Decentralized Control for Multimachine Power Systems with Nonlinear Interconnections and Disturbances

Kyu-Il Jung, Kwang-Youn Kim, Tae-Woong Yoon*, and Gilsoo Jang

Abstract: In this paper, a decentralized control problem is considered for multimachine power systems with nonlinear interconnections and disturbances. A direct feedback linearization compensator is employed to cancel most of the nonlinearities, and then a backstepping procedure is applied to deal with the interconnections and to reduce the effects of a disturbance that does not satisfy the matching condition. In this procedure, the disturbance is handled by using a smooth approximation of the signum function. Practical stability is achieved under the assumption that the infinite norm of the disturbance is known. However, even in the case where the infinite norm of the disturbance is not known precisely, the proposed control system still guarantees L_2 stability. Furthermore, the origin is globally uniformly asymptotically stable in the absence of the disturbance. A three-machine power system is considered as an application example.

Keywords: Backstepping, decentralized control, nonlinear systems, power system control, robust control.

1. INTRODUCTION

For large-scale systems composed of interconnections of many lower-dimensional subsystems, decentralized control is preferable since it can alleviate the computational burden, bypass communication between different subsystems, and make the control more feasible and simpler. A power system is such a large-scale system where generators are interconnected through transmission lines. Decentralized control is, therefore, considered for power systems. Electric power systems are becoming larger and more complex because they need to meet the increasing power demand; hence, it is important to improve the transient stability. Recently, nonlinear control theories have been employed to take into account the nonlinearities of the controlled power systems [3-8].

In this paper, a robust decentralized excitation control scheme is proposed to enhance the transient stability of multimachine power systems. Only local measurements are required for the proposed controller, and the concept of backstepping in [9] has been adopted. First, we employ a direct feedback linearization compensator to cancel most of the nonlinearities [3]; however, the resulting model still contains nonlinear interconnections. Therefore, we apply a backstepping procedure to deal with interconnection terms and to reduce the effects of the disturbance that does not satisfy the matching condition. In this procedure, the disturbance is handled by using a smooth approximation of the signum function. We achieve practical stability by assuming that the infinite norm of the disturbance is known. However, even in the case where the infinite norm of the disturbance is not known precisely, the proposed control system still guarantees L2 stability. Furthermore, the origin is globally uniformly asymptotically stable in the absence of the disturbance

As an application example, the proposed control technique is applied to a three-machine power system. Simulation results show that the proposed control scheme can enhance transient stability of the power system under a large sudden fault.

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2. MATHEMATICAL MODEL

In this section, a power system consisting of n synchronous machines is considered. The classic dynamic model in [1] and [2] is employed; the i-th machine with excitation control can be described as follows:

- Mechanical equations:

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

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

where

- δ_i power angle of the i-th generator, in rad
- ω_i relative speed of the i-th generator, in rad/sec
- P_{mi} mechanical input power, in p.u.
- P_{ei} electrical power, in p.u.
- ω_0 synchronous machine speed, in rad/sec
- D_i per unit damper constant
- H inertia constant, in sec
- d_i persistent disturbance, in p.u.

- Generator electrical dynamics:

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}(E_{fi} - E_{qi}), \tag{3}$$

where

- E'_{qi} transient EMF in the quadrature axis, in p.u.
- E_{fi} equivalent EMF in the excitation coil, in p.u.
- I_{di} direct axis current, in p.u.
- T'_{doi} direct axis transient short-circuit time constant, in sec
- x_{di} direct axis reactance, in p.u.
- x'_{di} direct axis transient reactance, in p.u.

- Electrical Equations:

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

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

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

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

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

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

$$E_{qi} = x_{adi}I_{fi}, \tag{10}$$

$$V_{ti} = \sqrt{(E'_{qi} - x'_{di}I_{di})^2 + (x'_{di}I_{qi})^2}, \tag{11}$$

where

- E_{qi} EMF in the quadrature axis, in p.u.
- x_{adi} mutual reactance between the excitation coil and the stator coil, in p.u.
- I_{fi} excitation current, in p.u.
- k_{ci} gain of the excitation amplifier, in p.u.
- u_{fi} input of the SCR amplifier, in p.u.
- Q_i reactive power, in p.u.
- B_{ij} i-th row and j-th column element of nodal susceptance matrix at the internal nodes after eliminating all physical buses, in p.u.

For this nonlinear model, by employing the direct feedback linearization compensation law in [3], we obtain

$$\begin{aligned} \dot{\delta}_i &= \omega_i, \\ \dot{\omega}_i &= -\frac{D_i}{2H_i}\omega_i - \frac{\omega_0}{2H_i}\Delta P_{ei} + d_i, \\ \Delta\dot{P}_{ei} &= -\frac{1}{T'_{doi}}\Delta P_{ei} + \frac{1}{T'_{doi}}v_{fi} + \gamma_i(\delta,\omega), \end{aligned} \tag{12}$$

where

$$\Delta P_{ei} = P_{ei} - P_{mi0}, \tag{13}$$

$$\begin{aligned} \gamma_i(\delta,\omega) &= E'_{qi}\sum_{j=1}^{n} \dot{E}'_{qj}B_{ij}\sin(\delta_i - \delta_j) \\ &\quad - E'_{qi}\sum_{j=1}^{n} E'_{qj}B_{ij}\cos(\delta_i - \delta_j)\omega_j, \end{aligned} \tag{14}$$

$$v_{fi} = I_{qi}k_{ci}u_{fi} - (x_{di} - x'_{di})I_{qi}I_{di} - P_{mi0} - T'_{doi}Q_{ei}\omega_i, \tag{15}$$

and P_{mi0} is the steady-state value of P_{mi}. The bound of the interconnection term $\gamma_i(\delta,\omega)$ is found as follow [4]:

$$|\gamma_i(\delta,\omega)| \le \sum_{j=1}^{n}(\gamma_{i1j}|\sin\delta_j| + \gamma_{i2}|\omega_j|), \tag{16}$$

where

$$\gamma_{i1j} \triangleq \begin{cases} \sum_{j=1,j\neq i}^{n} \frac{4p_{1ij}}{|T'_{doj}|_{\min}}|P_{ei}|_{\max} & when \quad j = i \\ \frac{4p_{1ij}}{|T'_{doj}|_{\min}}|P_{ei}|_{\max} & when \quad j \neq i, \end{cases} \tag{17}$$

$$\gamma_{i2} \triangleq p_{2ij}|Q_{ei}|_{\max},$$

and p_{1ij}, p_{2ij} are constants with values of either 1 or 0. (If they are 0, then the j-th subsystem has no connection with the i-th subsystem.)

3. DESIGN OF NONLINEAR DECENTRALIZED ROBUST CONTROLLER

Defining the states vectors

$$z = \begin{bmatrix} z_1 & \cdots & z_n \end{bmatrix}^T$$

$$\xi = \begin{bmatrix} \xi_1 & \cdots & \xi_n \end{bmatrix}^T$$

with

$$z_i = \begin{bmatrix} \delta_i & \omega_i \end{bmatrix}^T$$

$$\xi_i = \Delta P_{ei},$$

we rewrite the state equations as follows:

$$\begin{aligned} \dot{z}_i &= A_i z_i + B_i(\xi_i + k_i d_i), \\ \dot{\xi}_i &= -\frac{1}{T'_{doi}}\xi_i + \frac{1}{T'_{doi}}v_{fi} + \gamma_i(z), \end{aligned} \tag{18}$$

where

$$A_i = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{D_i}{2H_i} \end{bmatrix},\ B_i = \begin{bmatrix} 0 \\ -\dfrac{\omega_0}{2H_i} \end{bmatrix},\ k_i = -\frac{2H_i}{\omega_0} \tag{19}$$

and

$$|\gamma_i(z)| \le \sum_{j=1}^{n} (\gamma_{i1j}\left|\sin z_{j1}\right| + \gamma_{i2}\left|z_{j2}\right|). \tag{20}$$

In the controller design, we make the following assumptions:

Assumption 1: The mechanical input power is constant, i.e. $P_{mi} = P_{mi0}$.

Assumption 2: The disturbance is bounded, and an upper bound of its infinite norm is known, i.e.

$$|d_i|_\infty \le d_{i\max}$$

where $d_{i\max}$ is a known positive constant.

We now propose our decentralized controller, which is given by

$$v_{fi} = -T'_{doi}\left\{c_i\tilde{\xi}_i + \chi_i z_i^T P_i B_i - \frac{1}{T'_{doi}}\xi_i - \vartheta_i + \frac{1}{2}\tilde{\xi}_i \sum_{j=1}^{n} \rho_j\left(\gamma_{i1j}^2 + \gamma_{i2}^2\right) + \sigma_i d_{i\max}\,\mathrm{sgn}\left(\tilde{\xi}_i\sigma_i\right)\right\}, \tag{21}$$

where

$$\tilde{\xi}_i = \xi_i - \xi_i^*, \tag{22}$$

$$\chi_i = l_i + \frac{n}{\rho_i \lambda_{\min}(Q_i)}, \tag{23}$$

$$\xi_i^* = -\varepsilon_i B_i^T P_i z_i - |k_i| d_{i\max}\Phi_\alpha(z_i^T P_i B_i), \tag{24}$$

$$\dot{\xi}_i^* = \frac{\partial \xi_i^*}{\partial z_i}\left(A_i z_i + B_i\xi_i + B_i k_i d_i\right), \tag{25}$$

$$\triangleq \vartheta_i\left(z_i, \xi_i\right) + \sigma_i\left(z_i\right) d_i, \tag{26}$$

$$c_i > 0,\ \rho_i > 0,\ \sigma_i > 0$$

with

$$l_i > 0$$

$$\Phi_\alpha(x) = \begin{cases} -1 & , \quad x < -\alpha \\ -\dfrac{x^3}{2\alpha^3} + \dfrac{3x}{2\alpha} & , \quad -\alpha \le x < \alpha \\ 1 & , \quad x \ge \alpha \end{cases} \tag{27}$$

and $P_i > 0$ solving the algebraic Riccati equation:

$$A_i^T P_i + P_i A_i - 2\varepsilon_i P_i B_i B_i^T P_i + Q_i = 0 \tag{28}$$

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

The stability properties of the proposed scheme are given in the following theorem.

Theorem 1: Consider the plant (18) and the controller (21), and suppose that Assumptions 1 and 2 hold. Then the proposed control system is practically stable, i.e., uniformly ultimately bounded with an arbitrary bound. Furthermore, the origin is globally uniformly asymptotically stable in the absence of the disturbance.

Proof: We start by considering the z_i-subsystem with ξ_i as the virtual control input.

Choose the Lyapunov function candidate

$$V_i(z_i) = \chi_i z_i^T P_i z_i. \tag{29}$$

Differentiating $V_i(z_i)$, we obtain

$$\dot{V}_i = 2\chi_i z_i^T P_i\left[A_i z_i + B_i(\xi_i + k_i d_i)\right]. \tag{30}$$

By Assumption 2, we obtain the following inequality;

$$2\chi_i z_i^T P_i B_i k_i d_i \le 2\chi_i\left|z_i^T P_i B_i\right|\left|k_i\right| d_{i\max} \tag{31}$$

In view of (24), seting $\xi_i = \xi_i^*$ leads to

$$\begin{aligned} \dot{V}_i \le &-\chi_i z_i^T Q_i z_i \\ &+ 2\chi_i z_i^T P_i B_i |k_i| d_{i\max}\left[\mathrm{sgn}(z_i^T P_i B_i) - \Phi_\alpha(z_i^T P_i B_i)\right]. \end{aligned} \tag{32}$$

Next, to drive $\xi_i - \xi_i^*$ to become zero, we consider

$$W_i(z_i,\xi_i) = V_i(z_i) + \tilde{\xi}_i^2 \tag{33}$$

The time derivative of $W_i(z_i,\xi_i)$ is computed as

$$\begin{aligned}\dot{W}_i \le & -\chi_i z_i^T Q_i z_i \\ & + 2\chi_i z_i^T P_i B_i |k_i| d_{i\max}\left[\operatorname{sgn}(z_i^T P_i B_i) - \Phi_\alpha(z_i^T P_i B_i)\right] \\ & + 2\tilde{\xi}_i\left[\chi_i z_i^T P_i B_i - \frac{1}{T'_{doi}}\xi_i + \frac{1}{T'_{doi}}v_{fi} + \gamma_i - \vartheta_i - \sigma_i d_i\right].\end{aligned} \tag{34}$$

Using the inequality

$$\begin{aligned}2\tilde{\xi}_i\gamma_i \le \tilde{\xi}_i^2 \sum_{j=1}^{n}\Big[\rho_j\left(\gamma_{i1j}^2 + \gamma_{i2}^2\right) \\ + \sum_{j=1}^{n}\frac{1}{\rho_j}\left(\left|\sin z_{j1}\right|^2 + \left|z_{j2}\right|^2\right)\Big]\end{aligned} \tag{35}$$

and Assumption 2, we have

$$-2\tilde{\xi}_i\sigma_i d_i \le 2\left|\tilde{\xi}_i\sigma_i\right| d_{i\max}. \tag{36}$$

If then follows from the control law (21) that

$$\begin{aligned}\dot{W}_i \le & -\chi_i z_i^T Q_i z_i \\ & + 2\chi_i z_i^T P_i B_i |k_i| d_{i\max}\Big[\operatorname{sgn}(z_i^T P_i B_i) \\ & - \Phi_\alpha(z_i^T P_i B_i)\Big] - c_i\tilde{\xi}_i^2 \\ & + \sum_{j=1}^{n}\frac{1}{\rho_j}\left(\left|\sin z_{j1}\right|^2 + \left|z_{j2}\right|^2\right).\end{aligned} \tag{37}$$

Now, define the Lyapunov function candidate for the whole interconnected system as

$$W(z,\xi) = \sum_{i=1}^{n} W_i. \tag{38}$$

Differentiating $W(z,\xi)$, we have

$$\begin{aligned}\dot{W}(z,\xi) \le \sum_{i=1}^{n}\Big[& -\chi_i z_i^T Q_i z_i - c_i\tilde{\xi}_i^2 \\ & + \sum_{j=1}^{n}\frac{1}{\rho_j}\left(\left|\sin z_{j1}\right|^2 + \left|z_{j2}\right|^2\right) \\ & + 2\chi_i z_i^T P_i B_i |k_i| d_{i\max}\{\operatorname{sgn}(z_i^T P_i B_i) \\ & - \Phi_\alpha(z_i^T P_i B_i)\}\Big].\end{aligned} \tag{39}$$

Note that

$$\begin{aligned}\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{1}{\rho_j}\left(\left|\sin z_{j1}\right|^2 + \left|z_{j2}\right|^2\right) \\ = \sum_{i=1}^{n}\frac{n}{\rho_i}\left(\left|\sin z_{i1}\right|^2 + \left|z_{i2}\right|^2\right)\end{aligned} \tag{40}$$

$$\begin{aligned}\left|z_i^T P_i B_i\right| - z_i^T P_i B_i \Phi_\alpha(z_i^T P_i B_i) \\ \le \frac{3}{8}\left(-3 + 2\sqrt{3}\right)\alpha.\end{aligned} \tag{41}$$

From (23), we have

$$\dot{W}(z,\xi) \le \sum_{i=1}^{n}\left[-l_i z_i^T Q_i z_i - c_i\tilde{\xi}_i^2\right] + \Delta_\alpha, \tag{42}$$

where

$$\Delta_\alpha = \sum_{i=1}^{n} 2\chi_i |k_i| d_{i\max}\frac{3}{8}\left(-3 + 2\sqrt{3}\right)\alpha. \tag{43}$$

This proves that the proposed control system is practically stable since α can be chosen arbitrarily small.
Furthermore, in the absence of the disturbance, we have

$$\dot{W}(z,\xi) \le \sum_{i=1}^{n}\left[-l_i z_i^T Q_i z_i - c_i\tilde{\xi}_i^2\right]. \tag{44}$$

Hence, the overall closed-loop system is globally uniformly asymptotically stable when $d_i = 0$.

Corollary 1: Even when Assumption 2 is not satisfied, i.e. $d_{i\max} < |d_i|_\infty$, the proposed control system still guarantees L_2 stability.

Proof: From (39), we obtain

$$\begin{aligned}\dot{W}(z,\xi) \le \sum_{i=1}^{n}\Big[& -(1-\theta_{i10})\, l_i\lambda_{\min}(Q_i)\|z_i\|^2 \\ & -(1-\theta_{i20})\, c_i\tilde{\xi}_i^2 + \frac{1}{2}\left(\frac{1}{\theta_{i1}} + \frac{1}{\theta_{i2}}\right)d_i^2\Big],\end{aligned} \tag{45}$$

where

$$\theta_{i1} = \theta_{i10}\frac{l_i\lambda_{\min}(Q_i)}{2\chi_i^2 k_i^2 \lambda_{\max}(R_i)},$$

$$\theta_{i2} = \theta_{i20}\frac{c_i}{2k_i^2 \max\left\{\frac{\partial \xi_i^*}{\partial z_i}B_i\right\}}$$

with

$R_i = P_i B_i B_i^T P_i$, $0 < \theta_{i10} < 1$, $0 < \theta_{i20} < 1$.

Define the following state vectors

$$x = \begin{bmatrix} z_i \\ \tilde{\xi}_i \end{bmatrix}, \quad d = \begin{bmatrix} d_1 \\ \vdots \\ d_n \end{bmatrix}.$$

It then ensues from (45) that

$$\int_0^T \|x\|^2 \, dt \le \mu \int_0^T \|d\|^2 \, dt + v(z(0), \xi(0)), \tag{46}$$

where

$$\mu = \frac{\max\limits_{1 \le i \le n} \left[\frac{1}{2} \left(\frac{1}{\theta_{i1}} + \frac{1}{\theta_{i2}} \right) \right]}{\min\limits_{1 \le i \le n} \left[(1 - \theta_{i10}) l_i \lambda_{\min}(Q_i), (1 - \theta_{i20}) c_i \right]}, \tag{47}$$

$$v(z(0), \xi(0)) = \frac{W(z(0), \xi(0))}{\min\limits_{1 \le i \le n} \left[(1 - \theta_{i10}) l_i \lambda_{\min}(Q_i), (1 - \theta_{i20}) c_i \right]}. \tag{48}$$

Therefore, even if the infinite norm of the disturbance is not known precisely, the proposed control system still guarantees L_2 stability.

4. SIMULATION RESULTS

As an example, the three-machine system shown in Fig. 1 is considered. Since generator #3 is an infinite bus, $E'_{q3} = const. = 1\angle 0^\circ$ and generator #3 is the reference. The system parameters are given as follows [4]:

$x = 1.863$ p.u., $x' = 0.257$ p.u., $x = 0.129$ p.u.,
$T'_{do1} = 6.9$ sec., $H_1 = 4.0$ sec., $D_1 = 5.0$ p.u.,
$k_{c1} = 1.0$ p.u., $x_{ad1} = 1.712$ p.u., $x_{d2} = 2.36$ p.u.,
$x'_{d2} = 0.319$ p.u., $x_{T2} = 0.11$ p.u., $T'_{do2} = 7.96$ sec.,
$H_2 = 5.1$ sec., $D_2 = 3.0$ p.u., $k_{c2} = 1.0$ p.u.,
$x_{ad2} = 1.712$ p.u., $x_{12} = 0.55$ p.u., $x_{13} = 0.53$ p.u.,
$x_{23} = 0.6$ p.u.

The saturation limits for the excitation control are assumed to be

$-3 \le E_{fi} = k_{ci} u_{fi} \le 6$, $i = 1, 2$.

In the simulation, the saturation of synchronous machines is also considered as in [4]: (3) then becomes

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}} \left[E_{fi} - E_{qi} - (1 - k_{fi}) E'_{qi} \right], \tag{49}$$

where

$$k_{fi} = 1 + \frac{b_i}{a_i} \left(E'_{qi} \right)^{(n_i - 1)} \tag{50}$$

with

$a_1 = 0.95$, $b_1 = 0.051$, $n_1 = 8.727$,
$a_2 = 0.935$, $b_2 = 0.064$, $n_2 = 10.878$.

To assess the dynamic performance of the proposed scheme, we consider the situation where a symmetrical three-phase short-circuit fault occurs on the transmission line between generator #1 and generator #2, as shown in Fig. 1. Let λ denote the fraction of the line to the left of the fault; if $\lambda = 0$, the fault is on the bus bar of generator #1, $\lambda = 0.5$ puts the fault in the middle of generators #1 and #2. The persistent disturbance is assumed to be present such that $d_1 = d_2 = 0.3$ p.u. It is also assumed that the fault occurs at 0.1s, is cleared at 0.25s, and is restored at 1s.

To demonstrate the effectiveness of the proposed scheme over a wide operating region of the power system, simulations are carried out for the following three cases and their results are shown in Figs. 2, 3 and 4, respectively.

Case 1 : The operating points are:
$\delta_{10} = 60.78^\circ$, $P_{m10} = 1.10 p.u.$, $V_{t10} = 1.0 p.u.$
$\delta_{20} = 60.64^\circ$, $P_{m20} = 1.01 p.u.$, $V_{t20} = 1.0 p.u.$
Fault location: $\lambda = 0.2$.
(The simulation results are shown in Fig 2.)

Case 2 : The operating points are:
$\delta_{10} = 30.5^\circ$, $P_{m10} = 0.57 p.u.$, $V_{t10} = 1.01 p.u.$
$\delta_{20} = 32.5^\circ$, $P_{m20} = 0.56 p.u.$, $V_{t20} = 1.00 p.u.$
Fault location: $\lambda = 0.05$.
(The simulation results are shown in Fig 3.)

Case 3 : The operating points are:
$\delta_{10} = 56.09^\circ$, $P_{m10} = 1.0 p.u.$, $V_{t10} = 1.0 p.u.$
$\delta_{20} = 59.04^\circ$, $P_{m20} = 1.0 p.u.$, $V_{t20} = 1.0 p.u.$
Fault location: $\lambda = 0.5$.
(The simulation results are shown in Fig 4.)

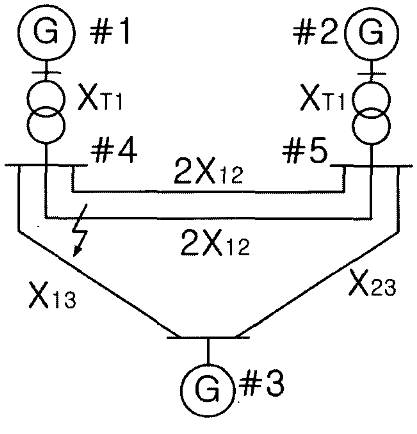
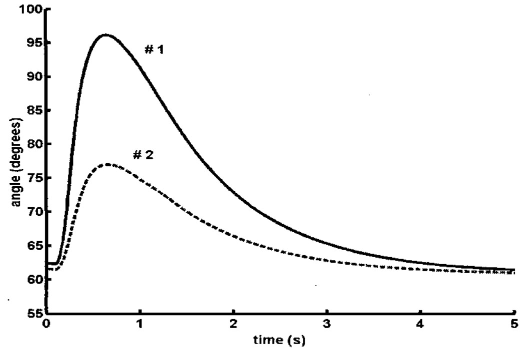
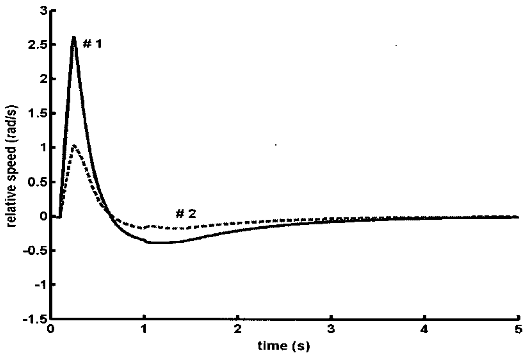


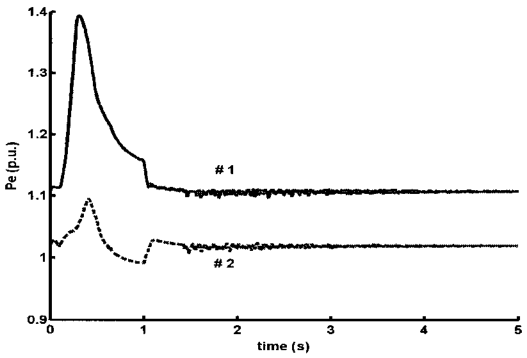
Fig. 1. Three-machine example system.



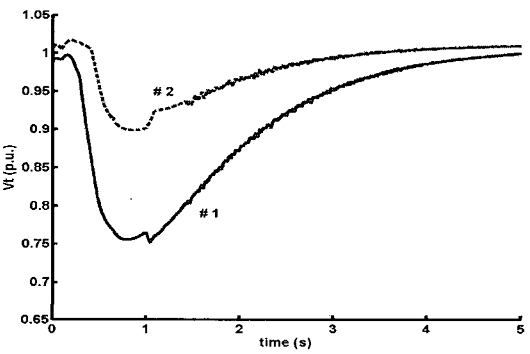
(a) Responses of δ_1 and δ_2.



(b) Responses of ω_1 and ω_2.

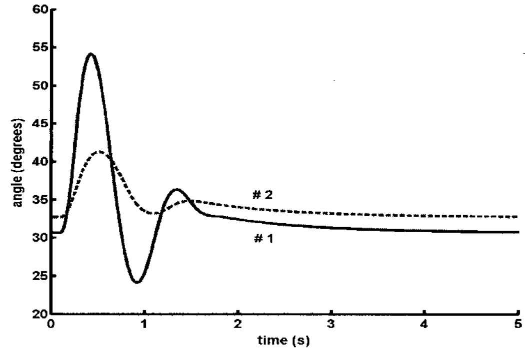


(c) Responses of Pe_1 and Pe_2.

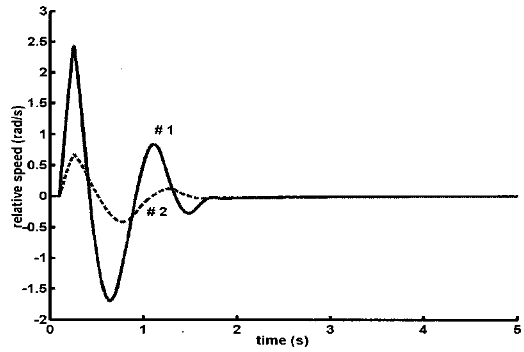


(d) Responses of V_{t1} and V_{t2}.

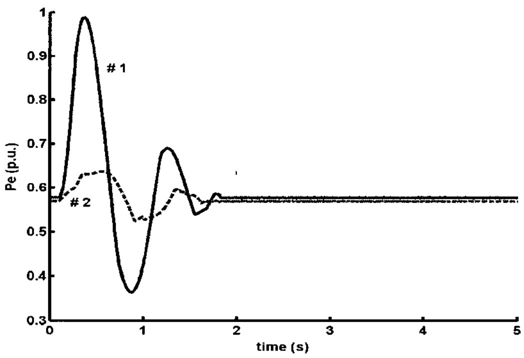
Fig. 2. Responses of excitation control: Case 1.



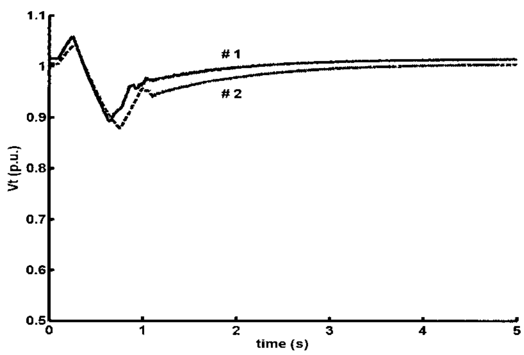
(a) Responses of δ_1 and δ_2.



(b) Responses of ω_1 and ω_2.

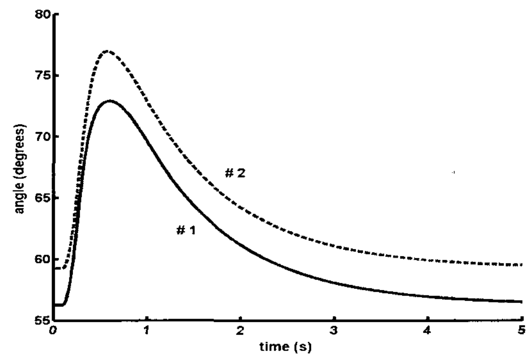


(c) Responses of Pe_1 and Pe_2.

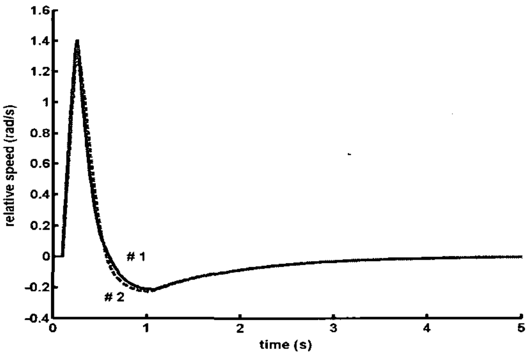


(d) Responses of V_{t1} and V_{t2}.

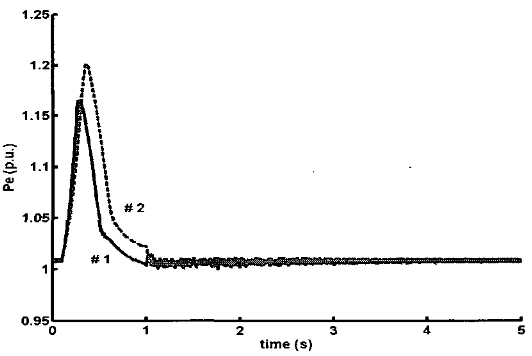
Fig. 3. Responses of excitation control: Case 2.



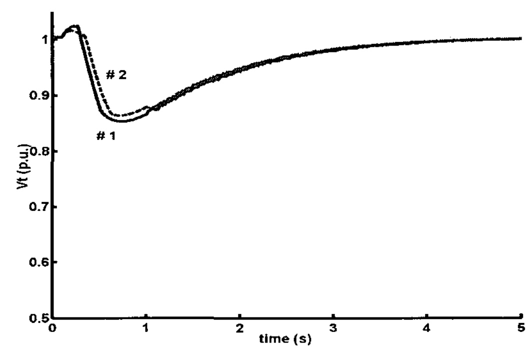
(a) Responses of δ_1 and δ_2.



(b) Responses of ω_1 and ω_2.



(c) Responses of Pe_1 and Pe_2.



(d) Responses of V_{t1} and V_{t2}.

Fig. 4. Responses of excitation control: Case 3.

As can be seen from Figs. 2-4, despite the different fault locations and operating points, the proposed excitation control scheme achieves good transient stability, and dampens out the power angle oscillations

5. CONCLUSION

In this paper, a robust decentralized excitation control scheme is proposed to enhance the transient stability of multimachine power systems. In Theorem 1, we prove that the proposed control system is practically stable and the origin is globally uniformly asymptotically stable in the absence of the disturbance We also prove that even when the upper bounds on the norms of disturbances are not known precisely, L_2 stability can still be guaranteed. Simulations for a three-machine power system demonstrate the effectiveness of the proposed scheme.

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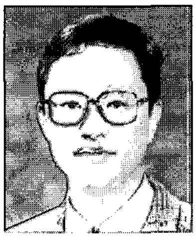

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