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

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In this paper, decentralized feedback linearizing excitation and governor control, a kind of decentralized nonlinear control, in multimachine 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 multimachine 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 recent 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 steam 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 multimachine 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 \( \delta_0 \) and the generator terminal voltage \( V_{f0} \), will be feedbacked as references. But when a fault occurs in the power system, the operating point will probably change a lot (especially for \( \delta_0 \)). 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 [6] 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 multimachine 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 2nd generator with AVR and GOV can be written as in Eq. (0), and the diagrams of AVR and GOV are shown in Fig. 1.

\[
\begin{align*}
\dot{\delta} &= \omega - \omega_b \\
\omega &= \frac{e_b - 2H}{p_m - p_e - D}{(\omega - \omega_b)} \\
E_q' &= \frac{1}{T_{d0}}[-E_q - (x_{dq} - x_{d0})x_d + E_{ad}] \\
E_{ad} &= \frac{1}{T_a}(e_{ad} - E_{ad0}) + \frac{K_a}{T_a}(V_{ad} - V_d) + K_aU_t \text{ (AVR)} \\
P_e &= \frac{K_m}{T_{r0}}(\omega - \omega_b) + \frac{P_m}{T_{r0}} + \frac{K_m}{T_{r0}}U_G \text{ (GOV)}
\end{align*}
\]

(1)

![Fig. 1. Block diagrams for AVR and GOV](image)

For the purpose of clarity, the subscript ‘T’ is omitted except explicitly declared. In Eq. (1), \( \delta \) is the rotor angle, \( \omega \) is the rotor speed, \( E_{ad0} \) is the exciting voltage, \( P_m \) is the input mechanical torque, \( P_e \) is the output electrical torque of the generator, \( U_t \) 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:

\[
\begin{align*}
\dot{X} &= F(X) + G \cdot U \\
Y &= H(X)
\end{align*}
\]

(2)

where

\[
\begin{align*}
X_i &= [\delta_i - \delta_{di} \quad x_i - \omega_{di} \quad E_q' \quad E_{ad0} \quad P_{mi}] \\
U_i &= [U_{ai} \quad U_{gi}] \\
Y_i &= [\delta_i - \delta_{di} \quad V_{ad} - V_{ad0} - [h_{ii}(x) \quad h_{di}(x)]
\end{align*}
\]

(3)

(4)

(5)

\[
\begin{align*}
F_i(x) &= [f_{ii}(x) \quad f_{2i}(x) \quad f_{3i}(x) \quad f_{4i}(x) \quad f_{5i}(x)] \\
G_i &= [g_{ii} \quad g_{2i}]
\end{align*}
\]

(6)

(7)

(8)

(9)

(10)

(11)

(12)

(13)

(14)

(15)

(16)

(17)

(18)

(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 checked at first.

For the first output variable of the ith generator, \( h_i(x) = \delta_i(t) - \delta_{di} \):

\[
\begin{align*}
L_{g_{ii}}L_{h_{ii}}\frac{\partial h_i}{\partial x}(x) &= \frac{\partial f_{2i}}{\partial x} \cdot g_{ii} = \beta_{1ii} = 0 \\
L_{g_{2i}}L_{h_{ii}}\frac{\partial h_i}{\partial x}(x) &= \frac{\partial f_{3i}}{\partial x} \cdot g_{2i} = \frac{\omega_{di}}{2H\text{ }} \cdot \frac{K_G}{T_G} = \beta_{12i} = 0
\end{align*}
\]

(20)
where \( L_{\rho}h(x) = \frac{\partial h(x)}{\partial x} \cdot F(x) \) means Lie Derivative of 

\( h(x) \) with respect to \( F(x) \).

For the second output variables, \( b_{2i}(x) = V_{2i}(t) - V_{\text{out}} \):

\[
\begin{align*}
L_{\rho}L_{\rho}h_{21}(x) &= \frac{\partial V_{2i}}{\partial E_{q_i}} \left( \frac{1}{T_{\text{el}}} - \frac{K_{\text{out}}}{T_{\text{el}}} - \beta_{21} \right) = 0 \\
L_{\rho}L_{\rho}h_{22}(x) &= \frac{\partial h_{2i}(x)}{\partial P_{\text{in}}} \frac{K_{\text{gi}}}{T_{\text{gi}}} - \beta_{22} = 0
\end{align*}
\]  

(21)

where

\[
b_{2i}(x) = V_{2i} - \frac{\partial V_{2i}}{\partial t} f_{1i} + \frac{\partial V_{2i}}{\partial E_{q_i}} f_{3i}
\]  

(22)

and then

\[
\det \begin{bmatrix}
\beta_{11} & \beta_{12} \\
\beta_{21} & \beta_{22}
\end{bmatrix}
= \det \begin{bmatrix}
L_{\rho}L_{\rho}h_{11} & L_{\rho}L_{\rho}h_{12} \\
L_{\rho}L_{\rho}h_{21} & L_{\rho}L_{\rho}h_{22}
\end{bmatrix}
= \begin{cases}
\omega_0 \frac{K_{\text{gi}}}{H_{\text{gi}}} - \frac{\partial V_{2i}}{\partial E_{q_i}} f_{3i} & = 0
\end{cases}
\]  

(23)

From Eqs.(20),(21) and (23), we can see that if the condition

\[
\frac{\partial V_{2i}}{\partial E_{q_i}} f_{3i} = 0
\]

nonlinear system (2) with respect to the two output variables of the \( i \)th 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 simlar 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:

\[
\phi_i(x) = \begin{bmatrix}
h_{1i}(x) & L_{\rho}h_{1i}(x) & L_{\rho}h_{1i}(x) & h_{2i}(x) & L_{\rho}h_{2i}(x)
\end{bmatrix}
\]  

(24)

\[
Z = \phi(x) - \begin{bmatrix}
\phi_1(x) \\
\phi_2(x) \\
\phi_3(x) \\
\vdots \\
\phi_n(x)
\end{bmatrix}
\]  

(25)

The obtained affine linear system is follows:

\[
\dot{Z} = A \cdot Z + B \cdot V
\]  

(26)

where

\[
Z = \begin{bmatrix}
Z_{1i} & Z_{2i} & Z_{3i} & Z_{4i} & Z_{5i}
\end{bmatrix}
\]  

(27)

\[
Z_{1i} = \left[ Z_{1i} \quad Z_{2i} \quad Z_{3i} \quad Z_{4i} \quad Z_{5i} \right]
\]  

(28)

\[
V_{1} = [V_{11} \quad V_{21}]
\]  

(29)

\[
V = [V_{11} \ldots V_{1n} \ldots V_{an}]
\]  

(30)

\[
A = \text{diag}[A_1 \ldots A_n]
\]  

(31)

\[
B = \text{diag}[B_1 \ldots B_n]
\]  

(32)

\[
A_1 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]  

(33)

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

\[
\begin{bmatrix}
\dot{z}_1 \\
\dot{z}_2 \\
\dot{z}_3 \\
\dot{z}_4 \\
\dot{z}_5
\end{bmatrix} = \begin{bmatrix}
z_2 \\
z_3 - \alpha_1(x) + \sum_{j=1}^n \beta_{1j} \cdot U_j - \alpha_2(x) \cdot \beta_{12} \cdot U_G \\
z_4 = z_5 \\
z_5 = \alpha_2(x) + \sum_{j=1}^n \beta_{2j} \cdot U_j - \alpha_2(x) \cdot \beta_{21} \cdot U_f
\end{bmatrix}
\]  

(34)

where

\[
\alpha_1(x) = -\frac{\omega_0}{2H} - \frac{\omega_0}{2H} \frac{1}{E_{q_i}^0} + \frac{\omega_0}{2H} f_i(x)
\]  

(35)

\[
\alpha_2(x) = \frac{\partial b(x)}{\partial t} f_1 + \frac{\partial b(x)}{\partial t} f_2 + \frac{\partial b(x)}{\partial t} f_3 + \frac{\partial b(x)}{\partial t} f_4
\]  

(36)

\[
\beta_{12} = \frac{\omega_0}{2H} \frac{K_{\text{gi}}}{T_{\text{gi}}}
\]  

(37)

\[
\beta_{21} = \frac{\partial V_{1i}}{\partial E_{q_i}} \left( \frac{1}{T_{\text{el}}} - \frac{K_{\text{out}}}{T_{\text{el}}} - \beta_{21} \right)
\]  

(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 \( i \)th generator can be designed by the pole placement approach as follow:

\[
\begin{bmatrix}
V_{1} = k_1 z_1 + k_2 z_2 + k_3 z_3 = k_1 (\dot{z} - \delta) + k_3 (\theta - \omega_e) + k_3 \omega \\
V_{2} = k_4 z_4 + k_5 z_5 = k_4 (V_1 - V_{10}) + k_5 V_1
\end{bmatrix}
\]  

(39)

At last, the feedback linearizing control of the original nonlinear system (2) can be obtained:
\[
\begin{align*}
U_G &= (v_1 - \alpha_1(x))/\beta_{12} \\
U_1 &= (v_2 - \alpha_2(x))/\beta_{21}
\end{align*}
\] (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:

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

Where \( P_{mi} \) is the mechanical torque which is changed during and after the fault, \( V_i = V_i \angle \phi_i \) is the \( i \)th generator terminal voltage, \( V_j = V_j \angle \phi_j \) is the \( j \)th node voltage which is connected with \( i \)th generator terminal (it may be a generator terminal, or a load node), \( C_{ij} \) represents whether the \( i \)th node is connected with the \( j \)th node or not:

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

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

\[
V_j = V_j \angle \phi_j = V_i + I_{ij} Z_{ij}
\] (43)

where \( I_{ij} \) is the current from node \( i \) to node \( j \), \( Z_{ij} \) is the impedance of line \( ij \). 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 \( i \)th generator terminal voltage of the postfault equilibrium can be calculated easily from Eq. (41):

\[
\phi_{el} = \cos^{-1} \left( \frac{G_{ij} V_i^2 - P_{mi}}{\sqrt{\alpha^2 + \beta^2}} \right) + \arg(\alpha + j\beta)
\] (44)

Where,

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

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

In Eq.(44), \( P_{mi} \) is the real time mechanical power of the \( i \)th generator. Secondly, using the generator terminal voltage \( V_i \), the generator internal induced voltage \( E_i' \) and the machine impedance as a single line, the offset angle \( \Delta \phi_i \) between \( V_i \) and \( E_i' \) is calculated. At last, the observing rotor angle \( \delta_{el} \) of the \( i \)th generator in the postfault equilibrium can be calculated as following:
\[ \delta_{cl} = \phi_{cl} + \Delta \phi_{f} \] (47)

Replacing \( \delta_{cl} \) in Eq.(39) by the observing rotor angle \( \delta_{cl} \) of the generator in Eq.(47), the proposed Decentralized Feedback Linearizing Excitation and Governor Control with the Observation Algorithm of Postfault Equilibrium (DFLEEG/COAPE) 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](image)

5.1. Completely feedback linearizable condition \( \frac{\Delta V_{f}}{\Delta E_{f}} = 0 \)

From Eq.(23) we know, the original nonlinear system (2) can be completely feedback linearized if the condition \( \frac{\Delta V_{f}}{\Delta E_{f}} = 0 \) 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 \( \frac{\Delta V_{f}}{\Delta E_{f}} \) approaches closely to zero, the nonlinear control signal \( U_{f} \) will become very large, resulting in the excitation voltage \( E_{f} \) varying only between the upper and the lower limits of the controller, and then the power system tends to be unstable.

If we set \( \frac{\Delta V_{f}}{\Delta E_{f}} \) 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. \( \delta_{21} \)](image)

It can be seen from Fig. 3 that the performance of the nonlinear control has robustness to \( \frac{\Delta V_{f}}{\Delta E_{f}} \). We have the similar results when the same fault occurs at the generator terminal nodes. Setting \( \frac{\Delta V_{f}}{\Delta E_{f}} \) 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, \( \frac{\Delta V_{f}}{\Delta E_{f}} \) 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 (DFLEEG/COAPE), the control mode of this generator is represented by “1” or by the ordinary AVR/GOV.
(the control mode is "U"). 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 DFLEGCOAPE 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

<table>
<thead>
<tr>
<th>Case</th>
<th>Controllers</th>
<th>Case</th>
<th>Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>000</td>
<td>4</td>
<td>110</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>5</td>
<td>101</td>
</tr>
<tr>
<td>2</td>
<td>010</td>
<td>6</td>
<td>011</td>
</tr>
<tr>
<td>3</td>
<td>001</td>
<td>7</td>
<td>111</td>
</tr>
</tbody>
</table>

(1—DFLEGCOAPE, 0—AVR/GOV)

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 $E_{id}$ of G2

Fig. 9. Generator terminal voltage $V_i$ of G2
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 $\delta_2$ and the online observing rotor angle of the postfault equilibrium $\delta_{e2}$ (output of OAPE) are shown in Fig. 15.

![Figure 10: Mechanical Power Pm of G2](image)

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 DFLEG, 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 DFLEG) 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 DFLEG, G2 and G3 are not controlled by DFLEG, 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 DFLEG or DFLEG/COAPE 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 DFLEG/COAPE can further enlarge the stable operating region of the power system even comparing with the DFLEG. But it also has a problem that the left "zero dynamics" may be unstable, similar to the cases of DFLEG.

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

![Figure 11: $\delta_{21}$ with or without OAPE](image)

Fig. 11. $\delta_{21}$ with or without OAPE

![Figure 12: $V_{12}$ with or without OAPE](image)

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

![Figure 13: $E_{62}$ with or without OAPE](image)

Fig. 13. $E_{62}$ with or without OAPE
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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 (DFLEG) has some robustness to $\frac{\partial V_L}{\partial E_q}$ and $\frac{\partial V_L}{\partial E_q}$ can be set as constant.

2. The Decentralized Feedback Linearizing Excitation and Governor Control with Observation Algorithm of the Postfault Equilibrium (DFLEG/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 DFLEG are not applied on all of the generators.

3. The proposed DFLEG/OAPE can converge to the postfault new stable operating point quickly. In this sense, it can be said that the DFLEG/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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References:


**Appendix A.**

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

\[ γ = E_q I_d + E_q I_q + E_q E_q + \frac{D}{\partial q} \frac{\partial}{\partial q} \]  \hspace{1cm} (1-1)

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

\[ D_{q} = \frac{\partial I_d}{\partial E_q} \quad D_{q} = \frac{\partial I_q}{\partial E_q} \]  \hspace{1cm} (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 \( D_{q} \) and \( D_{q} \) 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:

\[ \frac{\partial D_{q}}{\partial \delta} = \frac{\partial I_d}{\partial E_q} \frac{\partial I_q}{\partial E_q} \]  \hspace{1cm} (1-3)

\[ \frac{\partial D_{q}}{\partial \delta} = \frac{\partial I_q}{\partial E_q} \]  \hspace{1cm} (1-4)

\[ \frac{\partial D_{q}}{\partial \delta} = 0 \]  \hspace{1cm} (1-5)

According to Eq. (22), \( b(x) = V_1 \) can be expressed in details as follows:

\[ b(x) = \frac{S_1(x) + S_2(x) S_3(x)}{V_1} \]  \hspace{1cm} (1-6)

where

\[ S_1(x) = \left( \frac{x_4^2}{v_1} - \frac{x_2}{v_1} \right) I_4 + \frac{x_4 E_q I_4}{v_1} \]  \hspace{1cm} (1-7)

\[ S_2(x) = \left( \frac{x_3^2}{v_1} - \frac{x_1}{v_1} \right) I_3 + \frac{x_3 E_q I_3}{v_1} \]  \hspace{1cm} (1-8)

\[ S_3(x) = \left[ -E_q - (x_d - x_\text{ref}) \right] I_d + E_q I_d \]  \hspace{1cm} (1-9)

Using Eqs. (1-1) to (1-6), \( \frac{\partial b(x)}{\partial \delta}, \frac{\partial b(x)}{\partial E_q} \) and \( \frac{\partial b(x)}{\partial E_q} \) in Eq. (36) can be calculated as follows:

\[ \frac{\partial b(x)}{\partial \delta} = -\frac{1}{V_1} \left[ \frac{x_2}{v_1} - \frac{x_1}{v_1} \right] I_4 + \frac{x_3 E_q I_3}{v_1} \]  \hspace{1cm} (1-10)

\[ \frac{\partial b(x)}{\partial E_q} = \frac{1}{V_1} \left[ \frac{x_3^2}{v_1} I_3 + \frac{E_q v_1}{v_1} - \frac{x_3 E_q I_3}{v_1} \right] \]  \hspace{1cm} (1-11)

\[ \frac{\partial b(x)}{\partial E_q} = \frac{1}{V_1} \left[ \frac{x_2^2}{v_1} I_2 + \frac{E_q v_1}{v_1} - \frac{x_2 E_q I_2}{v_1} \right] \]  \hspace{1cm} (1-12)

\[ \frac{\partial b(x)}{\partial E_q} = \frac{1}{V_1} \left[ \frac{x_1^2}{v_1} I_1 + \frac{E_q v_1}{v_1} - \frac{x_1 E_q I_1}{v_1} \right] \]  \hspace{1cm} (1-13)

where

\[ \frac{\partial S_1}{\partial \delta} = \left( \frac{x_2^2 - x_1^2} {v_1^2} \right) I_4 + \frac{x_2 E_q I_4}{v_1} \]  \hspace{1cm} (1-14)

\[ \frac{\partial S_2}{\partial \delta} = \left( \frac{x_3^2 - x_1^2} {v_1^2} \right) I_3 + \frac{x_3 E_q I_3}{v_1} \]  \hspace{1cm} (1-15)

\[ \frac{\partial S_3}{\partial \delta} = \left( x_d - x_\text{ref} \right) I_d \]  \hspace{1cm} (1-16)

\[ \frac{\partial V_1}{\partial \delta} = \frac{1}{V_1} \left[ \frac{x_2^2}{v_1^2} I_4 + \frac{(E_q - I_4) I_4}{v_1} \right] \]  \hspace{1cm} (1-17)

\[ \frac{\partial S_1}{\partial E_q} = \left( \frac{x_2^2}{v_1^2} I_4 + D_{q4} \right) \]  \hspace{1cm} (1-18)

\[ \frac{\partial S_2}{\partial E_q} = \left( \frac{x_3^2}{v_1^2} I_3 + D_{q3} \right) \]  \hspace{1cm} (1-19)

\[ \frac{\partial S_3}{\partial E_q} = \left( \frac{x_d^2}{v_1^2} I_d + 1 - 2 x_d I_d \right) \]  \hspace{1cm} (1-20)
\[
\frac{\partial V_i}{\partial E_q} = -\frac{1}{V_i} \left[ E_q x_q (E_q - I_q x_q) \right] \tag{1.21}
\]

**Appendix 2. System Data[9]**

1. Power flow: (p.u.)

<table>
<thead>
<tr>
<th>Node</th>
<th>P</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.716</td>
<td>0.270</td>
</tr>
<tr>
<td>2</td>
<td>1.630</td>
<td>0.067</td>
</tr>
<tr>
<td>3</td>
<td>0.850</td>
<td>-0.109</td>
</tr>
<tr>
<td>5</td>
<td>-1.250</td>
<td>-0.500</td>
</tr>
<tr>
<td>6</td>
<td>-0.900</td>
<td>-0.300</td>
</tr>
<tr>
<td>8</td>
<td>-1.000</td>
<td>-0.350</td>
</tr>
</tbody>
</table>

2. Generators:

<table>
<thead>
<tr>
<th></th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (GVA)</td>
<td>1.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>H(s)</td>
<td>50</td>
<td>9</td>
<td>6</td>
</tr>
</tbody>
</table>

3. Limiters:

AVR: \(0.0 \leq E_{ref} \leq 8.0\)

GOV: \(0.0 \leq P_{in} \leq 1.05P_{max}\)

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

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