \theta_{vs}) + k_{22}\cos^2(\delta - \theta_{vs}) + k_{23}E_q^{'2} + k_{24}\sin(\delta - \theta_{vs})E_q^{'} \\ &+ k_{25}\cos(\delta - \theta_{vs})E_q^{'} + k_{26}\sin(\delta - \theta_{vs})\cos(\delta - \theta_{vs}) + V_s^2 \end{aligned}}$$

(6)

The definitions of the constants k_1 to k_{28} are given in the Appendix.

B. Input-Output Linearization based Controller Design

Since the control objective is speed ω, this is a single input single output control problem. Defining the speed deviation as $e = \omega - \omega_s$, then the control objective is to regulate e to zero. In order to get the expression of the speed deviation with respect to the control signal, we need to differentiate e several times until the control signal appears. The process is shown below:

$$\begin{aligned}\dot{e} = \dot{\omega} &= k_6 \sin^2(\delta - \theta_{vs}) + k_7 \cos^2(\delta - \theta_{vs}) + k_8 \sin(\delta - \theta_{vs})\cos(\delta - \theta_{vs}) \\ &+ k_9 \sin(\delta - \theta_{vs})E_q^{'} + k_{10}\cos(\delta - \theta_{vs})E_q^{'} + k_{11}E_q^{'2} + k_{12}\omega + k_{13}\end{aligned} \tag{7}$$

$$\begin{aligned}\ddot{e} = \ddot{\omega} &= (k_6 - k_7)\sin[2(\delta - \theta_{vs})]\dot{\delta} + k_8\dot{\delta}\cos[2(\delta - \theta_{vs})] + 2k_{11}E_q^{'}\dot{E}_q^{'} + k_{12}\dot{\omega} \\ &+ \cos(\delta - \theta_{vs})[k_9 E_q^{'}\dot{\delta} + k_{10}\dot{E}_q^{'}] + \sin(\delta - \theta_{vs})[k_9\dot{E}_q^{'} - k_{10}E_q^{'}\dot{\delta}]\end{aligned} \tag{8}$$

$$\begin{aligned}\dddot{e} = \dddot{\omega} &= \cos[2(\delta - \theta_{vs})][2(k_6 - k_7)\dot{\delta}^2 + k_8\dot{\omega}] \\ &+ \sin[2(\delta - \theta_{vs})][(k_6 - k_7)\dot{\omega} - 2k_8\dot{\delta}^2] \\ &+ [k_9\cos(\delta - \theta_{vs}) - k_{10}\sin(\delta - \theta_{vs})](2\dot{E}_q^{'}\dot{\delta} + E_q^{'}\dot{\omega}) \\ &- [k_9\sin(\delta - \theta_{vs}) + k_{10}\cos(\delta - \theta_{vs})]\{E_q^{'}\dot{\delta}^2 + k_{14}\dot{E}_{fd} - (k_{14} - k_{17})\dot{E}_q^{'} - \\ &[k_{16}\cos(\delta - \theta_{vs}) - k_{18}\sin(\delta - \theta_{vs})]\dot{\delta}\} \\ &+ [k_{16}\cos(\delta - \theta_{vs}) - k_{18}\sin(\delta - \theta_{vs})]2k_{11}E_q^{'}\dot{\delta} \\ &+ k_{12}\ddot{\omega} + 2k_{11}\dot{E}_q^{'2} + 2k_{11}k_{14}E_q^{'}\dot{E}_{fd} - 2k_{11}(k_{14} - k_{17})E_q^{'}\dot{E}_q^{'}\end{aligned} \tag{9}$$

$$e^{(4)} = \omega^{(4)} = f(X) + g(X)V_{pss} \tag{10}$$

where,

$$\begin{aligned}f(X) &= \sin[2(\delta - \theta_{vs})][(k_7 - k_6)(4\dot{\delta}^3 - \ddot{\omega}) - 6k_8\dot{\delta}\dot{\omega}] \\ &- \cos[2(\delta - \theta_{vs})][6(k_7 - k_6)\dot{\delta}\dot{\omega} + 4k_8\dot{\delta}^3 - k_8\ddot{\omega}] \\ &+ [k_9\cos(\delta - \theta_{vs}) - k_{10}\sin(\delta - \theta_{vs})]\cdot \\ &[2\ddot{E}_q^{'}\dot{\delta} + 3E_q^{'}\dot{\omega} + 2k_{11}k_{14}\dot{E}_q^{'}\dot{E}_{fd} - 2k_{11}(k_{14} - k_{17})\dot{E}_q^{'2}] \\ &- [k_9\sin(\delta - \theta_{vs}) + k_{10}\cos(\delta - \theta_{vs})]\cdot \\ &[3\dot{E}_q^{'}\dot{\delta}^2 + 3E_q^{'}\dot{\delta}\dot{\omega} + (k_{14} - k_{17})\ddot{E}_q^{'} - k_{14}k_{19}(\dot{E}_{fd} - k_{27}V_r + k_{28}V_t - k_{28}V_{ref})] \\ &+ [k_{16}\cos(\delta - \theta_{vs}) - k_{18}\sin(\delta - \theta_{vs})]\{[k_9\cos(\delta - \theta_{vs}) - k_{10}\sin(\delta - \theta_{vs})]\dot{\delta}^2 + \\ &[k_9\sin(\delta - \theta_{vs}) + k_{10}\cos(\delta - \theta_{vs}) + 2k_{11}E_q^{'}]\dot{\omega} + 2k_{11}\dot{E}_q^{'}\dot{\delta}\} \\ &- [k_9\sin(\delta - \theta_{vs}) + k_{10}\cos(\delta - \theta_{vs}) + 2k_{11}E_q^{'}][k_{16}\sin(\delta - \theta_{vs}) + k_{18}\cos(\delta - \theta_{vs})]\dot{\delta}^2 \\ &+ 2k_{11}\dot{E}_q^{'}[k_{14}\dot{E}_{fd} - (k_{14} - k_{17})\dot{E}_q^{'}] + 2[k_{11}(k_{17} - k_{14}) + 2k_{11}]\dot{E}_q^{'}\ddot{E}_q^{'} \\ &+ k_{12}\dddot{\omega} + 2k_{11}k_{14}k_{19}E_q^{'}(\dot{E}_{fd} - k_{27}V_r + k_{28}V_t - k_{28}V_{ref})\end{aligned} \tag{11}$$

$$g(X) = k_{14}k_{19}k_{28}[k_9\sin\alpha + k_{10}\cos\alpha + 2k_{11}E_q^{'}] \tag{12}$$

with,

$$\ddot{E}_q^{'} = -k_{14}\dot{E}_q^{'} + k_{16}\cos(\delta - \theta_{vs})\dot{\delta} + k_{17}\dot{E}_q^{'} - k_{18}\sin(\delta - \theta_{vs})\dot{\delta} + k_{14}\dot{E}_{fd} \tag{13}$$

Where X stands for the original state variables δ, ω, $E_q^{'}$, E_{fd} and V_r. Since ω is selected as the control objective, the control signal V_{pss} appears at the fourth derivative of ω. The feedback linearized system is fourth-order rather than the original fifth-order. Since the uncontrolled state δ satisfies $\dot{\delta} = \omega - \omega_s$, δ is bounded when ω is stabilized to ω_s. So even if δ is not defined as one of the states in the feedback linearized system, the system is still stable. Now defining the new state variables as:

$$\bar{x} = [x_1 \quad x_2 \quad x_3 \quad x_4]^T = [\omega \quad \dot{\omega} \quad \ddot{\omega} \quad \dddot{\omega}]^T \tag{14}$$

then the system is transformed into:

$$\begin{aligned}\dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= f(x) + g(x)u\end{aligned} \tag{15}$$

where u stands for the control signal V_{pss}. Defining the reference signals and the error signals as (17) and (18) respectively:

$$x_d = [x_{d1} \quad x_{d2} \quad x_{d3} \quad x_{d4}]^T = [\omega_s \quad \dot{\omega}_s \quad \ddot{\omega}_s \quad \dddot{\omega}_s]^T \tag{17}$$

$$\bar{e} = \bar{x} - \bar{x}_d = [e_1 \quad e_2 \quad e_3 \quad e_4]^T \tag{18}$$

Then error dynamics of the system can be expressed as:

$$\begin{aligned}\dot{e}_1 &= e_2 \\ \dot{e}_2 &= e_3 \\ \dot{e}_3 &= e_4 \\ \dot{e}_4 &= f(x) + g(x)u - \dot{x}_{d4}\end{aligned} \tag{19}$$

Since $\omega_s = 2\pi f$ is a constant value, all of its derivatives are zeros. So the error dynamics equals to:

$$\dot{\bar{e}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}\bar{e} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ f(x) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ g(x) \end{bmatrix}u \tag{20}$$

According to the theory of feedback linearization, the ideal control signal v can be chosen as:

$$v = \frac{1}{g(x)}[-K_v\bar{e} - f(x)] \tag{21}$$

where K_v is gain vector which is defined as:

$$K_v = [a_4 \quad a_3 \quad a_2 \quad a_1] \tag{22}$$

and a_1, a_2, a_3 and a_4 are a set of suitably chosen parameters to make the closed loop system stable, i.e. $s^4 + a_4 s^3 + a_3 s^2 + a_2 s + a_1 = 0$ is Hurwitz). Then the closed-loop

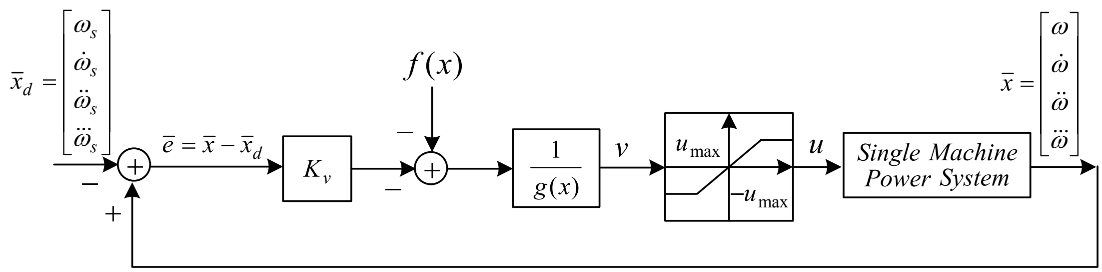

Fig. 2. Structure of the feedback linearization control system

dynamics can be transformed into the linear system with no magnitude constraint ($u = v$):

$$\dot{\bar{e}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_4 & -a_3 & -a_2 & -a_1 \end{bmatrix} \bar{e} = K\bar{e} \tag{23}$$

With an appropriate selection of a_1, a_2, a_3 and a_4, it can be shown that (23) is asymptotically stable ($e \to 0$). Since the actual control signal is subjected to magnitude constraints, the applied control signal u is given by

$$u = \begin{cases} v & while|v| \le u_{\max} \\ u_{\max} sign(v) & while|v| > u_{\max} \end{cases} \tag{24}$$

where $u_{\max}$ is the maximum allowed control signal magnitude. The structure of the controller is shown in Fig. 2.

C. Stability Analysis

Defining a new variable Δu as

$$\Delta u = u - v \tag{25}$$

where Δu is the difference between the ideal and actual control signal. Then, the dynamics of closed loop system become:

$$\dot{\bar{e}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_4 & -a_3 & -a_2 & -a_1 \end{bmatrix} \bar{e} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} g(x)\Delta u \tag{26}$$

Case 1, $|v| \le u_{\max}$, $\Delta u = 0$

This is the ideal case, the system is linearized to a linear system (23) which is stable and its performance is decided by the selection of K_v.

Case 2, $|v| > u_{\max}$, $\Delta u \ne 0$

Given the fact that $g(x)$ and Δu are both bounded, equation (25) is a linear stable system driven by a bounded input. According to linear system theory, the error should be bounded. The error bound depends upon the bound on Δu. Note that u is always bounded due to the magnitude constraint, and v is shown to be bounded if no limits are in place from (23). As a result, Δu is bounded. Therefore all the states of the closed loop system are bounded.

IV. Simulation Results

The proposed control algorithm is tested under three kinds of operating conditions, which are 3-phase short circuit at the infinite bus; the change of operating points and change of impedance between the generator and the infinite bus.

For comparison purpose, the performance of the proposed feedback linearization based controller is compared to the cases when no PSS is applied and when conventional power system stabilizer (CPSS) is applied. The transfer function of the CPSS used here is shown in (27) which is a simplified version of IEEE Std. 421.5 [14]. The values of the parameters are chosen by try and error as K_{pss}*=25*, T_1*=0.76*, T_2*=0.1*.

$$V_{pss}(s) = K_{pss} \frac{T_1 s + 1}{T_2 s + 1} \Delta\omega(s) \tag{27}$$

During simulations, the hard limit $V_{pss}^{\max}$ for the proposed feedback linearization based PSS design is set to $V_{pss}^{\max} = 0.5$. K_v is selected to be $[2500 \quad 1500 \quad 325 \quad 30]$ corresponding to the desired closed loop poles -10, -10, -5 and -5.

A. 3-phase Short Circuit at the Infinite

Figs. 3-5 show the system responses to a 100ms 3-phase short circuit fault happened at 0.5 second (P=0.5pu, Q=0.1pu). Fig. 3 shows the comparison of speed deviation response, Fig. 4 shows the comparison of terminal voltage response and Fig. 5 shows the comparison of control signals.

It can be seen from Fig. 3 that *case b* provides the best response, the performance of *case d* is much better than that of *case c* and similar to *case b*. Fig. 4 shows the comparison of the terminal voltage responses, it can be seen that the performance of voltage control is kept under the designed PSS. Fig. 5

explains the differences in performance. It can be seen the performances highly depend on the period and times when the ideal control signal overshoot the hard limit. Shorter period and fewer times will result in better performance. Similar results can be seen in B and C.

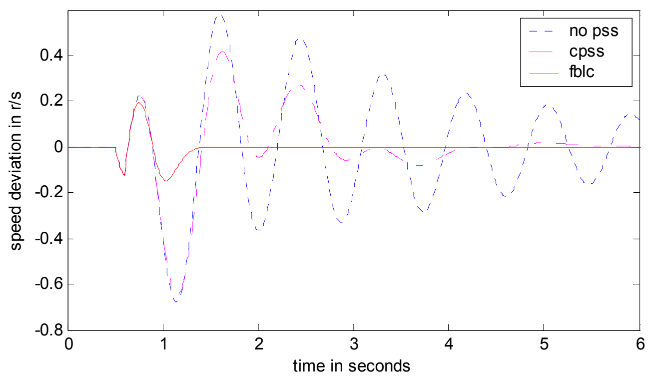

Fig. 3. Speed deviation responses to a 3-phase short circuit fault (P = 0.5pu, Q = 0.1pu)

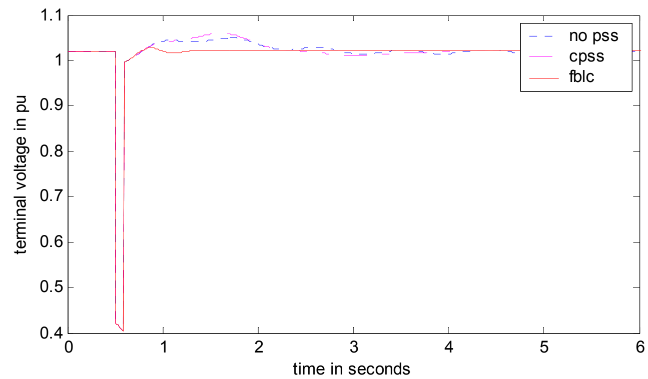

Fig. 4. Terminal voltage responses to a 3- phase short circuit fault (P = 0.5pu, Q = 0.1pu)

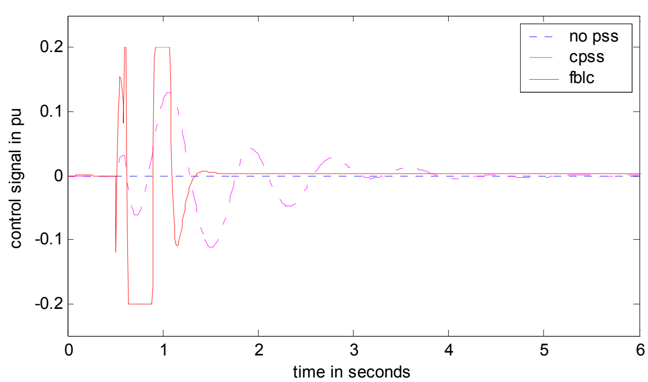

Fig. 5. Control signal responses to a 3-phase short circuit fault (P = 0.5pu, Q = 0.1pu)

B. Change of Operating Points

Figs. 6-7 show the system response to a change of the operating point at 0.5 second (P=0.5pu, Q=0.1pu to P=0.7pu, Q=0.2pu). Fig. 6 shows the comparison of speed deviation response, and Fig. 7 shows the comparison of control signals.

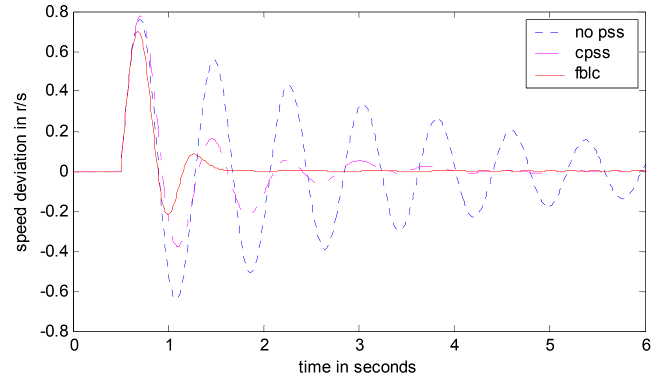

Fig.6. Speed deviation responses to operating point change (P = 0.5pu, Q = 0.1pu to P = 0.7pu, Q = 0.2pu)

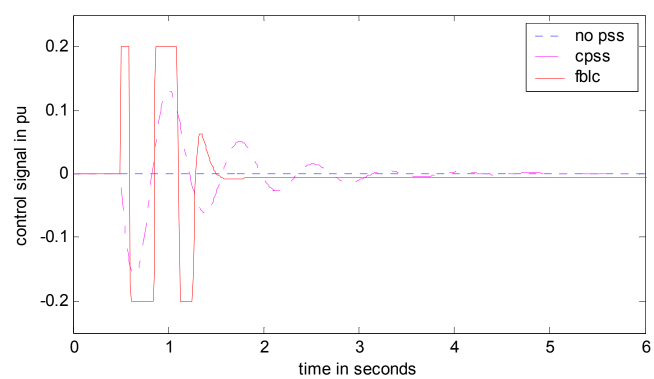

Fig.7. Control signal responses to operating point change (P = 0.5pu, Q = 0.1pu to P = 0.7pu, Q = 0.2pu)

C. Change of Impedance Connected to the Infinite Bus

Figs. 8-9 show the system response to a change of the impedance connected to the infinite bus at 0.5 second ($R_e = 0.025$, $X_{ep} = 0.085$ to $R_e = 0.05$ and $X_{ep} = 0.17$ while P=0.5pu, Q=0.1pu). Fig. 8 shows the comparison of speed deviation response, Fig. 9 shows the comparison of control signal

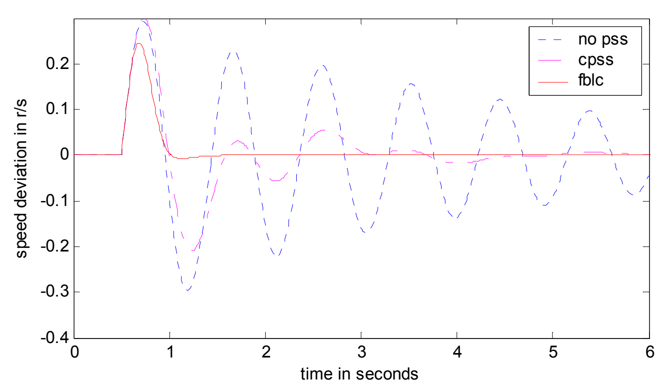

Fig. 8. Speed deviations responses to change of bus impedance (P = 0.5pu, Q = 0.1pu)

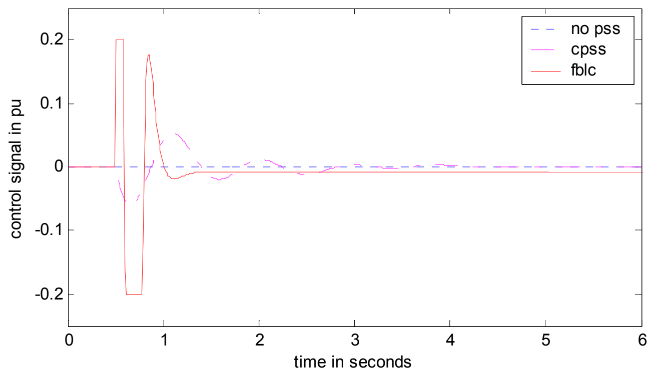

Fig.9. Control signal responses to change of bus impedance (P = 0.5pu, Q = 0.1pu)

V. Conclusion

This paper presents a feedback linearization based power system stabilizer design. Unlike pervious papers which often consider simplified power system models, here, the control algorithm is based on more detailed of a single machine infinite bus power system model. This paper also considered the limits on the magnitude of control signal and analysis the stability of the control system. Since the stabilizing control is implemented in the excitation system together with the voltage control, these two controls may interact with each other. The effect of the proposed PSS on the control of voltage is investigated through simulation. Simulation results under different kinds of operating conditions show the effectiveness of the proposed PSS design.

The Brunovsky Canonical form of the power system model presented in this paper can be used for other forms of controller design. Since feedback linearization require the model of the system to be known exactly so as to linearize it, future research can use neural networks or fuzzy logic approximators to overcome this requirement for the design of controllers.

References

[1] W Liu, G K Venayagamoorthy and D C Wunsch II, "Design of an adaptive neural network based power system stabilizer," *Neural Networks*, Vol. 16, No. 5-6, pp. 891-898.

[2] W Liu, G K Venayagamoorthy and D C Wunsch II, "A Heuristic Dynamic Programming based Power System Stabilizer for a Turbogenerator in a Single Machine Power System," IEEE Industry Applications Society 38th Annual Meeting, Salt Lake City, Utah USA.

[3] Q Lu and Y Sun, "Nonlinear stabilizing control of multimachine system," *IEEE Transactions on Power Systems*, Vol. 4, No. 1, pp. 236-241, February 1989.

[4] Z Qu, J F Dorsey, J Bond, and J D McCalley, "Application of robust control to sustained oscillations in power systems," *IEEE Transactions on Circuits and Systems-I: Fundamental Theory and Applications*, Vol. 39, No. 6, pp. 470-476, June 1992.

[5] J W Chapman, M D Ilic, C A King, L Eng and H Kaufman, "Stabilizing a multimachine power system via decentralized feedback linearizing excitation control," *IEEE Transactions on Power Systems*, Vol. 8, No. 3, pp. 830-839, August 1993.

[6] C A King, J W Chaman and M D Ilic, "Feedback linearizing excitation control on full-scale power system model," *IEEE Transactions on Power systems*, Vol. 9, No. 2, pp. 1102-1109, May 1994.

[7] M Nambu and Y Ohsawa, "Development of an advanced power system stabilizer using a strict linearization approach," *IEEE Transactions on Power Systems*, Vol. 11, No. 2, pp. 813-818, May 1996.

[8] H Jiang, H Cai, J F Dorsey and Z Qu, "Toward a globally robust decentralized control for large-scale power systems," *IEEE Transactions on Control System Technology*, Vol. 5, No. 3, pp. 309-319, May 1997.

[9] Y Wang, G Guo and D J Hill, "Robust decentralized nonlinear controller design for multimachine power systems," *Automatica*, Vol. 33, No. 9, pp. 1725-1733, 1997.

[10] Y Guo, D J Hill and Y Wang, "Global transient stability and voltage regulation for power systems," *IEEE Transactions on Power Systems*, Vol. 16, No. 4, pp. 678 -688, November 2001.

[11] P W Sauer and M A Pai, *Power system dynamics and stability*, Prentice Hall, First edition, 1997.

[12] D Cheng, Tzyh-Jong Tarn and Alberto Isidori, "Global external linearization of nonlinear system via feedback," *IEEE Transactions on Automatic Control*, Vol. 30, No. 8, pp. 808-811, August 1985.

[13] F L Lewis, S Jagannathan and A Yesildirek, *Neural network control of robot manipulators and nonlinear systems*, Taylor & Francis, London 1999.

[14] IEEE, "Recommended practice for excitation system models for power system stability studies", IEEE Std. 421.5-1992, 1992.

Appendix

A. The definition of the constants in

$$k_1 = \frac{R_e}{R_e^{\,2} + (X_d^{'} + X_{ep})(X_q + X_{ep})},\ k_2 = \frac{X_q + X_{ep}}{R_e^{\,2} + (X_d^{'} + X_{ep})(X_q + X_{ep})}$$

$$k_3 = \frac{-X_d^{'} - X_{ep}}{R_e^{\,2} + (X_d^{'} + X_{ep})(X_q + X_{ep})},\ k_4 = -(X_q - X_d^{'}),\ k_5 = \frac{\omega_s}{2H},$$

$$k_6 = k_1 k_3 k_4 k_5 V_s^2,\ k_7 = k_1 k_2 k_4 k_5 V_s^2,\ k_8 = (k_1^2 + k_2 k_3) k_4 k_5 V_s^2,$$

$$k_9 = (k_3 - (k_1^2 + k_2 k_3) k_4) k_5 V_s,\ k_{10} = (k_1 - 2k_1 k_2 k_4) k_5 V_s,$$

$$k_{11} = (k_1 k_2 k_4 - k_1) k_5,\ k_{12} = -D_{fw} k_5,\ k_{13} = k_5 (T_m + D_{fw} \omega_s)$$

$$k_{14} = \frac{1}{T_{d0}^{'}},\ k_{15} = -(X_d - X_d^{'}),\ k_{16} = -k_1 k_{14} k_{15} V_s,\ k_{17} = k_2 k_{14} k_{15},$$

$$k_{18} = -k_2 k_{14} k_{15} V_s,\ k_{19} = -\frac{1}{T_e},\ k_{20} = R_e^2 + X_{ep}^2,$$

$$k_{21} = (k_1^2 + k_3^2) k_{20} V_s^2 - 2k_1 R_e V_s^2 + 2k_3 X_{ep} V_s^2,$$

$$k_{22} = (k_1^2 + k_2^2) k_{20} V_s^2 - 2k_2 X_{ep} V_s^2 - 2k_1 R_e V_s^2,\ k_{23} = (k_1^2 + k_2^2) k_{20},$$

$$k_{24} = -2(k_1 k_2 + k_1 k_3) k_{20} V_s + 2k_2 R_e V_s - 2k_1 X_{ep} V_s,$$

$$k_{25} = -2(k_1^2 + k_2^2) k_{20} V_s + 2k_2 X_{ep} V_s + 2k_1 R_e V_s,$$

$$k_{26} = 2(k_2 + k_3) k_1 k_{20} V_s^2 - 2(k_2 + k_3) R_e V_s^2,\ k_{27} = -\frac{1}{T_a},\ k_{28} = \frac{k_a}{T_a}$$