Paper

MIMO Decentralized Nonlinear Control of Generator and Turbine To Enhance Transient Stability of Power System

Junyong Wu Akihiko Yokoyama (The University of Tokyo)
Qiang Lu (TsingHua University of China)
Masuo Goto Hiroo Konishi (Hitachi,Ltd.)

In this paper, decentralized feedback linearizing excitation and governor control, a kind of decentralized nonlinear control, in multi-machine power system is proposed to improve transient stability, and a local observation algorithm of the postfault equilibrium is also explored. Simulation results show that, it can improve the transient stability of the multi-machine power system to a great extent and enlarge the stable operating region even comparing to the decentralized feedback linearizing excitation control, and its adaptive ability to the changing postfault operating conditions is also verified.

Keywords: Power System, Decentralized Control, Nonlinear Control, Transient Stability, Automatic Voltage Regulator (AVR), Governor (GOV)

1. Introduction

In resent years, bulk power transmission systems are required to be operated effectively at high transmission levels due to economic or environmental constraints. Under these constraints, power system engineers have to face on a problem of interarea poorly-damped oscillations. With the theoretical developments of nonlinear control, a feedback linearizing control becomes one of the most powerful candidates in dealing with this problem. During the last decade, many papers are devoted to the researches of the feedback linearizing control of generator excitation and/or turbine governor [1-6]. A. Isidori interpreted systematically the principles of the feedback linearizing control of a nonlinear system in [7]. Qiang Lu et al. explored the nonlinear control of stream turbine valving at first [3], and then the nonlinear optimal excitation control [4]. J.W. Chapman and M.D. Ilic proposed the feedback linearizing excitation control of generators in a multi-machine power system [1,2]. In these papers, AVR and GOV were not included simultaneously into their original models.

In the feedback linearizing control of the generators, the information on the stable operating point , for example the rotating angle δ_0 and the generator terminal voltage $\mathbf{V}_{t0}$, will be feedbacked as references. But when a fault occurs in the power system, the operating point will probably change a lot (especially for δ_0). In an aspect of searching for the postfault equilibrium, J.Zaborszky et al. proposed the concept of Observation Decoupled State Space (ODSS), proved that the original point of the new state space was the postfault equilibrium if it existed uniquely, and used this idea in the active power control of generators in a large-scale power system [5]. J.W. Chapman and M.D. Ilic made use of the result in [5] to search for the postfault equilibrium, and applied it to the decentralized feedback linearizing excitation control [2]. But in these two papers, the input mechanical torque is considered to be constant and is assumed not to change before and after the fault.

This paper is organized as follows: Section 2 gives out a nonlinear model of a multi-machine power system including AVR and GOV. A completely feedback linearizing control of excitation and governor is derived in Section 3, in which the derivation of the first and second order differentials of the terminal voltage is given in Appendix 1. Section 4 proposes the observation algorithm of the postfault equilibrium when the input mechanical torque is changed. Section 5 shows the simulation results, in which the completely feedback linearizable condition is discussed, the results of the proposed nonlinear excitation and governor control are compared with the nonlinear control for only excitation[6], and the convergence characteristics of the proposed observation algorithm is explored. Conclusions are given in Section 6.

2. System Model

In this paper, the 3rd order one-axis generator model is used, and AVR and GOV are represented by a one time constant lag block respectively[8]. The model for the i^{th} generator with AVR and GOV can be written as in Eq. (1), and the diagrams of AVR and GOV are shown in Fig.1.

$$\begin{cases} \dot{\delta} = \omega - \omega_0 \\ \dot{\omega} = \frac{\omega_0}{2H}\left[P_m - P_e - \frac{D}{\omega_0}(\omega - \omega_0)\right] \\ \dot{E}'_q = \frac{1}{T'_{d0}}\left[-E'_q - (x_d - x'_d)I_d + E_{fd}\right] \\ \dot{E}_{fd} = -\frac{1}{T_A}(E_{fd} - E_{fd0}) + \frac{K_A}{T_A}(V_{t0} - V_t) + \frac{K_A}{T_A}\cdot U_f \quad \text{(AVR)} \\ \dot{P}_m = -\frac{P_m}{T_G} + \frac{K_G}{T_G}\left(\frac{\omega_0 - \omega}{\omega_0}\right) + \frac{P_{m0}}{T_G} + \frac{K_G}{T_G}\cdot U_G \quad \text{(GOV)} \end{cases} \tag{1}$$

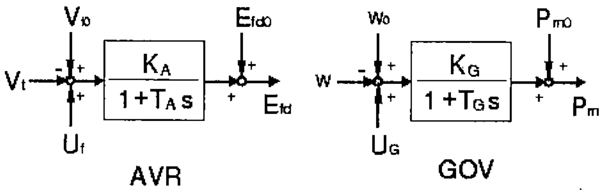

Fig.1. Block diagrams for AVR and GOV

For the purpose of clarity, the subscript "i" is omitted except explicitly declared. In Eq. (1), δ is the rotor angle, ω is the rotor speed, E_{fd} is the excitating voltage, P_m is the input mechanical torque, P_e is the output electrical torque of the generator, U_f and U_G are the supplementary control of AVR and GOV, for which the decentralized feedback linearizing control are designed.

The n-machine power system can be represented as follows:

$$\begin{cases} \dot{X} = F(X) + G\cdot U \\ Y = H(X) \end{cases} \tag{2}$$

where

$$X_i = \left[\delta_i - \delta_{0i} \quad \omega_i - \omega_{0i} \quad E'_{qi} \quad E_{fdi} \quad P_{mi}\right] \tag{3}$$

$$U_i = \left[U_{fi} \quad U_{Gi}\right] \tag{4}$$

$$Y_i = \left[\delta_i - \delta_{0i} \quad V_{ti} - V_{t0i}\right] = \left[h_{1i}(x) \quad h_{2i}(x)\right] \tag{5}$$

$$F_i(x) = \left[f_{1i}(x) \quad f_{2i}(x) \quad f_{3i}(x) \quad f_{4i}(x) \quad f_{5i}(x)\right] \tag{6}$$

$$G_i = \left[g_{1i} \quad g_{2i}\right] \tag{7}$$

$$f_{1i}(x) = \omega_i - \omega_0 \tag{8}$$

$$f_{2i}(x) = \frac{\omega_0}{2H_i}\left[P_{mi} - P_{ei} - \frac{D_i}{\omega_0}(\omega_i - \omega_0)\right] \tag{9}$$

$$f_{3i}(x) = \frac{1}{T'_{d0i}}\left[-E'_{qi} - (x_{di} - x'_{di})I_{di} + E_{fdi}\right] \tag{10}$$

$$f_{4i}(x) = -\frac{1}{T_{Ai}}(E_{fdi} - E_{fd0i}) + \frac{K_{Ai}}{T_{Ai}}(V_{t0i} - V_{ti}) \tag{11}$$

$$f_{5i}(x) = -\frac{P_{mi}}{T_{Gi}} + \frac{K_{Gi}}{T_{Gi}}\left(\frac{\omega_0 - \omega_i}{\omega_0}\right) + \frac{P_{m0i}}{T_{Gi}} \tag{12}$$

$$g_{1i} = \left[0 \quad 0 \quad 0 \quad \frac{K_{Ai}}{T_{Ai}} \quad 0\right]^T \tag{13}$$

$$g_{2i} = \left[0 \quad 0 \quad 0 \quad 0 \quad \frac{K_{Gi}}{T_{Gi}}\right]^T \tag{14}$$

$$X = \left[X_1 \quad \cdots \quad X_i \quad \cdots \quad X_n\right]^T \tag{15}$$

$$U = \left[U_1 \quad \cdots \quad U_i \quad \cdots \quad U_n\right]^T \tag{16}$$

$$Y = \left[Y_1 \quad \cdots \quad Y_i \quad \cdots \quad Y_n\right]^T \tag{17}$$

$$F(x) = \left[F_1(x) \quad \cdots \quad F_i(x) \quad \cdots \quad F_n(x)\right]^T \tag{18}$$

$$G = \mathrm{diag}\left[G_1 \quad \cdots \quad G_i \quad \cdots \quad G_n\right] \tag{19}$$

3. Feedback Linearizing Control

For the purpose of feedback linearizing the original nonlinear system (2), the relative degrees with respect to the output variables of the ith generator should be chacked at first.

For the first output variable of the ith generator, $h_{1i}(x) = \delta_i(t) - \delta_{0i}$:

$$\begin{cases} L_{g1i}L_F^2 h_{1i}(x) = \frac{\partial f_{2i}}{\partial x}\cdot g_{1i} = \beta_{11i} = 0 \\ L_{g2i}L_F^2 h_{1i}(x) = \frac{\partial f_{2i}}{\partial x}\cdot g_{2i} = \frac{\omega_0}{2H_i}\cdot\frac{K_{Gi}}{T_{Gi}} = \beta_{12i} \neq 0 \end{cases} \tag{20}$$

where $L_F h(x) = \frac{\partial h(x)}{\partial x} \cdot F(x)$ means Lie Derivative of h(x) with respect to F(x).

For the second output variables, $h_{2i}(x) = V_{ti}(t) - V_{t0i}$:

$$\begin{cases} L_{g1i} L_F h_{2i}(x) = \frac{\partial V_{ti}}{\partial E'_{qi}} \frac{1}{T'_{d0i}} \frac{K_{Ai}}{T_{Ai}} = \beta_{21i} \neq 0 \\ L_{g2i} L_F h_{2i}(x) = \frac{\partial b_i(x)}{\partial P_{mi}} \frac{K_{Gi}}{T_{Gi}} = \beta_{22i} = 0 \end{cases} \quad (21)$$

where

$$b_i(x) = \dot{V}_{ti} = \frac{\partial V_{ti}}{\partial \delta_i} f_{1i} + \frac{\partial V_{ti}}{\partial E'_{qi}} f_{3i} \quad (22)$$

and then

$$\det \begin{bmatrix} \beta_{11i} & \beta_{12i} \\ \beta_{21i} & \beta_{22i} \end{bmatrix} = \det \begin{bmatrix} L_{g1i} L_F^2 h_{1i} & L_{g2i} L_F^2 h_{1i} \\ L_{g1i} L_F h_{2i} & L_{g1i} L_F h_{2i} \end{bmatrix} = -\frac{\omega_0}{2H_i} \frac{K_{Gi}}{T_{Gi}} \frac{1}{T'_{d0i}} \frac{K_{Ai}}{T_{Ai}} \cdot \frac{\partial V_{ti}}{\partial E'_{qi}} \neq 0 \quad (23)$$

From Eqs.(20),(21) and (23), we can see that if the condition $\frac{\partial V_t}{\partial E'_q} \neq 0$ can be satisfied, the relative degrees of the nonlinear system (2) with respect to the two output variables of the ith generator are 3 and 2. The simulation results show that, this condition can always be satisfied, and that it will be discussed in details in Section 5.1. If we check that of all the other generators in the power system, we will have the similar results. Because the sum of all the relative degrees of the nonlinear system (2) with respect to every output variables is 5n, which equals exactly to the order of the system (2), according to the principles of the feedback linearizing control [1], the original nonlinear system (2) can be completely feedback linearized into an affine linear system by the following coordinate transformation:

$$\Phi_i(x) = \left[h_{1i}(x) \;\; L_F h_{1i}(x) \;\; L_F^2 h_{1i}(x) \;\; h_{2i}(x) \;\; L_F h_{2i}(x) \right] \quad (24)$$

$$Z = \Phi(x) = \left[\Phi_1(x) \;\; \cdots \;\; \Phi_i(x) \;\; \cdots \;\; \Phi_n(x) \right]^T \quad (25)$$

The obtained affine linear system is follows:

$$\dot{Z} = A \cdot Z + B \cdot V \quad (26)$$

where

$$Z_i = \left[\delta_i - \delta_{0i} \;\; \omega_i - \omega_0 \;\; \dot{\omega}_i \;\; V_{ti} - V_{t0i} \;\; \dot{V}_{ti} \right] = \left[Z_{1i} \;\; Z_{2i} \;\; Z_{3i} \;\; Z_{4i} \;\; Z_{5i} \right] \quad (27)$$

$$Z = \left[Z_1 \;\; \cdots \;\; Z_i \;\; \cdots \;\; Z_n \right]^T \quad (28)$$

$$V_i = \left[V_{1i} \;\; V_{2i} \right] \quad (29)$$

$$V = \left[V_1 \;\; \cdots \;\; V_i \;\; \cdots \;\; V_n \right] \quad (30)$$

$$A = \mathrm{diag}\left[A_1 \;\; \cdots \;\; A_i \;\; \cdots \;\; A_n \right] \quad (31)$$

$$B = \mathrm{diag}\left[B_1 \;\; \cdots \;\; B_i \;\; \cdots \;\; B_n \right] \quad (32)$$

$$A_i = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad B_i = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \quad (33)$$

For the ith generator, the state equation can be written in the following form (the subscript "i" are omitted):

$$\begin{cases} \dot{z}_1 = z_2 \\ \dot{z}_2 = z_3 \\ \dot{z}_3 = V_1 = \alpha_1(x) + \sum_{j=1}^{2} \beta_{1j} \cdot U_j = \alpha_1(x) + \beta_{12} \cdot U_G \\ \dot{z}_4 = z_5 \\ \dot{z}_5 = V_2 = \alpha_2(x) + \sum_{j=1}^{2} \beta_{2j} \cdot U_j = \alpha_2(x) + \beta_{21} \cdot U_f \end{cases} \quad (34)$$

where

$$\alpha_1(x) = -\frac{\omega_0}{2H} \cdot \gamma - \frac{\omega_0}{2H} I_q \dot{E}'_q + \frac{\omega_0}{2H} f_5(x) \quad (35)$$

$$\alpha_2(x) = \frac{\partial b(x)}{\partial \delta} f_1 + \frac{\partial b(x)}{\partial \omega} f_2 + \frac{\partial b(x)}{\partial E'_q} f_3 + \frac{\partial b(x)}{\partial E_{fd}} f_4 \quad (36)$$

$$\beta_{12} = \frac{\omega_0}{2H} \cdot \frac{K_G}{T_G} \quad (37)$$

$$\beta_{21} = \frac{\partial V_t}{\partial E'_q} \frac{1}{T'_{d0}} \frac{K_A}{T_A} \quad (38)$$

The derivations and calculations of Eqs.(35) to (38) are represented in details in Appendix 1. In Eq.(34), the feedback control for the ith generator can be designed by the pole placement approach as follow:

$$\begin{cases} V_1 = k_1 z_1 + k_2 z_2 + k_3 z_3 = k_1(\delta - \delta_0) + k_2(\omega - \omega_0) + k_3 \dot{\omega} \\ V_2 = k_4 z_4 + k_5 z_5 = k_4(V_t - V_{t0}) + k_5 \dot{V}_t \end{cases} \quad (39)$$

At last, the feedback linearizing control of the original nonlinear system (2) can be obtained:

$$\begin{cases} U_G = (V_1 - \alpha_1(x))/\beta_{12} \\ U_f = (V_2 - \alpha_2(x))/\beta_{21} \end{cases} \quad (40)$$

It is seen from the derivations that the feedback linearizing controls make use of only the local information of the generator and the turbine, and have nothing to do with other generators or network. Therefore, the "decentralized" nonlinear control is called.

4. Postfault Equilibrium

From Eq.(39), we know that the rotor angles and the terminal voltages of the generators at the stable operating point are feedbacked as setpoint references in the nonlinear feedback controls (see Eq.(39)). The terminal voltage references of the generators are considered to be constants because the terminal voltages will not change obviously between the stable operating points before and after the disturbances. But when a fault occurs in the power system, the rotor angles of the generators will probably change to a great extent, and the rotor angles of the generators at the postfault new equilibrium should be feedbacked as the rotor angle reference in Eq.(39). As mentioned in the introduction of this paper, in references [2] and [5], the turbine governor is not included, and the input mechanical torque is considered to be constant and is assumed not to change before and after the fault.

In this paper, the mechanical torque is changed by the nonlinear control of GOV. Based on the concept of ODSS, Observation Algorithm of the Postfault Equilibrium (OAPE) using only the local information at the generator node has been proposed, which is similar to that used in [2] but with the changing mechanical torque. The performance of the nonlinear controller with or without OAPE will be compared in the following section 5.3, from which it can be seen that the observing rotor angle and the practical rotor angle converge together and the nonlinear controller with OAPE can control the system to converge to the postfault new operating point quickly.

The postfault equilibrium must satisfy the following equation:

$$P_{mi} - V_i \sum_{j=1}^{n} C_{ij} V_j \left[G_{ij} \cos(\phi_i - \phi_j) + B_{ij} \sin(\phi_i - \phi_j) \right] = 0 \quad (41)$$

Where P_{mi} is the mechanical torque which is changed during and after the fault, $\overline{V}_i = V_i \angle \phi_i$ is the ith generator terminal voltage, $\overline{V}_j = V_j \angle \phi_j$ is the jth node voltage which is connected with ith generator terminal (it maybe a generator terminal, or a load node), C_{ij} represents whether the ith node is connected with the jth node or not:

$$C_{ij} = \begin{cases} 1 & \text{connect} \\ 0 & \text{not connect} \end{cases} \quad (42)$$

In Eq.(41), G_{ij}, B_{ij} and C_{ij} are known, V_i, ϕ_i and P_{mi} can be measured at the generator terminal, and $\overline{V}_j$ can be calculated with respect to $\overline{V}_i$ as following:

$$\overline{V}_j = V_j \angle \phi_j = \overline{V}_i + \overline{I}_{ij} \overline{Z}_{ij} \quad (43)$$

where $\overline{I}_{ij}$ is the current from node i to node j, $\overline{Z}_{ij}$ is the impedance of line i-j. The reference coordinate does not need to be the same for every generator because only the difference of the angles is used. Therefore, the angle of the ith generator terminal voltage of the postfault equilibrium can be calculated easily from Eq. (41):

$$\phi_{ei} = \cos^{-1}\left(\frac{G_{ii} V_i^2 - P_{mi}}{\sqrt{\alpha^2 + \beta^2}} \right) + \arg(\alpha + j\beta) \quad (44)$$

Where,

$$\alpha = V_i \sum_{j=1}^{n} C_{ij} V_j \left[G_{ij} \cos \phi_j - B_{ij} \sin \phi_j \right] \quad (45)$$

$$\beta = V_i \sum_{j=1}^{n} C_{ij} V_j \left[G_{ij} \sin \phi_j + B_{ij} \cos \phi_j \right] \quad (46)$$

In Eq.(44), P_{mi} is the real time mechanical power of the ith generator. Secondly, using the generator terminal voltage $\overline{V}_i$, the generator internal induced voltage $\overline{E}_i'$ and the machine impedance as a single line, the offset angle $\Delta\phi_i$ between $\overline{V}_i$ and $\overline{E}_i'$ is calculated. At last, the observing rotor angle δ_{ei} of the ith generator in the postfault equilibrium can be calculated as following:

$$\delta_{ei} = \phi_{ei} + \Delta\phi_i \tag{47}$$

Replacing δ_{0i} in Eq.(39) by the observing rotor angle δ_{ei} of the generator in Eq.(47), the proposed Decentralized Feedback Linearizing Excitation and Governor Control with the Observation Algorithm of Postfault Equilibrium (DFLEGC/OAPE) can converge quickly to the new postfault equilibrium due to the disturbance, and have adaptive ability to the changing operating points.

5. Simulations

The nonlinear dynamic simulations have been done for a three-machine power system. The system diagram is shown in Fig.2, the power flow condition, rated capacities and inertias of generators, and limiters are given in Appendix 2, the other parameters of the generators, lines, AVR and GOV are given in [9]. In the simulations, the 6th order generator model is used, although the nonlinear control is derived based on the 3rd order generator model. So we can see the adaptivity of the nonlinear control to the un-modeling properties. The limiters of the AVR and GOV are also included.

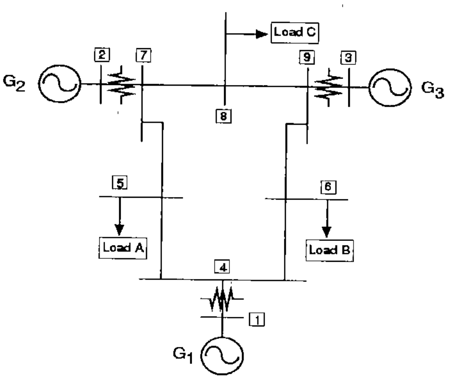

Fig.2 Diagram of model power system

5.1. Completely feedback linearizable condition $\frac{\partial V_t}{\partial E'_q} \neq 0$:

From Eq.(23) we know, the original nonlinear system (2) can be completely feedback linearized if the condition $\frac{\partial V_t}{\partial E'_q} \neq 0$ can be satisfied. It equals a positive value under the usual operating conditions, and has small oscillations during the ordinary transient state when the generators are controlled by the usual AVR/GOV. But when the nonlinear control is applied to the generators, this variable varies violently when some fault occurs, sometimes from positive to negative and inverse. When the absolute value of $\frac{\partial V_t}{\partial E'_q}$ approaches closely to zero, the nonlinear control signal U_f will become very large, resulting in the excitation voltage E_{fd} varying only between the upper and the lower limits of the controller, and then the power system tends to be unstable.

If we set $\frac{\partial V_t}{\partial E'_q}$ to be constant as its initial value, we will see that this will not give obvious negative influences on the performance of the nonlinear control. Supposing that a three phase to ground fault occurs at node 5 in Fig.2 from 0.1s and is cleared at 0.17s, the rotor angle of G2 relative to G1 are shown in Fig.3.

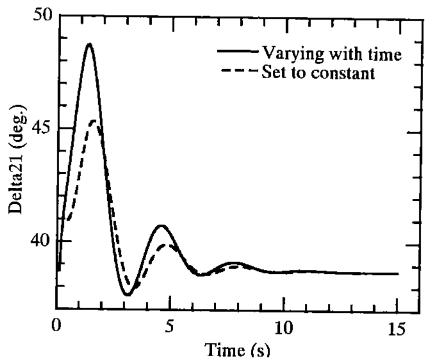

Fig.3. δ_{21}

It can be seen from Fig. 3 that the performance of the nonlinear control has robustness to $\frac{\partial V_t}{\partial E'_q}$. We have the similar results when the same fault occurs at the generator terminal nodes. Setting $\frac{\partial V_t}{\partial E'_q}$ to be constant will stabilize the algorithm of the nonlinear control. It can eliminate the structural drawback of the nonlinear controller, and do not give unacceptable influences on the performance of the controller (sometimes have good effect on the performance as shown in Fig. 3). For this reason, $\frac{\partial V_t}{\partial E'_q}$ is set to constant in the following simulations of this paper.

5.2. Decentralized nonlinear control:

Because the proposed nonlinear control is decentralized, the generators can be selected which are controlled by the Decentralized Feedback Linearizing Excitation and Governor Controller with Observation Algorithm of Postfault Equilibrium (DFLEGC/OAPE, the control mode of this generator is represented by "1") or by the ordinary AVR/GOV (the control mode is "0"). The combinations of the controller of the three generators in Fig. 2 are shown in Table 1. For example, "100" of case 1 in Table 1 means that, only G1 is controlled by DFLEGC/OAPE combination, G2 and G3 are still controlled by ordinary AVR/GOV. Supposing that a three phase to ground fault occurs at node 5 side on one of the two circuits between nodes 5 and 7 in Fig. 2 from 0.1s to 0.17s, and then this circuit is opened. The rotor angles of G2 relative to G1 under different cases are shown in Figs. 4 to 5. The supplementary nonlinear control signals of AVR and GOV, U_f and U_G of G1 in case 7, are shown in Figs. 6 and 7. The excitation voltage, the generator terminal voltage and the input mechanical power (for example, G2) in case 0 and case 7 are shown from Fig. 8 to 10.

Table 1. Combinations of the controller under different cases

Case	Controllers	Case	Controllers
0	000	4	110
1	100	5	101
2	010	6	011
3	001	7	111

(1—DFLEGC/OAPE, 0—AVR/GOV)

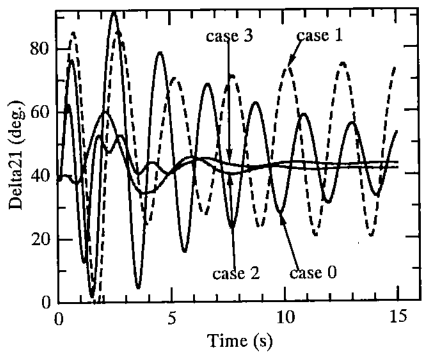

Fig. 4. δ_{21} (case 0-3)

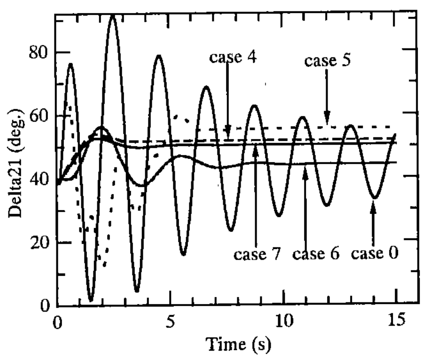

Fig. 5. δ_{21} (case 0, case 4-7)

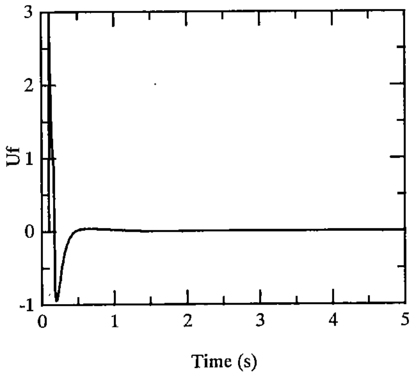

Fig. 6. Supplementary control of AVR, U_f of G1, case 7

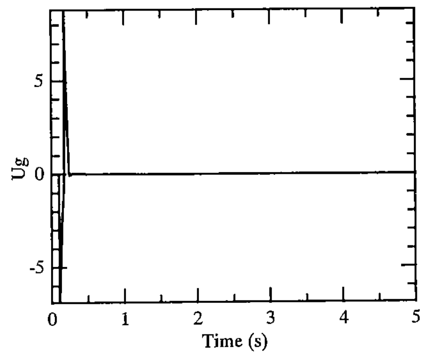

Fig. 7. Supplementary control of GOV, U_G of G1, case 7

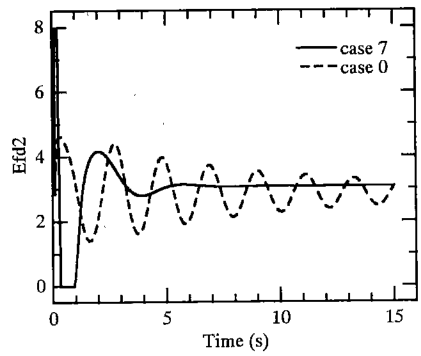

Fig. 8. Excitation voltage E_{fd} of G2

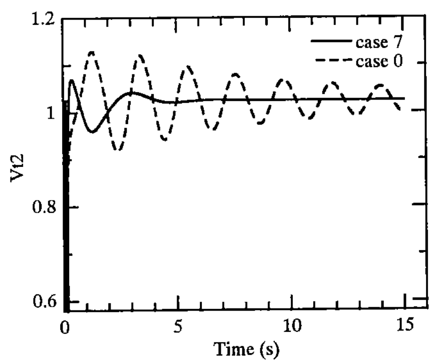

Fig. 9. Generator terminal voltage V_t of G2

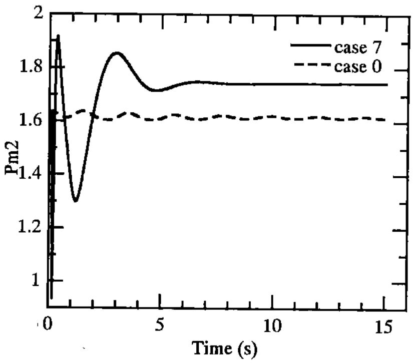

Fig. 10. Mechanical Power Pm of G2

It can be seen in Figs. 4 and 5 that the power system is stable and the transient stability has been improved to a great extent under different combinations of the controllers except only case 1, in which only G1 is controlled by DFLEGC, G2 and G3 are still controlled by AVR/GOV. This is because the left "zero dynamics" of the power system after only G1 is feedback linearized is unstable. When the nonlinear control is applied only on G1, only the nonlinear characteristics of G1 are feedback linearized, the nonlinear characteristics of G2 and G3 are remained and called "zero dynamics". These nonlinear part are so complicated that we have to check whether they are stable or not by the simulations. In [6], the authors applied the Decentralized Feedback Linearizing Excitation Control (nonlinear control only for excitation, abbreviated as **DFLEC**) to the same three-machine power system. The simulation results showed that power system is stable except in the case 1, 4 and 5. That means, when G1 is controlled by DFLEC, G2 and G3 are not controlled by DFLEC, the power system turns to be unstable. In this power system, difference between G1 and G2(G3) is the inertia of G1 (H_1=50) is greater than that of G2 (H_2=9) and G3 (H_3=6). It seems that when DFLEC or DFLEGC/OAPE is applied only to a generator with the greatest inertia, the power system may turn to be unstable. Comparing with the simulation results in this paper, we can see that the DFLEGC/OAPE can further enlarge the stable operating region of the power system even comparing with the DFLEC. But it also has a problem that the left "zero dynamics" may be unstable, similar to the cases of DFLEC.

5.3. Observation Algorithm of Postfault Equilibrium (OAPE):

The difference of the observation algorithm of the postfault equilibrium between [2,5] and this paper is that, the input mechanical torque is considered to be constant in [2,5], but it is changed and controlled by governor in this paper. Supposing that a three phase to ground fault occurs at node 5 side on one of the two circuits between nodes 5 and 7 in Fig. 2 from 0.1s to 0.17s, and then this circuit is opened. The rotor angles of G2 relative to G1, the generator terminal voltage (G2), the excitation voltage (G2) and the mechanical torque (G2) in the case 7 with or without Observation Algorithm of Postfault Equilibrium (OAPE), are shown in Figs. 11 to 14. The rotor angle of the generator G2 with OAPE δ_2 and the online observing rotor angle of the postfault equilibrium δ_{e2} (output of OAPE) are shown in Fig. 15.

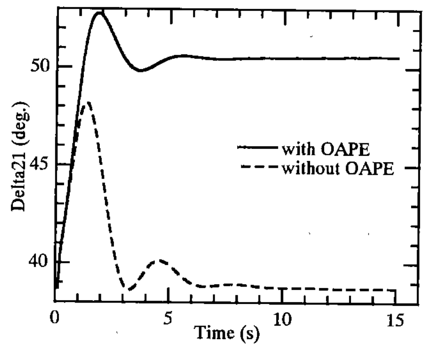

Fig. 11. δ_{21} with or without OAPE

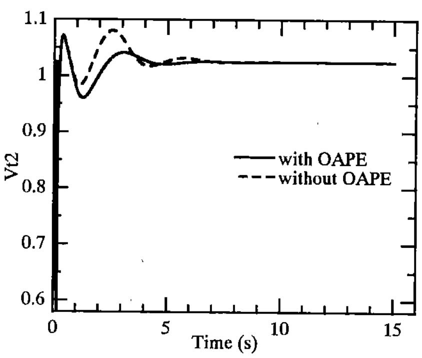

Fig. 12. V_{t2} with or without OAPE

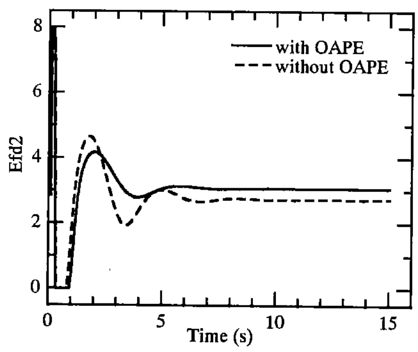

Fig. 13. E_{fd2} with or without OAPE

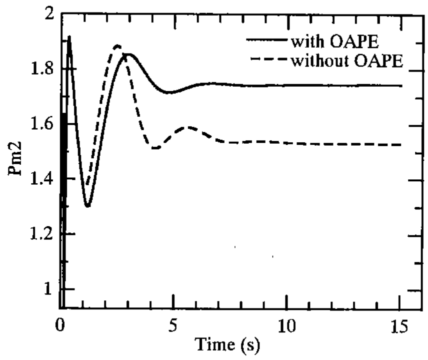

Fig. 14. P_{m2} with or without OAPE

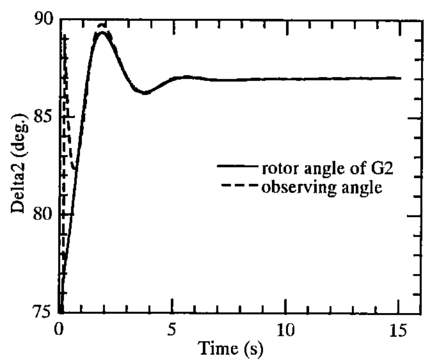

Fig. 15. δ_2 and δ_{e2}

It can be seen that the observing rotor angle and the real rotor angle converge together (Fig.15), and the generators controlled by DFLEGC/OAPE can converge to the postfault new equilibrium quickly than that without OAPE(Fig.11--14). This is because, in the cases without OAPE, the mechanical torque is adjusted to maintain the rotor angles and control the rotor angles to come back to the former initial values before the disturbance, but in the cases with OAPE, both of the mechanical torques and the rotor angle references can be adjusted altogether and converge to the postfault new equilibrium quickly. From this meaning it can be said that, the DFLEGC/OAPE can adapt the generators automatically according to the disturbances, and has adaptive ability to the changing operating conditions. It also can be seen from Fig.15 that, OAPE is very sensitive to the disturbance and try to access the new postfault equilibrium point at a high speed, this causes an abrupt change in nonlinear control $\mathbf{U}_G$ (Fig.7) and bring the system to the neighbor of the postfault equilibrium. After a little period of time (e.g. one second), the difference between the real rotor angle and the observing rotor angle becomes small, the supplementary nonlinear controls are completed (Figs.6 and 7), the whole system converges quickly to the new equilibrium point under the control of the normal AVR/GOV.

6. Conclusion

In this paper, the decentralized feedback linearizing control of the generator excitation and the turbine governor, a kind of nonlinear control, in the multi-machine power system has been proposed, and the locally online observation algorithm of the postfault equilibrium is also applied. Simulation results show that:

(1). The performance of the Decentralized Feedback Linearizing Excitation and Governor Control (DFLEGC) has some robustness to $\frac{\partial V_t}{\partial E'_q}$, and $\frac{\partial V_t}{\partial E'_q}$ can be set as constant.

(2). The Decentralized Feedback Linearizing Excitation and Governor Control with Observation Algorithm of the Postfault Equilibrium (DFLEGC/OAPE) can improve the transient stability of the power system to a great extent, even comparing with DFLEC, the nonlinear control only for excitation. But it also has the problem that the left "zero dynamics" may be unstable if DFLEGC are not applied on all of the generators.

(3). The proposed DFLEGC/OAPE can converge to the postfault new stable operating point quickly. In this sense, it can be said that the DFLEGC/OAPE has adaptive ability to the changing operating conditions.

(4). The proposed control strategy including OAPE makes use of only the local information of the generators, and can be realized easily in the large-scale power system.

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Appendix 1.

In Eq. (35), γ is defined as following:

$$\gamma = \dot{E}'_d I_d + E'_q \dot{I}_q + E'_d \dot{I}_d + \frac{D}{\omega_0}\dot{\omega} \tag{1-1}$$

In order to calculate the derivation of $\mathbf{I_d}$ and $\mathbf{I_q}$, two variables are need to be introduced as following [1,2]:

$$D_{dq} = \frac{\partial i_d}{\partial E'_q} \qquad D_{qq} = \frac{\partial i_q}{\partial E'_q} \tag{1-2}$$

According to the simulation results in [1], the performance of the nonlinear control has some robustness relative to these two variables. That is to say, whether D_{dq} and D_{qq} change with the operating conditions or set as constant as their initial values has little influence on the nonlinear control results. Moreover, from Eq. (1-2) we have:

$$\frac{\partial D_{qq}}{\partial \delta} = \frac{\partial\left(\frac{\partial i_q}{\partial \delta}\right)}{\partial E'_q} = \frac{\partial i_d}{\partial E'_q} = D_{dq} \tag{1-3}$$

$$\frac{\partial D_{dq}}{\partial \delta} = \frac{\partial\left(\frac{\partial i_d}{\partial \delta}\right)}{\partial E'_q} = \frac{\partial(-i_q)}{\partial E'_q} = -D_{qq} \tag{1-4}$$

$$\frac{\partial D_{dq}}{\partial E'_q} = \frac{\partial D_{qq}}{\partial E'_q} = 0 \tag{1-5}$$

According to Eq. (22), $\mathbf{b(x) = \dot{V}_t}$ can be expressed in details as follows:

$$b(x) = \frac{S_1(x)}{V_t} + \frac{S_2(x)\cdot S_3(x)}{T'_{d0}V_t} \tag{1-6}$$

where

$$S_1(x) = \left\{\left(x_q^2 - (x'_d)^2\right)I_d I_q + x'_d E'_q I_q\right\}(\omega - \omega_0) \tag{1-7}$$

$$S_2(x) = \left\{x_q^2 I_q D_{qq} + E'_q - x'_d E'_q D_{dq} - I_d x'_d + (x'_d)^2 I_d D_{dq}\right\} \tag{1-8}$$

$$S_3(x) = \left[-E'_q - (x_d - x'_d)I_d + E_{fd}\right] \tag{1-9}$$

Using Eqs. (1-1) to (1-6), $\frac{\partial b(x)}{\partial \omega}$, $\frac{\partial b(x)}{\partial E_{fd}}$, $\frac{\partial b(X)}{\partial \delta}$, and $\frac{\partial b(x)}{\partial E'_q}$ in Eq.(36) can be calculated as follows:

$$\frac{\partial b(x)}{\partial \omega} = \frac{1}{V_t}\left\{\left(x_q^2 - x_d'^2\right)I_d I_q + x'_d E'_q I_q\right\} \tag{1-10}$$

$$\frac{\partial b(x)}{\partial E_{fd}} = \frac{1}{T'_{d0}V_t}\left\{x_q^2 I_q D_{qq} + E'_q - x'_d E'_q D_{dq} - I_d x'_d + x_d'^2 I_d D_{dq}\right\} \tag{1-11}$$

$$\frac{\partial b(x)}{\partial \delta} = \frac{1}{V_t^2}\left\{\left(\frac{\partial S_1(x)}{\partial \delta} + \frac{\frac{\partial S_2(x)}{\partial \delta}S_3(x) + S_2(x)\frac{\partial S_3(x)}{\partial \delta}}{T'_{d0}}\right)V_t - \left(S_1(x) + \frac{S_2(x)S_3(x)}{T'_{d0}}\right)\cdot\frac{\partial V_t}{\partial \delta}\right\} \tag{1-12}$$

$$\frac{\partial b(x)}{\partial E'_q} = \frac{1}{V_t^2}\left\{\left(\frac{\partial S_1(x)}{\partial E'_q} + \frac{\frac{\partial S_2(x)}{\partial E'_q}S_3(x) + S_2(x)\frac{\partial S_3(x)}{\partial E'_q}}{T'_{d0}}\right)V_t - \left(S_1(x) + \frac{S_2(x)S_3(x)}{T'_{d0}}\right)\cdot\frac{\partial V_t}{\partial E'_q}\right\} \tag{1-13}$$

where

$$\frac{\partial S_1}{\partial \delta} = \left[\left(x_q^2 - x_d'^2\right)\left(I_d^2 - I_q^2\right) + x'_d E'_q I_d\right]\cdot(\omega - \omega_0) \tag{1-14}$$

$$\frac{\partial S_2}{\partial \delta} = \left(i_d D_{qq} + i_q D_{dq}\right)\left(x_q^2 - x_d'^2\right) + x'_d\left(i_q + E'_q D_{qq}\right) \tag{1-15}$$

$$\frac{\partial S_3}{\partial \delta} = (x_d - x'_d)I_q \tag{1-16}$$

$$\frac{\partial V_t}{\partial \delta} = \frac{1}{V_t}\left[x_q^2 I_d I_q + \left(E'_q - I_d x'_d\right)\left(x'_d I_q\right)\right] \tag{1-17}$$

$$\frac{\partial S_1}{\partial E'_q} = \left[\left(x_q^2 - x_d'^2\right)\left(D_{dq} I_q + D_{qq} I_d\right) + x'_d I_q + x'_d E'_q D_{qq}\right]\cdot(\omega - \omega_0) \tag{1-18}$$

$$\frac{\partial S_2}{\partial E'_q} = \left(x_q^2 D_{qq}^2 + 1 - 2x'_d D_{dq} - x_d'^2 D_{dq}^2\right) \tag{1-19}$$

$$\frac{\partial S_3}{\partial E'_q} = -1 - (x_d - x'_d)D_{dq} \tag{1-20}$$

$$\frac{\partial V_t}{\partial E'_q} = \frac{1}{V_t}\left[x_q^2 I_q D_{qq} + \left(E'_q - I_d x'_d\right)\left(1 - x'_d D_{dq}\right)\right] \quad (1\text{-}21)$$

Appendix 2. System Data[9]

(1). Power flow: (p.u.)

Node	P	Q
1	0.716	0.270
2	1.630	0.067
3	0.850	-0.109
5	-1.250	-0.500
6	-0.900	-0.300
8	-1.000	-0.350

(2). Generators:

	G1	G2	G3
Capacity(GVA)	1.0	2.0	1.0
H(s)	50	9	6

(3). Limiters:

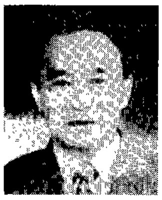
AVR: $\mathbf{0.0 \le E_{fd} \le 8.0}$

GOV: $\mathbf{0.0 \le P_m \le 1.05 P_{max}}$

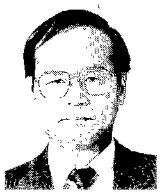
The other parameters of lines and generators are given in [9].

Junyong Wu (Non-member): Born on July 27th, 1966. He graduated as a Bachelor, Master and a Ph.D from the Department of Electrical Engineering, Huazhong University of Science and Technology, China in 1987, 1989 and 1994 respectively. He became a lecturer in 1994, and an associate professor in 1997. He has been doing the research work as a post doctor in the University of Tokyo, Japan from October 1998 to September 2000. His research interests are the nonlinear control, robust control and their applications in power system, the analysis and operation of power system.

Akihiko Yokoyama (Member): Born in Osaka Prefecture, Oct. 9, 1956. Obtained BS, MS and Dr.Eng all from the University of Tokyo in 1979, 1981 and 1984 respectively. He has been with the Department of Electrical Engineering, the University of Tokyo after 1984 and currently a professor in charge of Power System Engineering. He was a visiting research fellow at University of Texas, Arlington and University of California, Berkeley during the period of February 1987-February 1989. He is a member of IEEE and CIGRE.



Qiang Lu (Non-member): Born in Anhui, China, on April 19, 1937. He graduated from Graduate Student School of Tsinghua University, Beijing, in 1963 and joined the faculty of the same University. From 1984 to 1986 he was a visiting professor in Colorado State University, Ft. Collins, and is now a professor of Electrical Engineering Department of Tsinghua University. His work has been in the power system stabilization area. Currently, professor Lu is responsible for nonlinear control system studies. Dr. Lu is a senior member of IEEE.



Masuo Goto (Member): Born in Takamatsu, Japan, on May 9, 1942. He received his B.E. and Dr.E. degree from University of Osaka Prefecture, Japan in 1965 and 1979, respectively. He joined Hitachi Research Laboratory of Hitachi, Ltd. in 1965. From 1965 to 1986 he was engaged in research and development on the field of power system analysis and control. He is currently a Chief Engineer in Power and Industrial Systems Division, Hitachi Ltd., where he is responsible for development and evaluation of new power apparatuses, control systems and protection systems. Dr. Goto received the IEE of Japan Advanced Technology Award for the development of an advanced power system simulator in 1991. Dr. Goto is a member of IEEJ and an IEEE Fellow.

Hiroo Konishi (Member): Born in Tokushima Prefecture, Japan, on February 6, 1948. He graduated from the M.S. degree in electrical engineering of Osaka University, Osaka in 1972. He joined the Hitachi Research Laboratory, Hitachi Ltd,. Japan in 1972. Since 1972 he has been working in the research and development of the control and protection systems of HVDC system and FACTS system. He is currently interested in analysis and modeling of the power system. He received Ph.D. degree in electrical engineering from Osaka University in 1989.