Decentralized Nonlinear Voltage Control of Multi-machine Power Systems with Nonlinear Interconnections

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Abstract: In this paper, an adaptive robust decentralized excitation control scheme is proposed to enhance the transient stability of a multi-machine power system. We employ a state model where the terminal voltage of each generator is regarded as part of the state. Using this state model, the proposed controller is obtained in two steps: firstly, a robust controller is designed for the nominal system with no interconnection terms; then an adaptive compensator is proposed to deal with those interconnection terms, whose upper bounds are estimated. The resulting adaptive scheme guarantees the practical stability of the closed-loop, and also the uniform ultimate boundedness in the presence of disturbances.

Keywords: decentralize, power systems, nonlinear, voltage control, adaptive robust control

1. INTRODUCTION

For large-scale systems which are composed of interconnections of many lower-dimensional subsystems, decentralized control is preferable since it can alleviate the computational burden, avoid 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 recently become large and complex due to 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 [7-12].

One of the main objectives of the excitation control is to regulate the generator terminal voltage in the presence of various faults as well as under normal operating conditions [1-3, 6]. In recent years, considerable efforts have been made to enhance power system stability, but less attention has been paid to the problem of voltage control design [1]. This paper seeks to design an adaptive robust controller, which can lead to voltage regulation as well as stability enhancement despite the presence of nonlinearities and nonlinear interconnections.

In this paper, we first employ the DFL technique used in [4-5, 10] to cancel most of the nonlinearities of the power system, and then consider a state model where the terminal voltage of each generator is regarded as part of the state. Using this state model, the proposed controller is obtained in two steps: firstly, a robust controller is designed for the nominal system with no interconnection terms; then an adaptive compensator is proposed to deal with those interconnection terms, whose upper bounds are estimated. The resulting adaptive scheme guarantees the practical stability of the closed-loop, and also the uniform ultimate boundedness in the presence of disturbances.

The proposed controller is applied to a three-machine example system. In order to illustrate closed-loop performance, we consider a symmetrical three-phase short-circuit fault. The simulation results show that the proposed nonlinear voltage controller can achieve both voltage regulation and system stability enhancement.

2. DYNAMIC MODEL

In this section, we consider a power system consisting of n synchronous machines. Following [3, 6], a dynamical model of the i-th machine with excitation control is given below (Note that the system has already been reduced into a network retaining only generator nodes [2]).

2.1 Mechanical equations

$$\dot{\delta}_i = \omega_i \quad (1)$$

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

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_i	inertia constant, in sec
d_i	persistent disturbance, in p.u.

(subscript i means the ith generator.)

2.2 Generator electrical dynamics

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

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.

2.3 Electrical equations

$$E_{qi} = E'_{qi} + (x_{di} - x'_{di})I_{di}$$
$$E_{fi} = k_{ci}u_{fi}$$
$$P_{ei} = \sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\sin(\delta_i - \delta_j)$$
$$Q_{ei} = -\sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\cos(\delta_i - \delta_j)$$
$$I_{di} = -\sum_{j=1}^{n} E'_{qj}B_{ij}\cos(\delta_i - \delta_j)$$
$$I_{qi} = \sum_{j=1}^{n} E'_{qj}B_{ij}\sin(\delta_i - \delta_j)$$
$$E_{qi} = x_{adi}I_{fi}$$
$$V_{ti} = \sqrt{(E'_{qi} - x'_{di}I_{di})^2 + (x'_{di}I_{qi})^2} \tag{4}$$

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_{ei}	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 direct feedback linearization compensation law in [7], we obtain

$$\dot{\delta}_i = \omega_i$$
$$\dot{\omega}_i = -\frac{D_i}{2H_i}\omega_i - \frac{\omega_0}{2H_i}\Delta P_{ei} + d_i$$
$$\Delta\dot{P}_{ei} = -\frac{1}{T'_{doi}}\Delta P_{ei} + \frac{1}{T'_{doi}}v_{fi} + \gamma_{i1} \tag{5}$$

where

$$\Delta P_{ei} = P_{ei} - P_{mi0} \tag{6}$$
$$\gamma_{i1} = E'_{qi}\sum_{j=1}^{n} \dot{E}'_{qj}B_{ij}\sin(\delta_i - \delta_j) - E'_{qi}\sum_{j=1}^{n} E'_{qj}B_{ij}\cos(\delta_i - \delta_j)\omega_j \tag{7}$$
$$v_{fi} = I_{qi}k_{ci}u_{fi} - (x_{di} - x'_{di})I_{qi}I_{di} - P_{mi0} - T'_{doi}Q_{ei}\omega_i. \tag{8}$$

The DFL compensated system (5)-(8) is valid except when $I_{qi} = 0$, which does not happen under normal operating region. We thus assume that the model (5)-(8) is valid all the time. Note also that E'_{qi}, I_{di} and I_{qi} can be calculated from P_{ei}, Q_{ei}, and I_{fi} which are available, and thus u_{fi} can be implemented using v_{fi}.

3. DECENTRALIZED NONLINEAR VOLTAGE CONTROLLER DESIGN

In sections 3.1-3.3 below, we assume that there is no disturbance, i.e. $d_i = 0$.

3.1 Voltage state equation

For the power system (5) resulting from the DFL compensator (8), consider for example a decentralized control law of the following form

$$v_{fi} = -k_{\omega i}\omega_i - k_{pi}\Delta P_{ei} - k_{vi}\Delta V_{ti} \tag{9}$$

for some constants $k_{\omega i}$, k_{pi}, and k_{vi}. To facilitate designing such a control, we write a state equation containing ω_i, ΔP_{ei}, and ΔV_{ti}. To this end, consider

$$\begin{aligned}\Delta\dot{V}_{ti} &= \frac{\partial V_{ti}}{\partial\delta_i}\dot{\delta}_i + \frac{\partial V_{ti}}{\partial E'_{qi}}\dot{E}'_{qi} + \frac{\partial V_{ti}}{\partial\delta_j}\dot{\delta}_j + \frac{\partial V_{ti}}{\partial E'_{qj}}\dot{E}'_{qj} \\ &= f_{i1}\omega_i - \frac{f_{i2}}{T'_{d0i}}\Delta P_{ei} + \frac{f_{i2}}{T'_{d0i}}v_{fi} + \gamma_{i2}\end{aligned} \tag{10}$$

where

$$f_{i1} = \frac{\left(1 + x'_{di}B_{ii}\right)\left(E'^2_{qi}B_{ii} + Q_{ei}\right)V_{tqi}}{V_{ti}I_{qi}} - \frac{x'_{di}\left(1 + x'_{di}B_{ii}\right)V_{tqi}}{V_{ti}I_{qi}} \tag{11}$$
$$f_{i2} = \frac{\left(1 + x'_{di}B_{ii}\right)V_{tqi}}{V_{ti}I_{qi}} \tag{12}$$
$$\gamma_{i2} = f_{i2}\gamma_{i1} \tag{13}$$

Defining $X_i = \left[\omega_i, \Delta P_{ei,} \Delta V_{ti}\right]^T$ as the new state vector, the power system model (5) can be written as follows:

$$\dot{X}_i = A_iX_i + B_iv_{fi} + \gamma_i \tag{14}$$

where

$$A_i = \begin{bmatrix} -\frac{D_i}{2H_i} & -\frac{\omega_0}{-T'_{d0i}} & 0 \\ 0 & -\frac{1}{T'_{d0i}} & 0 \\ f_{i1} & -\frac{f_{i2}}{T'_{d0i}} & 0 \end{bmatrix}, B_i = \begin{bmatrix} 0 \\ -\frac{1}{T'_{d0i}} \\ \frac{f_{i2}}{T'_{d0i}} \end{bmatrix}, \gamma_i = \begin{bmatrix} 0 \\ \gamma_{i1} \\ \gamma_{i2} \end{bmatrix}$$

For this system, we set the control input v_{fi} as

$$v_{fi} = v_{fi1} + v_{fi2} \tag{15}$$

and design v_{fi1} and v_{fi2} in Section 3.2 and Section 3.3, respectively.

3.2 Robust controller design

In this section, we design a robust controller for v_{fi1} assuming that $\gamma_i = 0$, i.e.

$$\dot{X}_i = A_iX_i + B_iv_{fi1} \tag{16}$$

The procedure parallels closely that in [14, 4].

In view of equations (11)-(12), suppose

$$f_{i1\min} \le f_{i1} \le f_{i1\max}, \quad f_{i2\min} \le f_{i2} \le f_{i2\max}$$

Note that the upper and lower bounds above are obtained in view of equations (11) and (12), and the range of variables involved under normal operating circumstances. Using these bounds for f_{i1} and f_{i2}, the model (16) is rewritten as follows:

$$\begin{aligned}\dot{X}_i &= \left(\bar{A}_i + \Delta A_i\right)X_i + \left(\bar{B}_i + \Delta B_i\right)v_{fi1} \\ &= \left(\bar{A}_i + r_{i1}D_iE_{i1}^T + r_{i2}D_iE_{i2}^T\right)X_i + \left(\bar{B}_i + r_{i2}D_iF_i^T\right)v_{fi1}\end{aligned} \tag{17}$$

where

$$\bar{A}_i = \begin{bmatrix} -\dfrac{D_i}{2H_i} & -\dfrac{\omega_0}{-T_{d0i}^{'}} & 0 \\ 0 & -\dfrac{1}{T_{d0i}^{'}} & 0 \\ \bar{f}_{i1} & -\dfrac{\bar{f}_{i2}}{T_{d0i}^{'}} & 0 \end{bmatrix},\ \bar{B}_i = \begin{bmatrix} 0 \\ -\dfrac{1}{T_{d0i}^{'}} \\ \dfrac{\bar{f}_{i2}}{T_{d0i}^{'}} \end{bmatrix}$$

$$E_{i1} = \begin{bmatrix} f_{i1\max} - \bar{f}_{i1} \\ 0 \\ 0 \end{bmatrix},\ E_{i2} = \begin{bmatrix} 0 \\ -\dfrac{f_{i2\max} - \bar{f}_{i2}}{T_{d0i}^{'}} \\ 0 \end{bmatrix},\ D_i = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$r_{i1} = \frac{f_{1i} - \bar{f}_{1i}}{f_{i1\max} - \bar{f}_{i1}},\ r_{i2} = \frac{f_{i2} - \bar{f}_{i2}}{f_{i2\max} - \bar{f}_{i2}}$$

and $\bar{f}_{i1}$ and $\bar{f}_{i2}$ are the average values of f_{i1} and f_{i2}. Using the plant (17), we now determine the control v_{fi1} as follows:

$$v_{fi1} = -R_i^{-1}\bar{B}_i^TP_iX_i \tag{18}$$

where R_i and P_i are positive definite matrices such that

$$\begin{aligned}&P_i\left(\bar{A}_i - \bar{B}_iR_i^{-1}F_iE_{i2}^T\right) + \left(\bar{A}_i - \bar{B}_iR_i^{-1}F_iE_{i2}^T\right)^T P_i \\ &+P_i\left(2D_iD_i^T + \bar{B}R_i^{-1}F_iF_i^TR_i^{-1}\bar{B}_i^T - 2\bar{B}_iR_i^{-1}\bar{B}_i^T\right)P_i \\ &+E_{i1}E_{i1}^T + E_{i2}E_{i2}^T + Q_i = 0\end{aligned} \tag{19}$$

with Q_i being a given positive definite matrix. The control (18) stabilizes the system (16) or (17) as shown below.

Theorem 1 [14]: Consider the power system in equation (16) or (17) with no interconnection terms, and the control input v_{fi1} in (18). Then the closed-loop is asymptotically stable (in the absence of interconnections and disturbances).

Proof : Consider the following Lyapunov function candidate

$$V_{0i}\left(X_i\right) = X_i^TP_iX_i \tag{20}$$

Then the time derivative of the function (20) is obtained as

$$\dot{V}_{0i}\left(X_i\right) = X_i^TW_iX_i \tag{21}$$

where

$$\begin{aligned}W_i \le\ &P_i\left(\bar{A}_i - \bar{B}_iR_i^{-1}F_iE_{i2}^T\right) + \left(\bar{A}_i - \bar{B}_iR_i^{-1}F_iE_{i2}^T\right)^T P_i \\ &+P_i\left(2D_iD_i^T + \bar{B}R_i^{-1}F_iF_i^TR_i^{-1}\bar{B}_i^T - 2\bar{B}_iR_i^{-1}\bar{B}_i^T\right)P_i \\ &+E_{i1}E_{i1}^T + E_{i2}E_{i2}^T\end{aligned} \tag{22}$$

It then follows from the Riccati equation (19) that

$$\dot{V}_{0i}\left(X_i\right) \le -X_i^TQ_iX_i$$

This completes the proof.

3.3 Adaptive controller design for interconnection terms

In this section, we consider again the interconnection term γ_i, which is ignored in section 3.2. Firstly, using (7) and (13), write γ_i as

$$\gamma_i = B_iT_{d0i}^{'}\gamma_{i1}$$

Then the power system (14) is obtained as

$$\dot{X}_i = A_iX_i + B_i\left(v_{fi} + T_{d0i}^{'}\gamma_{i1}\right) = A_iX_i + B_i\left(v_{fi} + \gamma_{i1}^{'}\right) \tag{23}$$

where

$$\gamma_{i1}^{'} = T_{d0i}^{'}\gamma_{i1}$$

Rewrite (23) as

$$\begin{aligned}\dot{X}_i &= \left(A_iX_i + B_iv_{fi1}\right) + B_i\left(v_{fi2} + \gamma_{i1}^{'}\right) \\ &=: F_i\left(X_i\right) + B_i\left(v_{fi2} + \gamma_{i1}^{'}\right)\end{aligned} \tag{24}$$

Note that $\dot{X}_i = F_i\left(X_i\right)$ is a stable system as shown in section 3.2.

We now consider an upper bound for the absolute value of $\gamma_{i1}^{'}$ given in (7). Making the same assumptions as in [7], we obtain

$$\left|\gamma_{i1}^{'}\right| \le \theta_{i1}^* + \theta_{i2}^*\left\|X_i\right\| = \rho_i^T\theta_i^*$$

where

$$\rho_i = \begin{bmatrix}1 & \left\|X_i\right\|\end{bmatrix}^T,\ \theta_i^* = \begin{bmatrix}\theta_{i1}^* & \theta_{i2}^*\end{bmatrix}^T$$

and θ_i^* is a vector, which is assumed to be unknown in this paper. The design of the proposed adaptive controller for the power system (14) or (23) is then completed by determining v_{fi2} to counteract the effect of the interconnection term $\gamma_{i1}^{'}$ as follows:

$$v_{fi2} = \frac{\mu_i\rho_i^T\hat{\theta}_i}{\left\|\mu_i\right\|\rho_i^T\hat{\theta}_i + \varepsilon_i}\rho_i^T\hat{\theta}_i \tag{25}$$

where ε_i is an arbitrary positive constant and the vector $\hat{\theta}_i$ is the estimate of the unknown parameter vector θ_i^*, which is updated by the following adaptation law:

$$\dot{\hat{\theta}}_i = -\sigma_i\Gamma_i\hat{\theta}_i + \frac{1}{2}\left\|\mu_i\right\|\Gamma_i\rho_i \tag{26}$$

where σ_i is a positive constant, and Γ_i is a positive definite matrix.

Theorem 2: Consider the power system (14) or (23) with the interconnection $\gamma_{i1}^{'}$, and the adaptive control law (15), (18), (25) and (26). Then the closed-loop system is practically stable (in the absence of disturbances).

Proof:
Consider the following Lyapunov function candidate

$$V_i\left(X_i,\tilde{\theta}_i\right) = X_i^TP_iX_i + \tilde{\theta}_i^T\Gamma_i^{-1}\tilde{\theta}_i \tag{27}$$

where $\tilde{\theta}_i$ is the parameter estimation error defined as

$$\tilde{\theta}_i = \hat{\theta}_i - \theta_i^*$$

Note that the adaptation law in (26) can be written in terms of $\tilde{\theta}_i$ as follows:

$$\dot{\tilde{\theta}}_i = -\sigma_i\Gamma_i\tilde{\theta}_i + \frac{1}{2}\left\|\mu_i\right\|\Gamma_i\rho_i - \sigma_i\Gamma_i\theta_i^* \tag{28}$$

The derivative of V_i is then obtained as

$$\begin{aligned}\dot{V}\left(X_i,\tilde{\theta}_i\right) &\le -X_i^TQ_iX_i + 2X_i^TP_iB_iu_{i2} + 2X_i^TP_iB_i\gamma_{i1}^{'} + 2\tilde{\theta}_i^T\Gamma_i^{-1}\dot{\tilde{\theta}}_i \\ &\le -X_i^TQ_iX_i + \varepsilon_i - \sigma_i\left\|\tilde{\theta}_i\right\|^2 + \sigma_i\left\|\theta_i^*\right\|^2\end{aligned} \tag{29}$$

Hence we have

$$\dot{V}\left(X_i,\tilde{\theta}_i\right) \le -\left(X_i^T Q_i X_i + \sigma_i \left\|\tilde{\theta}_i\right\|^2\right) + \left(\varepsilon_i + \sigma_i \left\|\theta_i^*\right\|^2\right) \qquad (30)$$

This implies that $\left(X_i,\tilde{\theta}_i\right)$ is uniformly bounded with an ultimate bound, which can be made arbitrarily small as can be ε_i and σ_i. In other words, the closed-loop system is practically stable.

3.4 Effect of disturbance

Finally we consider the case where there is a disturbance; then the system model (14) becomes

$$\dot{X}_i = A_i X_i + B_i v_{fi} + \gamma_i + d_i \qquad (31)$$

where $d_i = \left[d_{\omega i} \quad 0 \quad 0\right]^T$. To see the effects of this disturbance, consider the positive definite function (27). Then

$$\dot{V} \le -\left(\left(\lambda_{\min}(Q_i) - \alpha_i\right)\left\|X_i\right\|^2 + \sigma_i \left\|\tilde{\theta}_i\right\|^2\right) + \left(\varepsilon_i + \sigma_i \left\|\theta_i^*\right\|^2\right) + \frac{1}{\alpha_i}\left\|P_i\right\|^2 \left\|d_i\right\|^2$$

where α_i is any positive number, and thus can be made smaller than $\lambda_{\min}(Q_i)$. This inequality implies that the closed-loop is uniformly ultimately bounded even in the presence of the disturbance.

4. SIMULATION RESULTS

For simulations, a three-machine power system is considered as shown in Figure 1. The system parameters are given in Table 1.

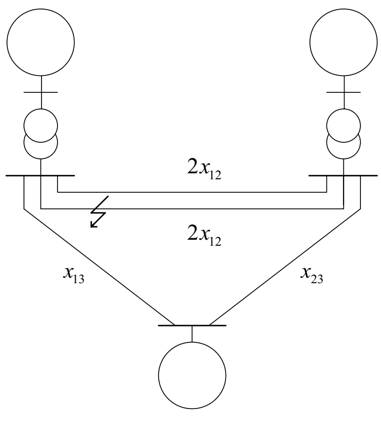

Fig. 1 Three-machine example system

Table 1 Generator parameters

	Generator #1	Generator #2
x_d (p.u.)	1.863	2.36
x_d' (p.u.)	0.657	0.719
x_T (p.u.)	0.129	0.127
x_{ad} (p.u.)	1.712	1.712
T_{d0}' (sec)	6.9	7.96
H(sec)	4.0	5.1
D (p.u.)	5.0	3.0
k_c	1.0	1.0

For more realistic simulations, the physical limit of the excitation voltage and the saturation effect of the synchronous generator are also considered as follows:

$$\left|k_{c1} v_{f1}\right| \le 6.0 \ p.u., \quad \left|k_{c2} v_{f2}\right| \le 6.0 \ p.u.$$

When the saturation effect of the synchronous generator is taken into account, equation (3) can be rewritten as:

$$\dot{E}_{qi}' = \frac{1}{T_{d0i}'}\left(E_{fi} - \left(x_{di} - x_{di}'\right)I_{di} - k_{fi}E_{qi}'\right)$$

where $k_{fi} = 1 + \frac{b_i}{a_i}\left(E_{qi}'\right)^{n_i - 1}$ [15]. The saturation parameters are assumed to be

$$a_1 = a_2 = 0.95, \quad b_1 = b_2 = 0.051, \quad n_1 = n_2 = 8.727$$

When finding the uncertainty bounds of f_{i1} and f_{i2}, the change of network structure is also taken into account; consider the bound of B_{ii} as follows:

$$B_{ii} = \left(1 + \beta_i\right) B_{ii0}$$

where B_{ii0} is the value of B_{ii} at a certain steady operating condition, and β_i is a proportional parameter. Also the following operating regions are assumed.

$$-30\% \le \beta_i \le 30\%, \ 0.2 \le I_{qi} \le 1.0, \ 0.1 \le P_{ei} \le 1.2$$

$$-0.2 \le Q_{ei} \le 1.0, \ 0.8 \le E_{qi}' \le 1.3, \ 5° \le \delta_{qti} \le 45°$$

$0.8 \le V_{ti} \le 1.1$ (u_{fi} usually reaches limit when $V_{ti} < 0.8$)

Then the bounds of f_{i1} and f_{i2} can be found as follows:

$$-3.526 \le f_{11} \le -0.259, \quad 0.266 \le f_{12} \le 3.794$$

$$-2.832 \le f_{21} \le -0.233, \quad 0.241 \le f_{22} \le 3.670$$

The adaptation parameters are chosen to be

$$\Gamma_1 = \Gamma_2 = I_2, \quad \sigma_1 = \sigma_2 = 1, \quad \varepsilon_1 = \varepsilon_2 = 0.01$$

In order to compare the proposed controller with a DFL-based nonlinear controller, we design an LQ optimal control for the power system (5) as follows:

$$v_{f1} = 22.4\Delta\delta_1 + 12.8\omega_1 - 82.5\Delta P_{e1}$$

$$v_{f2} = 22.4\Delta\delta_2 + 14.2\omega_2 - 82.6\Delta P_{e2}$$

In the simulations below, the proposed controller and the above DFL-based optimal controller are compared for the following two cases:

Case 1. Symmetrical three-phase short circuit:
A symmetrical three phase short circuit fault occurs on one of the transmission lines between Generator #1 and Generator #2 at t = 0.1, the fault is removed by opening the breaker of the faulted line at t = 0.25 (postfault state), and then the transmission lines are restored at t = 1 (prefault state).

Case 2. Permanent serious fault:
A symmetrical three phase short circuit fault occurs on one of the transmission lines between Generator #1 and Generator #2 at t = 0.1, the fault is removed by opening the breaker of the faulted line at t = 0.25 (postfault state), and the transmission lines are not restored.

Figures 2-5 present simulation results for case 1, and figures

6-9 present simulation results for case 2. In each figure, the solid and dashdot lines concern the proposed and DFL-based controllers, respectively.

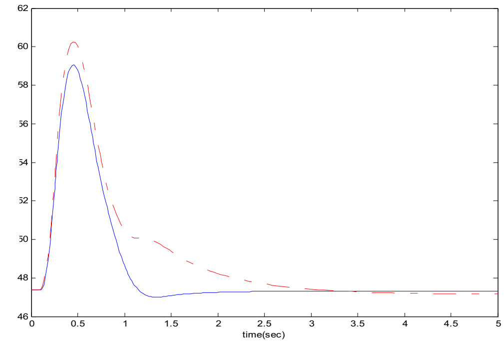

Fig 2. Power angle(in degree) responses (#1) (Case 1.)

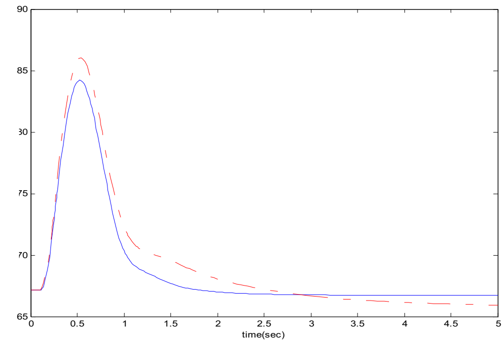

Fig 3. Power angle(in degree) responses (#2) (Case 1.)

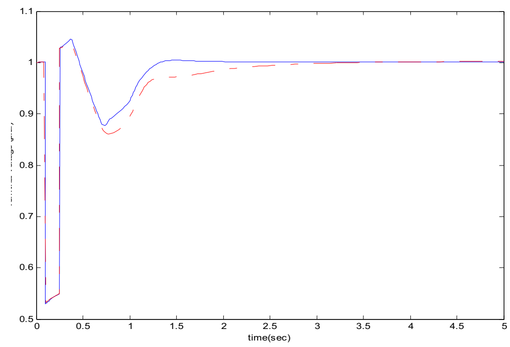

Fig 4. Terminal voltage (in p.u.) responses (#1) (Case 1.)

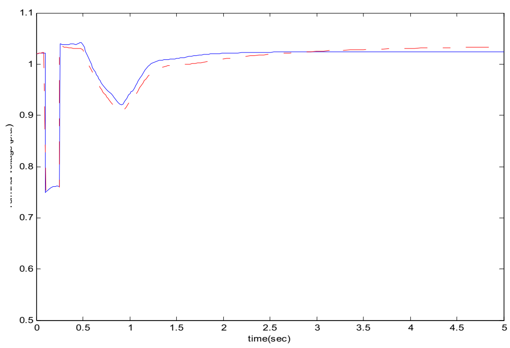

Fig 5. Terminal voltage (in p.u.) responses (#2) (Case 1.)

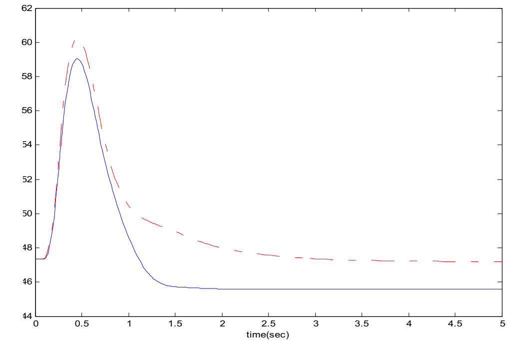

Fig 6. Power angle(in degree) responses (#1) (Case 2.)

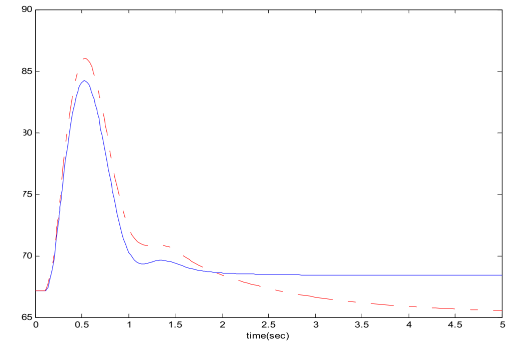

Fig 7. Power angle(in degree) responses (#2) (Case 2.)

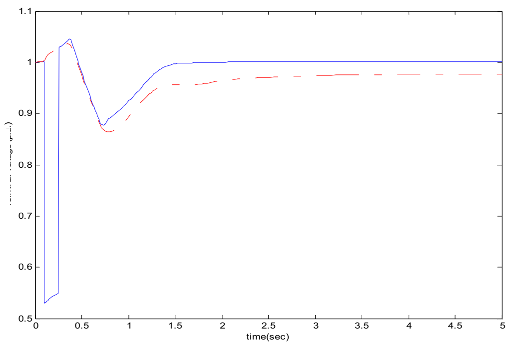

Fig 8. Terminal voltage (in p.u.) responses (#1) (Case 2.)

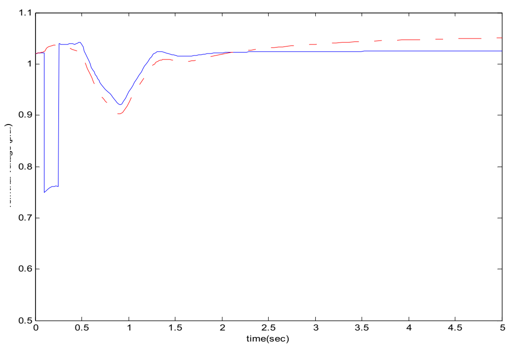

Fig 9. Terminal voltage (in p.u.) responses (#2) (Case 2.)

As illustrated in all the figures, the proposed controller leads to satisfactory performance, outperforming the DFL-based nonlinear controller.

5. CONCLUSION

This paper proposes a decentralized nonlinear voltage controller for multi-machine power systems. In order to achieve voltage regulation as well as stability enhancement, we first consider a state model where the terminal voltage of each generator is regarded as part of the state. Using the resulting model, a robust controller is designed assuming that there is no interconnection between generators; then another control is designed and added to deal with the interconnection via an adaptive technique.

The proposed control system is shown to be practically stable in the absence of disturbances, and to be uniformly ultimately bounded even in the presence of disturbances. The effectiveness of the proposed scheme is demonstrated through simulations. However some variables are assumed to be bounded during the design phase, and this problem needs to be solved for more rigorous proof of stability analysis.

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