Robust Decentralized Excitation Control of Multimachine Power Systems

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Abstract

This paper is an application of the nonlinear decentralized robust control [3] to the multimachine power systems. A decentralized excitation controller is designed explicitly to maintain a transiently stable closed-loop system at the present of uncertain network parameters. The effect of persistent disturbance whose bound is not known as a priori is effectively attenuated. The simulation of the proposed controller on a two-generator infinite bus power system shows the transient stability is greatly enhanced at different conditions of operation points, fault locations and network parameters.

1 Introduction

Since differential geometric tools were introduced to nonlinear control systems design, various stabilizing control results based on nonlinear power system models have been obtained by [5, 6] *etc.* for single machine systems and [7, 8, 9, 10, 11] *etc.* for multimachine systems. Decentralized control has been widely used in multimachine power system control. The authors of [7] apply the direct feedback linearization to transfer a nonlinear multimachine power system model to a linear one with linear bounded interconnections, then a robust decentralized control is applied and solving a set of algebriac Riccati equations gives controllers which guarantee the overall stability of the excitation system. [11] uses adaptive backstepping to design output feedback decentralized control for the turbine-governor system.

Recently in the nonlinear decentralized control work [3], we extend the result of [12] by allowing general nonlinear bound of interconnections. Robust backstepping and centralized H_∞ almost disturbance decoupling method have been combined with nonlinear decentralized design in [3]. In this paper we apply the nonlinear decentralized control scheme developed in [3] to the excitation control of multimachine power systems. Firstly by a nonlinear coordinate transformation the excitation system is transfered to a lower-triangular structured system, and the interconnection satisfies a *general nonlinear* bound. The decentralized controller is designed explicitly and the resulting closed-loop systems are transiently stable and attenuate the effect of persistent disturbance. The bound of disturbance is not known as a priori in the design. The proposed controller is simulated on a two generator infinite bus power system where the saturation effects of magnetizing inductances is also considered. The simulation results exhibit the robustness and enhancement of transient stability of the closed-loop system.

2 Power System Dynamic Model

For a large-scale power system consisting of n generators interconnected through a transmission network, we apply the classic dynamic model [1, 2]. A model for each generator with excitation control can be written as follows:

Mechanical equations:

$$\dot{\delta}_i = \omega_i \tag{1}$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}\omega_i + \frac{\omega_0}{2H_i}(P_{mi0} - P_{ei}) + d_i \tag{2}$$

Generator electrical dynamics:

$$\dot{E}_{qi}^{'} = \frac{1}{T_{doi}^{'}}(E_{fi} - E_{qi}) \tag{3}$$

Electrical equations:

$$E_{qi} = E_{qi}^{'} + (x_{di} - x_{di}^{'})I_{di}, \tag{4}$$

$$E_{fi} = k_{ci}u_{fi}, \tag{5}$$

$$P_{ei} = \sum_{j=1}^{n} E_{qi}^{'}E_{qj}^{'}B_{ij}\sin(\delta_i - \delta_j), \tag{6}$$

$$Q_{ei} = -\sum_{j=1}^{n} E_{qi}^{'}E_{qj}^{'}B_{ij}\cos(\delta_i - \delta_j), \tag{7}$$

$$I_{di} = -\sum_{j=1}^{n} E_{qj}^{'}B_{ij}\cos(\delta_i - \delta_j), \tag{8}$$

$$I_{qi} = \sum_{j=1}^{n} E_{qj}^{'}B_{ij}\sin(\delta_i - \delta_j), \tag{9}$$

$$V_{ti} = \sqrt{(E_{qi}^{'} - x_{di}^{'}I_{di})^2 + (x_{di}^{'}I_{qi})^2}. \tag{10}$$

where δ_i is the power angle of the ith generator (in *radian*), ω_i is the relative speed, P_{mi0} is the mechanical input power, P_{ei} is the electrical power and $E_{qi}^{'}$ is the transient EMF in the quadrature axis. Notations for other variables and parameters are same as those in [7, 13]. d_i is a persistent disturbance which could, for example, represent minor load changes, or fluctuations of the mechanical input power arising from nonideal behaviour of the power plant. We concern the disturbance effect on the power system frequency, *i.e.* $f_i = \frac{1}{2\pi}\omega_i$.

By applying direct feedback linearization compensation to (1)-(3) (see [7] for detail), we obtain:

$$\begin{aligned}
\dot{\delta}_i &= \omega_i \\
\dot{\omega}_i &= -\frac{D_i}{2H_i}\omega_i - \frac{\omega_0}{2H_i} \triangle P_{ei} + d_i \\
\triangle\dot{P}_{ei} &= -\frac{1}{T'_{doi}}x_{i3} + \frac{1}{T'_{doi}}v_{fi} + \gamma_i(\delta,\omega) \qquad (11)
\end{aligned}$$

where

$$\begin{aligned}
\triangle P_{ei} &= P_{ei} - P_{mi0}, \qquad (12)\\
\gamma_i(\delta,\omega) &= E'_{qi}\sum_{j=1}^{n} \dot{E}'_{qj}B_{ij}\sin(\delta_i-\delta_j) \\
&\quad -E'_{qi}\sum_{j=1}^{n} E'_{qj}B_{ij}\cos(\delta_i-\delta_j)\omega_j, \qquad (13)\\
v_{fi} &= I_{qi}k_{ci}u_{fi} - (x_{di}-x'_{di})I_{qi}I_{di} - P_{mi0} \\
&\quad -T'_{d0i}Q_{ei}\omega_i. \qquad (14)
\end{aligned}$$

Now we seek the bound of the interconnection term $\gamma_i(\delta,\omega)$. Since the electrical power P_{ei} and the reactive power Q_{ei} of each generator and the electrical power flow through each transmission line are all bounded, and the excitation voltage E_{fi} may raise by 5 times of the E_{qi} when there is no load in the system, by simple substitutions (see [13] for detail) we have

$$|\gamma_i(\delta,\omega)| \leq \sum_{j=1}^{n}\left(\gamma_{i1j}|\sin\delta_j| + \gamma_{i2}|\omega_j|\right) \qquad (15)$$

where

$$\begin{aligned}
\gamma_{i1j} &\triangleq \begin{cases} \sum_{j=1,j\neq i}^{n} \frac{4p_{1ij}}{|T'_{doj}|_{\min}}|P_{ei}|_{\max} & \text{when} \quad j=i \\ \frac{4p_{1ij}}{|T'_{doj}|_{\min}}|P_{ei}|_{\max} & \text{when} \quad j\neq i, \end{cases}\\
\gamma_{i2} &\triangleq p_{2ij}|Q_{ei}|_{\max}. \qquad (16)
\end{aligned}$$

and p_{1ij}, p_{2ij} are constants with values either 1 or 0 (if they are 0, it means that jth subsystem has no connection with the ith subsystem).

The fault we consider in this paper is a symmetrical three-phase short circuit on one of the transmission lines. We test the transient stability of the power control system under the following temporary fault sequence:

Stage 1: The system is in a prefault steady state;δ_i: the power angle of the ith generator, in *radian*; ω_i: the relative speed of the ith generator, in *rad/s*; P_{mi0}: the mechanical input power, in *p.u.*; P_{ei}: the electrical power, in *p.u.*; ω_0: the synchronous machine speed, in *rad/s*;
Stage 2: A fault occurs at $t=t_0$;
Stage 3: The fault is removed by opening the breakers of the faulted line at $t=t_1$;
Stage 4: The transmission lines are restored at $t=t_2$;
Stage 5: The system is in a postfault state.

The control task we address in this paper is as follows:

Design decentralized nonlinear feedback control law $u_{fi}(i=1,2,\ldots,n)$ for the excitation system, such that the resulting closed-loop systems are transiently stable when a major fault occurs; furthermore, the effect of the persistent disturbance on the system frequency is reduced to a certain level.

3 Decentralized Excitation Controller Design

Defining the states as $[z_{i1}, z_{i2}, \xi_i] = [\delta_i, \omega_i, \triangle P_{ei}]$, we represent the excitation system model after coordinate transformation in state space:

$$\begin{aligned}
\dot{z}_{i1} &= z_{i2} \\
\dot{z}_{i2} &= -\frac{D_i}{2H_i}z_{i2} - \frac{\omega_0}{2H_i}\xi_i + d_i \\
\dot{\xi}_i &= -\frac{1}{T'_{doi}}\xi_i + \frac{1}{T'_{doi}}v_{fi} + \gamma_i(z) \qquad (17)
\end{aligned}$$

where d_i is the disturbance, v_{fi} is the to-be-designed input, and

$$|\gamma_i(z)| \leq \sum_{j=1}^{n}\left(\gamma_{i1j}|\sin z_{j1}| + \gamma_{i2}|z_{j2}|\right). \qquad (18)$$

The to-be-controlled output (power system frequency) is defined as $y_i = \frac{1}{2\pi}z_{i2}$.
It is clear that (17) exhibits a lower-triangular dependence on the local coordinates, disturbance enters the system without matching condition, and the interconnections among subsystems are bounded by general nonlinear functions. The nonlinear decentralized control scheme proposed in [3] can be applied. Only an outline is given here; for more detail see [13].

Step 1: Considering the $z_i = (z_{i1}, z_{i2})$-subsystem, seeing ξ_i as the virtual control, we have

$$\dot{z}_i = A_i z_i + B_i(\xi_i + k_i d_i) \qquad (19)$$

where

$$A_i = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{D_i}{2H_i}\end{bmatrix}, B_i = \begin{bmatrix} 0 \\ -\frac{\omega_0}{2H_i}\end{bmatrix}, k_i = -\frac{2H_i}{\omega_0}.$$

Choose the Lyapunov function candidate:

$$V_i(z_i) = \phi_i(V_{i0}(z_i)) \qquad (20)$$

where ϕ_i is a smooth $\mathcal{K}_\infty$ function which will be defined in the last step of the design, and $V_{i0} = z_i^T P_i z_i$ with $P_i > 0$ solving the algebraic Riccati equation:

$$A_i^T P_i + P_i A_i - 2\varepsilon_i P_i B_i B_i^T P_i + Q_i = 0 \qquad (21)$$

with $\varepsilon_i > 0$, and $Q_i > 0$.

Differentiating (20) along the solution of z_i-subsystem,

$$\dot{V}_i = \frac{\partial \phi_i}{\partial V_{i0}} 2 z_i^T P_i \left[A_i z_i + B_i \left(\xi_i + k_i d_i\right)\right] \quad (22)$$

Notice that

$$\begin{aligned} & \frac{\partial \phi_i}{\partial V_{i0}} 2 z_i^T P_i B_i k_i d_i \\ \leq \; & \frac{1}{\tau_i} \left(\frac{\partial \phi_i}{\partial V_{i0}}\right)^2 \left(z_i^T P_i B_i k_i\right)^2 + \tau_i |d_i|^2 \end{aligned} \quad (23)$$

Choose the virtual control $\xi_i = \xi_i^*$ as

$$\xi_i^* = -\left\{\varepsilon_i B_i^T P_i z_i + 0.5 \frac{1}{\tau_i} \frac{\partial \phi_i}{\partial V_{i0}} \left(z_i^T P_i B_i\right) k_i^2\right\} (24)$$

then we have the dissipation inequality

$$\dot{V}_i \leq -\frac{\partial \phi_i}{\partial V_{i0}} \left(z_i^T Q_i z_i\right) + \tau_i |d_i|^2. \quad (25)$$

Step 2: Augment the z_i-subsystem with the ξ_i-subsystem, and choose a Lyapunov function as

$$W_i(z_i, \xi_i) = V_i(z_i) + \left(\xi_i - \xi_i^*\right)^2 \quad (26)$$

Note that $\dot{\xi}_i^* \triangleq \vartheta_i(z_i, \xi_i) + \sigma_i(z_i) d_i$.
Differentiating W_{i1} along the solutions of the (z_i, ξ_i)-subsystem yields (with $\widetilde{\xi}_i = \xi_i - \xi_i^*$):

$$\begin{aligned} \dot{W}_i \leq & \left\{-\frac{\partial \phi_i}{\partial V_{i0}} \left(z_i^T Q_i z_i\right) + \tau_i |d_i|^2\right\} + 2\widetilde{\xi}_i \cdot \\ & \left\{\frac{\partial \phi_i}{\partial V_{i0}} z_i^T P_i B_i - \frac{1}{T'_{doi}} \xi_i + \frac{1}{T'_{doi}} v_{fi} + \gamma_i(z) \right. \\ & \left. - \vartheta_i - \sigma_i(z_i) d_i \right\} \end{aligned} \quad (27)$$

For the interconnected term in (27), we have

$$\begin{aligned} & 2\widetilde{\xi}_i \gamma_i(z) \leq 2|\widetilde{\xi}_i| \cdot |\gamma_i(z)| \\ \leq \; & |\widetilde{\xi}_i|^2 \sum_{j=1}^{n} \varrho_j + \sum_{j=1}^{n} \varrho_j^{-1} \left(\gamma_{i1j} |\sin z_{j1}| + \gamma_{i2} |z_{j2}|\right)^2 \end{aligned}$$

For the disturbance term in (27), we have

$$2\widetilde{\xi}_i \left[-\sigma_i(z_i) d_i\right] \leq \frac{1}{\tau_i} \widetilde{\xi}_i^2 \sigma_i^2(z_i) + \tau_i |d_i|^2 \quad (28)$$

Choose the true control as

$$\begin{aligned} v_{fi} = & -T'_{doi} \left\{ c_i \widetilde{\xi}_i + \frac{\partial \phi_i}{\partial V_{i0}} z_i^T P_i B_i - \frac{1}{T'_{doi}} \xi_i - \vartheta_i \right. \\ & \left. + 0.5 |\widetilde{\xi}_i| \sum_{j=1}^{n} \varrho_j + 0.5 \frac{1}{\tau_i} \widetilde{\xi}_i \sigma_i^2(z_i) \right\} \end{aligned} \quad (29)$$

then we have the dissipation inequality

$$\begin{aligned} \dot{W}_i \leq & -\frac{\partial \phi_i}{\partial V_{i0}} \left(z_i^T Q_i z_i\right) - c_i \widetilde{\xi}_i^2 + 2\tau_i |d_i|^2 \\ & + \sum_{j=1}^{n} \varrho_j^{-1} \left(\gamma_{i1j} |\sin z_{j1}| + \gamma_{i2} |z_{j2}|\right)^2. \end{aligned} \quad (30)$$

Step 3: We construct the $\mathcal{K}_\infty$ function ϕ_i in this step.

Define Lyapunov function for the whole interconnected system as

$$W(z, \xi) = \sum_{i=1}^{n} W_i = \sum_{i=1}^{n} \left\{\phi_i \left(V_{i0}(z_i)\right) + \left(\xi_i - \xi_i^*\right)^2\right\}$$

From (30) we obtain

$$\begin{aligned} \dot{W}(z, \xi) \leq & \sum_{i=1}^{n} \left\{ -\frac{\partial \phi_i}{\partial V_{i0}} \left(z_i^T Q_i z_i\right) - c_i \widetilde{\xi}_i^2 + 2\tau_i |d_i|^2 \right. \\ & \left. + \sum_{j=1}^{n} \varrho_j^{-1} \left(\gamma_{i1j} |\sin z_{j1}| + \gamma_{i2} |z_{j2}|\right)^2 \right\} \end{aligned} \quad (31)$$

Construct the derivative of ϕ_i as

$$\frac{\partial \phi_i}{\partial (V_{i0})} = l_i + \frac{1}{\lambda_{\min}(Q_i)} \sum_{j=1}^{N} \varrho_i^{-1} \max\left\{\gamma_{j1i}^2, \gamma_{j2}^2\right\} \quad (32)$$

Then we have

$$\dot{W}(z, \xi) \leq \sum_{i=1}^{n} \left\{-l_i \lambda_{\min}(Q_i) |z_i|^2 - c_i \widetilde{\xi}_i^2 + 2\tau_i |d_i|^2\right\}.$$

Theorem 1 *The decentralized control (29) globally stabilizes the transformed power system model (17), with all admissible uncertainties in the interconnection which satisfies (18); and the L_2 gain from the persistent disturbance to the power system frequency can be reduced to a given level.*

Following the design procedure presented above, the proof of Theorem 1 can be easily obtained from the proof of the main theorem in [3].

Since the coordinate transformation between (1)-(3) and (17) is a diffeomorphism, the control task defined in Section 2 is achieved for the power system model (1)-(3). The excitation control input u_{fi} can be obtained by an inverse transform of (14) which gives

$$\begin{aligned} u_{fi} = & \frac{1}{k_{ci} I_{qi}} \left\{ v_{fi} + P_{mi0} + (x_{di} - x'_{di}) I_{qi} I_{di} \right. \\ & \left. + T'_{d0i} Q_{ei} \omega_i \right\}. \end{aligned} \quad (33)$$

Note that u_{fi} is well-defined since $I_{qi} = 0$ is not in the normal working region for a generator.

4 Simulation Results

The decentralized controller designed above was simulated on a two-generator infinite bus power system which is shown in Figure 1. The generator and the transmission line parameters are listed in Table 1. The fault sequence is as stated in Section 2, where it is chosen that $t_0 = 0.1s, t_1 = 0.25s, t_2 = 1s$. According to Table 1, we

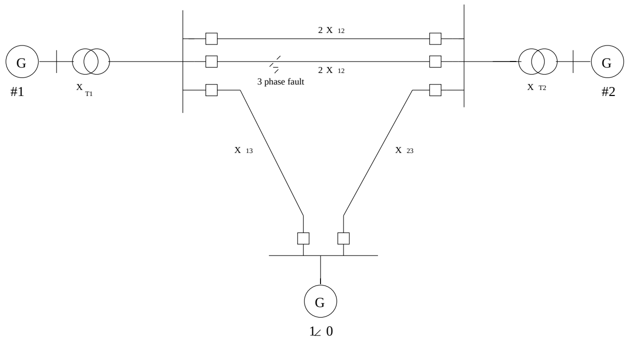

Figure 1: A two machine infinite bus power system

Table 1: System parameters

	Generator #1	Generator #2
x_d (pu)	1.863	2.36
x_d' (pu)	0.257	0.319
x_T (pu)	0.129	0.11
x_{ad} (pu)	1.712	1.712
T_{d0}' (pu)	6.9	7.96
H (s)	4	5.1
D (pu)	5	3
k_c	1	1
x_{12} (pu)	0.55	
x_{13} (pu)	0.53	
x_{23} (pu)	0.6	
ω_0 (rad/s)	314.159	

have the system data used in Section 4 as

$$\begin{aligned} A_1 &= \begin{bmatrix} 0 & 1 \\ 0 & -0.625 \end{bmatrix}, & B_1 &= \begin{bmatrix} 0 \\ -39.27 \end{bmatrix}; \\ A_2 &= \begin{bmatrix} 0 & 1 \\ 0 & -0.2941 \end{bmatrix}, & B_1 &= \begin{bmatrix} 0 \\ -30.8 \end{bmatrix}; \\ \gamma_{111} &= \gamma_{112} = 0.7817, & \gamma_{12} &= 1.4; \\ \gamma_{211} &= \gamma_{212} = 0.9662, & \gamma_{22} &= 1.5. \end{aligned} \tag{34}$$

In the controller design, we choose $Q_1 = Q_2 = 0.8I, \varepsilon_1 = \varepsilon_2 = 14$ to get

$$P_1 = \begin{bmatrix} 0.8043 & 0.0043 \\ 0.0043 & 0.0043 \end{bmatrix}, P_2 = \begin{bmatrix} 0.8055 & 0.0055 \\ 0.0055 & 0.0055 \end{bmatrix}.$$

And other design parameters are chosen as

$$\varrho_1 = \varrho_2 = 0.1, \tau_1 = \tau_2 = 0.5, l_1 = l_2 = 2, c_1 = c_2 = 0.1.$$

Using the above parameters, the decentralized controllers we derived are:

$$\begin{aligned} v_{f1} &= 19.68(\delta_1 - \delta_{10}) + 20.60\omega_1 - 93.81(P_{e1} - P_{m10}), \\ v_{f2} &= 19.69(\delta_2 - \delta_{20}) + 21.45\omega_2 - 73.95(P_{e2} - P_{m20}); \end{aligned}$$

and the original excitation control for the two-generator infinite bus power system can be obtained using (33) with $i = 1, 2$. The deduced L_2 gain from the persistent disturbance to the system frequency is $\mu_1 = \mu_2 = 0.63/(2\pi) = 0.1$.

In the simulation, saturation of synchronous machines is also considered, so (3) becomes

$$\dot{E}_{qi}' = \frac{1}{T_{doi}'}[E_{fi} - E_{qi} - (1 - k_{fi})E_{qi}'] \tag{35}$$

where $k_{fi} = 1 + \frac{b_i}{a_i}(E_{qi}')^{(n_i-1)}$ with $a_1 = 0.95, b_1 = 0.051, n_1 = 8.727; a_2 = 0.935, b_2 = 0.064, n_2 = 10.878$.
The excitation control input limitations are $-3 \leq E_{fi} = k_{ci}u_{fi} \leq 6, i = 1, 2$.
We demonstrate the performance of the proposed controller in the following two cases of different sets of operation points, fault locations. The symmetrical 3-phase short circuit fault occurs on one of the transmission lines between the generator #1 and the generator #2. The fault location is indexed by a constant λ which is the fraction of the line to the left of the fault. The persistent disturbance $d_1 = d_2 = 0.3p.u.$ is used in the simulation.
Case 1: The operating points are:

$$\begin{aligned} \delta_{10} &= 60.78°, \quad P_{m10} = 1.10p.u., \quad V_{t10} = 1.0p.u., \\ \delta_{20} &= 60.64°, \quad P_{m20} = 1.01p.u., \quad V_{t20} = 1.0p.u. \end{aligned}$$

The fault location is $\lambda = 0.2$. The corresponding closed-loop system responses are shown in Figure 2.
Case 2: The operating points are:

$$\begin{aligned} \delta_{10} &= 18.51°, \quad P_{m10} = 0.32p.u., \quad V_{t10} = 0.99p.u., \\ \delta_{20} &= 23.68°, \quad P_{m20} = 0.42p.u., \quad V_{t20} = 0.98p.u. \end{aligned}$$

The fault location is $\lambda = 0.05$. The corresponding closed-loop system responses are shown in Figure 3.

From the simulation results we can see that the proposed decentralized controllers enhance the system transient stability and dampen out the power angle oscillations. And the effect of persistent disturbance on the system frequency is reduced to quite small.

5 Conclusions

In this paper we apply the recently developed nonlinear decentralized robust control scheme [3] to the excitation control of multimachine power systems. A decentralized robust controller is designed stepwisely in Section 4. The proposed controller guarantees the overall stability of the large-scale power systems and is robust with regard to uncertain network parameters. The interconnection bound is a nonlinear function which achieves less conservativeness of the controller. The effectiveness of the controller are demonstrated on a two-generator infinite bus example system.

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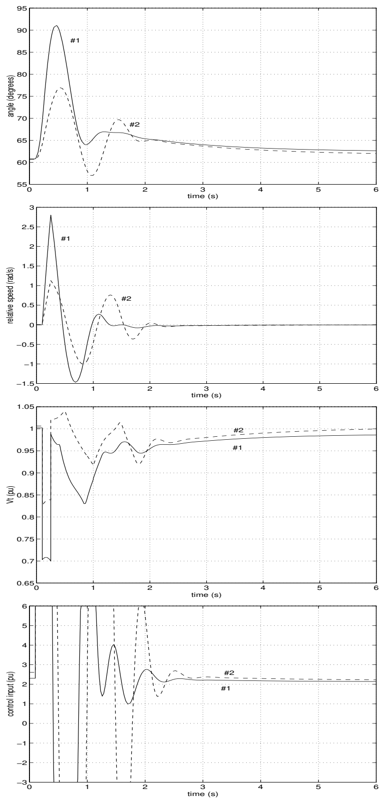

Figure 2: System responses of Case 1

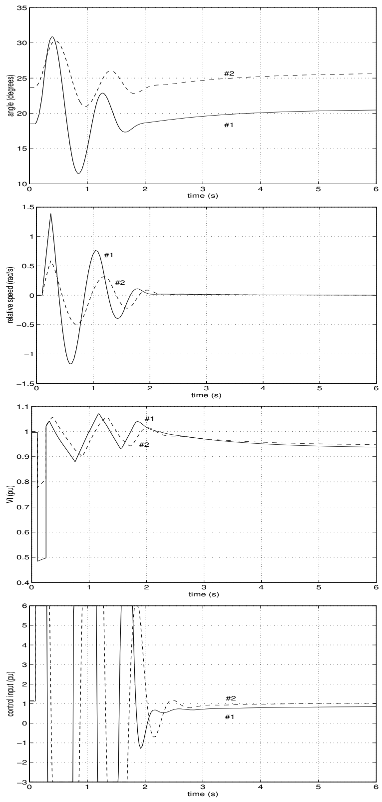

Figure 3: System responses of Case 2