ISTANBUL UNIVERSITY –
JOURNAL OF ELECTRICAL & ELECTRONICS ENGINEERING

YEAR : 2003 (917-925)
VOLUME : 3
NUMBER : 2

MULTI-OBJECTIVE NONLINEAR INTEGRATED CONTROL FOR TURBINE GENERATOR UNIT

Xiaocong LI[1], Shijie CHENG[2], *Senior Member, IEEE*, Hua WEI[3], and Jia MA[4]

[1,2,4]Department of Electrical Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.
[3]Department of Electrical Engineering, Guangxi University, Nanning 530004, China

[1]*Email: lhtlsj@263.net*

ABSTRACT

A novel scheme for design of multi-objective nonlinear control is proposed in this paper. With this scheme, the performance objective for various state variables of a control system can be coordinated satisfactorily in a unitary nonlinear control framework. Applying the proposed control scheme in the design of the turbogenerator integrated controller, a multi-objective nonlinear integrated controller for turbine generator units is proposed, in which the problem to coordinate the dynamic and steady-state integrated performances of various state variables is solved. Simulation results of using the proposed controller in a one-machine infinite-bus power system show that both the dynamic performances and the steady-state performance of the synchronous generator units are greatly improved. Both the generator terminal voltage and the generator active power output can still be kept at their setting values after a step disturbance. Also, the stability of the generator unit when subjected to the disturbances is greatly enhanced. The proposed controller is valuable for industrial application.

Keywords: *Multi-objective nonlinear control, excitation systems, generator terminal voltage performance, generator steady-state performances, power system stability.*

I. INTRODUCTION

Integrated generator control that combines excitation control and governor control represents a necessary trend of generator control strategies. In the past, due to the limitations of development of the control theories, these two main kinds of generator controls are designed and realized separately, let alone their coordination and integration. However, with the further development of the control theories, the integrated generator control is gaining more attention. Kinds of modern control theories has been introduced into the integrated generator control, such as the linear optimal control, the adaptive control, the variable structure control, the H_∞ robust control, the differential geometrical nonlinear control, the inverse system control, the ANN based control and the fuzzy logic control, etc. Among them, the nonlinear control strategies are in a very important position

Received Date : *31.10.2002*
Accepted Date: 02.06.2003

due to their noticeable effectiveness and perspicuous physical concepts.

Our research work shows that the choice of output functions will put a great influence on the performance indexes of the controlled system. In brief, an alteration of the state variables contained in the output functions or their computational combination will cause great change in the steady state and dynamic performances of the controlled system. To some extent, the output functions represent the control objectives. So it's very important to choose an output function properly in the design of a nonlinear controller, for it determines both the steady state and dynamical performances of the future controlled system. Otherwise a satisfactory nonlinear control law can't be deducted successfully.

Based on extensive researches on nonlinear control methods, the concept and realization approach of a novel multi-objective nonlinear control are presented in this paper. Of this method, in order to design a nonlinear control law applicable to practical system operations, the output functions of the nonlinear system are chosen as combinations of multiple state variables.

Applying the multi-objective nonlinear control method proposed in this paper to the design of the integrated control for turbine generators, a nonlinear integrated control law is found out successfully with the output functions of $y_1 = c_{11}\Delta U_f + c_{12}\Delta\omega$ and $y_2 = c_{21}\Delta P_e + c_{22}\Delta\omega + c_{23}\Delta\dot{\omega}$, which can solve the problem of the nonlinear integrated control for turbine generators effectively. Digital simulation results show that the proposed nonlinear control law can not only improve notably the dynamic stability of turbine generators but also control accurately the terminal voltage U_f and the active power output P_e of the generator, thus making them operate on their self set values without deviations caused by disturbances.

2. State feedback Linearization for MIMO Nonlinear Systems

Without losing generality, take a two-input two-output system for example. A MIMO nonlinear system can be described by the following state space equations:

$$
\begin{aligned}
&\dot{\mathbf{X}}(t) = \mathbf{f}(\mathbf{X}) + \mathbf{g}_1(\mathbf{X})u_1 + \mathbf{g}_2(\mathbf{X})u_2 \\
&y_1(t) = h_1(\mathbf{X}) \\
&y_2(t) = h_2(\mathbf{X})
\end{aligned}
\qquad (1)
$$

where $\mathbf{X}$ stands for an n-dimension state vector; $\mathbf{f}(\mathbf{X})$, $\mathbf{g}_1(\mathbf{X})$, $\mathbf{g}_2(\mathbf{X})$ are the n-dimension vector fields in the state space; u_1 and u_2 represent the control scalars; $h_1(\mathbf{X})$ and $h_2(\mathbf{X})$ are the scalar output functions; y_1 and y_2 are the output scalars.

According to the nonlinear control theories, if the relative degree of system (1) is $r = r_1 + r_2 < n$, but the vector field set $\{\mathbf{g}_1(\mathbf{X}), \mathbf{g}_2(\mathbf{X})\}$ is involutory, then the other n-r functions $\eta_1(\mathbf{X}), \cdots, \eta_{n-r}(\mathbf{X})$ can be found which will satisfy the following requirements: $L_{g_1}\eta_i(\mathbf{X}) = 0$, $L_{g_2}\eta_i(\mathbf{X}) = 0$, $i = 1, 2, \cdots, (n-r)$. Also, the following nonlinear coordinate transform can be chosen

$$
\mathbf{Z} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_{r_1} \\ z_{r_1+1} \\ z_{r_1+2} \\ \vdots \\ z_r \\ z_{r+1} \\ \vdots \\ z_n \end{bmatrix} = \begin{bmatrix} h_1(\mathbf{X}) \\ L_f h_1(\mathbf{X}) \\ \vdots \\ L_f^{r_1-1} h_1(\mathbf{X}) \\ h_2(\mathbf{X}) \\ L_f h_2(\mathbf{X}) \\ \vdots \\ L_f^{r_2-1} h_2(\mathbf{X}) \\ \eta_1(\mathbf{X}) \\ \vdots \\ \eta_{n-r}(\mathbf{X}) \end{bmatrix} = \begin{bmatrix} \varphi_1(\mathbf{X}) \\ \varphi_2(\mathbf{X}) \\ \vdots \\ \varphi_{r_1}(\mathbf{X}) \\ \phi_1(\mathbf{X}) \\ \phi_2(\mathbf{X}) \\ \vdots \\ \phi_{r_2}(\mathbf{X}) \\ \eta_1(\mathbf{X}) \\ \vdots \\ \eta_{n-r}(\mathbf{X}) \end{bmatrix} = \Phi(\mathbf{X}) \qquad (2)
$$

to transfer the nonlinear system (1) to the following standard form:

$$
\begin{aligned}
&\dot{z}_1 = z_2 \\
&\dot{z}_2 = z_3 \\
&\cdots\cdots \\
&\dot{z}_{r_1} = v_1 \\
&\dot{z}_{r_1+1} = z_{r_1+2} \\
&\dot{z}_{r_1+2} = z_{r_1+3} \\
&\cdots\cdots \\
&\dot{z}_r = v_2 \\
&\dot{z}_{r+1} = q_1(\mathbf{Z}) \\
&\cdots\cdots \\
&\dot{z}_n = q_{n-r}(\mathbf{Z}) \\
&y_1 = h_1(\Phi^{-1}(\mathbf{Z})) = z_1 \\
&y_2 = h_2(\Phi^{-1}(\mathbf{Z})) = z_{r_1+1}
\end{aligned}
\qquad (3)
$$

in which:

$$
\begin{aligned}
v_1 &= L_f^{r_1} h_1(\Phi^{-1}(\mathbf{Z})) + L_{g_1} L_f^{r_1-1} h_1(\Phi^{-1}(\mathbf{Z}))u_1 \\
&+ L_{g_2} L_f^{r_1-1} h_1(\Phi^{-1}(\mathbf{Z}))u_2 \\
v_2 &= L_f^{r_2} h_2(\Phi^{-1}(\mathbf{Z})) + L_{g_1} L_f^{r_2-1} h_2(\Phi^{-1}(\mathbf{Z}))u_1 \\
&+ L_{g_2} L_f^{r_2-1} h_2(\Phi^{-1}(\mathbf{Z}))u_2
\end{aligned} \tag{4}
$$

and

$$q_1(\mathbf{Z}) = L_f \eta_1(\Phi^{-1}(\mathbf{Z}))$$

……

$$q_{n-r}(\mathbf{Z}) = L_f \eta_{n-r}(\Phi^{-1}(\mathbf{Z}))$$

The necessary condition for the existence of the transform (2) is that the following Jacobian matrix is nonsingular in the neighborhood $\mathbf{X}^0$:

$$
\begin{aligned}
\mathbf{\Phi}(\mathbf{X}) = [&\varphi_1(\mathbf{X}),\cdots,\varphi_{r_1}(\mathbf{X}),\phi_1(\mathbf{X}),\cdots,\phi_{r_2}(\mathbf{X}), \\
&\eta_1(\mathbf{X}),\cdots,\eta_{n-r}(\mathbf{X})]^T
\end{aligned}.
$$

It can be seen from (3) that the system in the new coordinate space can be divided into two subsystems according to the state variables, a linear subsystem $\mathbf{Z}_{\mathrm{L}} = [z_1, \cdots, z_r]^T$ and a nonlinear subsystem $\mathbf{Z}_{\mathrm{NL}} = [z_{r+1}, \cdots, z_n]^T$.

The control variables $\mathbf{V} = [v_1, v_2]^T$ of the linear subsystem $\mathbf{Z}_{\mathrm{L}}$ in (3) can be determined by Linear Optimal Control (LOC) method as follow:

$$
\begin{aligned}
\mathbf{V} &= -\mathbf{R}^{-1}\mathbf{B}^{\mathbf{T}}\mathbf{P}\mathbf{Z}_{\mathrm{L}} = -\mathbf{K}\mathbf{Z}_{\mathrm{L}} \\
&= \begin{bmatrix} -k_{11}z_1 - k_{12}z_2 - \cdots - k_{1r}z_r \\ -k_{21}z_1 - k_{22}z_2 - \cdots - k_{2r}z_r \end{bmatrix}_{\mathbf{Z}=\Phi(\mathbf{X})}
\end{aligned} \tag{5}
$$

After v is obtained, the nonlinear optimal control law $\mathbf{U} = [u_1, u_2]^T$ can be calculated from (4) as follows:

$$\mathbf{U} = \overline{\mathrm{B}}(\mathbf{X})^{-1}\left[\mathbf{V} - \overline{\mathrm{A}}(\mathbf{X})\right] \tag{6}$$

where,

$$\overline{\mathbf{B}}(\mathbf{X}) = \begin{bmatrix} L_{g_1} L_f^{r_1-1} h_1(\mathbf{X}) & L_{g_2} L_f^{r_1-1} h_1(\mathbf{X}) \\ L_{g_1} L_f^{r_2-1} h_2(\mathbf{X}) & L_{g_2} L_f^{r_2-1} h_2(\mathbf{X}) \end{bmatrix}$$

$$\overline{\mathbf{A}}(\mathbf{X}) = \begin{bmatrix} L_f^{r_1} h_1(\mathbf{X}) \\ L_f^{r_2} h_2(\mathbf{X}) \end{bmatrix}$$

From (6), it can be concluded that the nonlinear control law has close relationship with the output function selected. Noticing that the state variables $\mathbf{Z}_{\mathrm{L}}$ of the linear subsystem of (3) is actually composed of the output variable and their corresponding derivatives, that is:

$$\mathbf{Z}_{L1} = \left[z_1, z_2 \cdots z_{r_1}\right]^T = \left[y_1, y_1^{(1)} \cdots y_1^{(r_1-1)}\right]^T \tag{7}$$

$$\mathbf{Z}_{L2} = \left[z_{r_1+1}, z_{r_1+2} \cdots z_r\right]^T = \left[y_2, y_2^{(1)} \cdots y_2^{(r_2-1)}\right]^T \tag{8}$$

As for the linear quadratic optimal regulator, the performance indexes selected is as follows:

$$
\begin{aligned}
J &= \frac{1}{2}\int_0^\infty (\mathbf{Z}_L^T\mathbf{Q}\mathbf{Z}_L + \mathbf{V}^T\mathbf{R}\mathbf{V})dt \\
&= \frac{1}{2}\int_0^\infty (\mathbf{Z}_{L1}^T\mathbf{Q}_1\mathbf{Z}_{L1} + \mathbf{Z}_{L2}^T\mathbf{Q}_2\mathbf{Z}_{L2} + \mathbf{V}^T\mathbf{R}\mathbf{V})dt
\end{aligned} \tag{9}
$$

in which: $\mathbf{Q}_1$ and $\mathbf{Q}_2$ is a positive definite or positive semi-definite weight matrix of $r_1 \times r_1$ orders and $r_2 \times r_2$ orders. **R** is a positive definite weight matrix of 2×2, and $\mathbf{Q} = diag[\mathbf{Q}_1 \quad \mathbf{Q}_2]$.

It can be inferred from above discussion that those state variables selected in the output function and their derivatives will be represented in the transformed linear subsystem (3), and then can also be represented in the quadratic performance index (9) and in the linear control low (5). Thus, the dynamic behavior of those state variables would be directly restricted. In this sense, the output function embodies the performance indexes requirement for the nonlinear controller. The state variables selected in the output function can be treated as the control objectives and they will be directly controlled in the closed-loop system.

Since in the design of nonlinear controller, the dimensions of the output variables are often required to be the same as those of the input variables, thus the dimensions of the output variables are limited. In this condition, if the output functions are chosen as a single state variable function, then the performance requirements of only few variables can be put forward in (9). However, in the past nonlinear controller designs of the power system, it was used to choosing an output function consisted of only one state variable, that is:

$$y(t) = x_i$$

Thus the derived linear control law $\mathbf{V}$ contains the feedback information of only this state variable x_i and its derivatives of corresponding orders. It can be easily known that this control law is not a full state feedback control law. And under such a control law, it would be very difficult to coordinate comprehensively both the static and dynamic state performance indexes of all the state variables of the whole system.

According to the analysis given above, this paper proposes that, the output functions should be selected as the combination of multiple state variables, such as:

$$y_1 = [c_{11}, c_{12}, \cdots, c_{1n}]\mathbf{X} = \mathbf{c}_1\mathbf{X} \tag{10}$$

$$y_2 = [c_{21}, c_{22}, \cdots, c_{2n}]\mathbf{X} = \mathbf{c}_2\mathbf{X} \tag{11}$$

then in the transformed linear subsystem, the state variables are(substituting (10) and (11) into (7) and (8):

$$\begin{aligned} z_i &= y_1^{(i-1)} = [c_{11}, c_{12}, \cdots, c_{1n}]\mathbf{X}^{(i-1)}, \quad i = 1, \cdots, r_1 \\ z_j &= y_2^{(j-r_1-1)} = [c_{21}, c_{22}, \cdots, c_{2n}]\mathbf{X}^{(j-r_1-1)}, \ j = r_1+1, \cdots, r \end{aligned} \tag{12}$$

The above formula can be written in matrix form as:

$$\begin{aligned} \mathbf{Z}_{L1} &= \mathbf{C}_1\mathbf{X}_{r_1} \\ \mathbf{Z}_{L2} &= \mathbf{C}_2\mathbf{X}_{r_2} \end{aligned} \tag{13}$$

in which: $\mathbf{Z}_{L1} = [z_1 \cdots z_{r_1}]^T$, $\mathbf{Z}_{L2} = [z_{r_1+1} \cdots z_r]^T$,

$$\mathbf{X}_i = \left[\mathbf{X}^T, \mathbf{X}^{(1)^T}, \cdots, \mathbf{X}^{(i-1)^T}\right]^T$$

and $\mathbf{C}_1 = diag(\underbrace{\mathbf{c}_1, \mathbf{c}_1, \cdots, \mathbf{c}_1}_{r_1})$, $r_1 \times (r_1 \times n) order$,

$\mathbf{C}_2 = diag(\underbrace{\mathbf{c}_2, \mathbf{c}_2, \cdots, \mathbf{c}_2}_{r_2})$, $r_2 \times (r_2 \times n) order$,

So the performance indexes shown in (9) has the following form in the original nonlinear system (1):

$$\begin{aligned} J &= \frac{1}{2}\int_0^{\infty} (\mathbf{Z}_L^T\mathbf{Q}\mathbf{Z}_L + \mathbf{V}^T\mathbf{R}\mathbf{V})dt \\ &= \frac{1}{2}\int_0^{\infty} (\mathbf{Z}_{L1}^T\mathbf{Q}_1\mathbf{Z}_{L1} + \mathbf{Z}_{L2}^T\mathbf{Q}_2\mathbf{Z}_{L2} + \mathbf{V}^T\mathbf{R}\mathbf{V})dt \\ &= \frac{1}{2}\int_0^{\infty} (\mathbf{X}_{r_1}^T\mathbf{C}_1^T\mathbf{Q}_1\mathbf{C}_1\mathbf{X}_{r_1} + \mathbf{X}_{r_2}^T\mathbf{C}_2^T\mathbf{Q}_2\mathbf{C}_2\mathbf{X}_{r_2} + \mathbf{V}^T\mathbf{R}\mathbf{V})dt \end{aligned} \tag{14}$$

Formula (14) manifests the control performance indexes requirement for the state variables of the original system, when selecting the output function as (10) and (11). And it shows the relationship between the performance indexes of the systems under the linear and nonlinear coordinates.

3. Multi-Objective Nonlinear Integrated Control for Turbine Generator Unit

For a single turbine generator connected to an infinite bus power system, the active power output of the generator unit is greater than 30% of its rating load. In this case, only the control of the high-pressure regulation valve is considered. The state space equation of the system can be represented as follows:

$$\begin{bmatrix} \dot{E}_q' \\ \dot{\delta} \\ \dot{\omega} \\ \dot{P}_H \end{bmatrix} = \begin{bmatrix} -E_q / T_{d0}' \\ \omega - \omega_0 \\ \frac{\omega_0}{T_j}(P_H + C_{ML}P_{m0} - P_e) - \frac{D}{T_j}\Delta\omega \\ (-P_H + C_H P_{m0}) / T_{H\Sigma} \end{bmatrix} + \begin{bmatrix} \frac{1}{T_{d0}'} \\ 0 \\ 0 \\ 0 \end{bmatrix} E_{qe} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{C_H}{T_{H\Sigma}} \end{bmatrix} U_H \tag{15}$$

Where, E_q' , δ , ω and P_H are the state variables. They represent the transient internal voltage, the rotor angle, the rotor angular speed and the high-pressure turbine input mechanical power of generator respectively. E_{qe} and U_H are the control variables. They represent the excitation voltage of the generator and the high-pressure regulation valve opening control signal of the high-pressure turbine respectively.

As illustrated previously, the key problem in design of a multi-objective nonlinear control lies on the appropriate selection of state variables contained in the system output functions and their combinations. In the present application, selection of the system output functions can be briefly mentioned as follows. For the first output function $h_1(\mathbf{X})$, as this output function mainly corresponds to the excitation control E_{qe}, obviously the deviation of the generator terminal voltage ΔU_f should be chosen as a part of the output function. Considering the fact that the excitation control can also be used to improve the power system stability, the deviation of the rotor angular speed $\Delta\omega$ is also selected. For the second output function $h_2(\mathbf{X})$, as this output function mainly corresponds to the valve opening control U_H, thus the deviation of the rotor angular speed $\Delta\omega$ must be selected. Further more, in order to improve the dynamic characteristic of a mechanical rotating system, the rotor angular acceleration $\Delta\dot{\omega}$ is commonly used as a feedback variable. This variable is also selected. In addition to this, control of the generator active power output is another main objective of the governor control, so the deviation of the active power output ΔP_e is also selected. The overall representation of the two output function $h_1(\mathbf{X})$ and $h_2(\mathbf{X})$ are given below.

$$\begin{aligned} y_1 &= h_1(\mathbf{X}) = c_{11}\Delta U_f + c_{12}\Delta\omega \\ y_2 &= h_2(\mathbf{X}) = c_{21}\Delta P_e + c_{22}\Delta\omega + c_{23}\Delta\dot{\omega} \end{aligned} \tag{16}$$

where, $h_1(\mathbf{X})$ and $h_2(\mathbf{X})$ are the output functions. y_1 and y_2 are the output variables.

Therefore, the system (15) and (16) can be represented in the following compact form:

$$\begin{aligned}&\dot{\mathbf{X}} = \mathbf{f}(\mathbf{X}) + \mathbf{g}_1(\mathbf{X})u_1 + \mathbf{g}_2(\mathbf{X})u_2\\ &y_1 = h_1(\mathbf{X})\\ &y_2 = h_2(\mathbf{X})\end{aligned} \quad (17)$$

where, $\mathbf{X} = [E_q', \delta, \omega, P_H]^T$, $u_1 = E_{qe}$, $u_2 = U_H$,

$$\mathbf{g}_1(\mathbf{X}) = [1/T_{d0}',\ 0\ ,\ 0\ ,\ 0]^T$$

$$\mathbf{g}_2(\mathbf{X}) = [0,0,0,C_H/T_{H\Sigma}]^T$$

$$\mathbf{f}(\mathbf{X}) = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} = \begin{bmatrix} -E_q/T_{d0}' \\ \omega - \omega_0 \\ (\omega_0(P_H + C_{ML}P_{m0} - P_e) - D\Delta\omega)/T_j \\ (-P_H + C_H P_{m0})/T_{H\Sigma} \end{bmatrix}$$

$$h_1(\mathbf{X}) = c_{11}\Delta U_f + c_{12}\Delta\omega$$

$$h_2(\mathbf{X}) = c_{21}\Delta Pe + c_{22}\Delta\omega + c_{23}\Delta\dot{\omega}$$

For system (15), as

$$\overline{\mathbf{B}}(\mathbf{X}) = \begin{bmatrix} L_{g_1}L_f^0 h_1(\mathbf{X}) & L_{g_2}L_f^0 h_1(\mathbf{X}) \\ L_{g_1}L_f^0 h_2(\mathbf{X}) & L_{g_2}L_f^0 h_2(\mathbf{X}) \end{bmatrix}$$

$$= \begin{bmatrix} \dfrac{c_{11}U_{fq}x_e}{U_f x_{d\Sigma}' T_{d0}'} & 0 \\ (c_{21} - \dfrac{c_{23}\omega_0}{T_j})\dfrac{U\sin\delta}{x_{d\Sigma}' T_{d0}'} & \dfrac{c_{23}\omega_0 C_H}{T_j T_{H\Sigma}} \end{bmatrix}$$

is nonsingular, the child relative degree of system (15) corresponding to $h_1(\mathbf{X})$ is r_1=1, and that corresponding to $h_2(\mathbf{X})$ is r_2=1. Therefore, the total relative degree of the system is $r = r_1 + r_2 = 1 + 1 = 2$.

Furthermore, because

$$rank[\mathbf{g}_1(\mathbf{X}) \quad \mathbf{g}_2(\mathbf{X})] = \begin{bmatrix} 1/T_{d0}' & 0 & 0 & 0 \\ 0 & 0 & 0 & C_H/T_{H\Sigma} \end{bmatrix}^T = 2$$

and the Lie Bracket of $\mathbf{g}_2$ to $\mathbf{g}_1$ is:

$$ad_{\mathbf{g}_1}\mathbf{g}_2 = \frac{\partial \mathbf{g}_2}{\partial \mathbf{X}}\mathbf{g}_1 - \frac{\partial \mathbf{g}_1}{\partial \mathbf{X}}\mathbf{g}_2 = [0 \quad 0 \quad 0 \quad 0]^T,$$

then the rank of the augmented matrix $[\mathbf{g}_1, \mathbf{g}_2, ad_{\mathbf{g}_1}\mathbf{g}_2]$ can be calculated as:

$$rank[\mathbf{g}_1, \mathbf{g}_2, ad_{\mathbf{g}_1}\mathbf{g}_2] = rank\begin{bmatrix} 1/T_{d0}' & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & C_H/T_{H\Sigma} & 0 \end{bmatrix} = 2$$

It can be concluded from the above deduction that the set of the vector fields $\{\mathbf{g}_1(\mathbf{X}), \mathbf{g}_2(\mathbf{X})\}$ is involutory. Therefore, two functions $\eta_1(\mathbf{X})$ and $\eta_2(\mathbf{X})$ satisfying the conditions $L_{g_1}\eta_i(\mathbf{X}) = 0$, $L_{g_2}\eta_i(\mathbf{X}) = 0$, $i = 1,2$ can be found. As

$$L_{g_1}\Delta\delta = L_{g_1}(\delta - \delta_0) = 0\ ,\ L_{g_2}\Delta\delta = L_{g_2}(\delta - \delta_0) = 0$$

$$L_{g_1}\Delta\omega = L_{g_1}(\omega - \omega_0) = 0, L_{g_2}\Delta\omega = L_{g_2}(\omega - \omega_0) = 0$$

then $\Delta\delta$ and $\Delta\omega$ can be selected as the functions $\eta_1(\mathbf{X})$ and $\eta_2(\mathbf{X})$. By doing this, the nonlinear coordinate transform can be found as:

$$\mathbf{Z} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} c_{11}\Delta U_f + c_{12}\Delta\omega \\ c_{21}\Delta P_e + c_{22}\Delta\omega + c_{23}\Delta\dot{\omega} \\ \Delta\delta \\ \Delta\omega \end{bmatrix} = \begin{bmatrix} h_1(\mathbf{X}) \\ h_2(\mathbf{X}) \\ \eta_1(\mathbf{X} \\ \eta_2(\mathbf{X}) \end{bmatrix} = \mathbf{\Phi}(\mathbf{X}) \quad (18)$$

It can be found from the following equation that the Jacobian matrix of (18) is nonsingular.

$$\det(J_\Phi) = \det(\partial\Phi\ (\mathbf{X})/\partial\mathbf{X}) =$$

$$\begin{vmatrix} c_{11}A_1 & c_{11}A_3 & c_{12} & 0 \\ (c_{21} - c_{23}\dfrac{\omega_0}{T_j})A_2 & (c_{21} - c_{23}\dfrac{\omega_0}{T_j})A_4 & (c_{22} - c_{23}\dfrac{D}{T_j}) & c_{23}\dfrac{\omega_0}{T_j} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{vmatrix}$$

$$= c_{11}A_1(c_{23}\frac{\omega_0}{T_j}) \neq 0$$

where, $A_1 = \dfrac{U_{fq}x_e}{U_f x_{d\Sigma}'}$, $A_2 = \dfrac{U}{x_{d\Sigma}'}\sin\delta$,

$$A_3 = (-\frac{U_{fq}x_d'}{U_f x_{d\Sigma}'}U\sin\delta + \frac{U_{fd}x_q}{U_f x_{q\Sigma}}U\cos\delta)$$

$$A_4 = (\frac{E_q'U}{x_{d\Sigma}'}\cos\delta + \frac{x_{d\Sigma}' - x_{q\Sigma}}{x_{d\Sigma}' x_{q\Sigma}}U^2\cos 2\delta)$$

The aforementioned deduction indicates that (18) is a local diffeomorphism between the state spaces of $[E_q', \delta, \omega, P_H]^T$ and $[z_1, z_2, z_3, z_4]^T$. Using (18), system (15) can be transformed into the following equations (Notice, because of too complex, the state variables of original state space are not all substituted with that of **Z** state space):

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ z_4 \\ (z_2 - c_{21}\Delta P_e - z_4)/c_{23} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \quad (19)$$

For the nonlinear system (15), the multi-objective nonlinear integrated control can be finally concluded from (5) and (6).

In system (19), whether the system is asymptotically stable lies on whether the zero dynamics constituted by z_3 and z_4 are asymptotically stable. To examine the stability of the zero dynamics, the zero dynamic system formulas are deduced as (20).

$$\begin{aligned} &\dot{z}_3 = z_4 \\ &\dot{z}_4 = -c_{21}\left[\left(\sqrt{\left(\frac{-c_{12}z_4}{c_{11}} + U_{f0}\right)^2 - \left(\frac{x_q}{x_{q\Sigma}}U\sin(z_3+\delta_0)\right)^2} \right.\right. \\ &\quad \left. - \frac{x'_d}{x'_{d\Sigma}}U\cos(z_3+\delta_0)\right)\frac{U}{x_e}\sin(z_3+\delta_0) \\ &\quad \left. + \frac{x'_{d\Sigma}-x_{q\Sigma}}{2x'_{d\Sigma}x_{q\Sigma}}U^2\sin 2(z_3+\delta_0) - P_{e0}\right] - c_{22}z_4 \end{aligned} \tag{20}$$

From (20), we can see that it is too difficult to find the Lyapunov function. But with phase-plane method, the phase-plane diagram of the zero dynamics can be plot as Fig.1. It shows that the zero dynamics are local asymptotically stable.

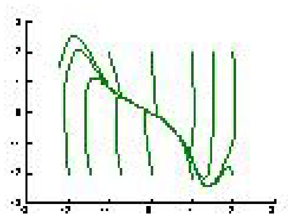

Fig.1 The phase-plane diagram of the zero dynamics

4. Simulation Results and Discussions

In order to verify the effectiveness of the multi-objective control proposed in this paper, simulations of the aforementioned system subjected to the different kinds of disturbances are carried out. The parameters of the system are as follows:

$x_d = 2.12$, $x_q = 2.12$, $x'_d = 0.26$, $x_e = 0.24$, $D = 2$, $T_j = 4.06$, $T'_{d0} = 5.8$, $C_H = 0.3$, $C_{ML} = 0.7$, $T_{H\Sigma} = 0.4$.

The following three kinds of disturbances are considered in the paper:

a. The disturbance caused by the change in the input mechanical power P_m of the generator;

b. The disturbance caused by the change in the input excitation voltage E_{qe} of the generator;

c. The disturbance caused by the change in the boundary conditions of the generator.

The first two kinds of disturbances are mainly used to examine the steady state performance of the controlled system when it is subjected to the disturbances. The third kind of disturbance is mainly used to test the dynamic performances of the closed-loop system.

4.1 A 20% Step Increase of the Setting Value of the Active power output

In this case, the system is subjected to a 20% step increase in the setting value of the active power output. The responses of the variables ΔPe , ΔU_f , $\Delta\delta$ and E_{qe} are shown in Fig.2 to Fig.5 respectively, which are marked with "1".

It can be seen from Fig.2 that the active power output of the generator can track the variation of the setting value rapidly.

Fig.3 indicates that although there is a small deviation of the terminal voltage at the beginning of the disturbance, it is soon forced back to the original operation value by the controller. No steady state deviation is found.

Fig.4 indicates that the response characteristic of the rotor angle is also very satisfactory. With an increase in the active power output, the rotor angle of the generator also increases.

Fig.5 shows that with the increasing of the active power output, the excitation voltage increases correspondingly, so as to meet the requirement of both an increasing active power output and a constant terminal voltage.

4.2 A 5% Step Increase in the Setting Value of the Terminal Voltage

In this case, the system is subjected to a 5% step increase in the setting value of the terminal voltage. The responses of the variables ΔPe , ΔU_f , $\Delta\delta$ and E_{qe} are shown in Fig.2 to Fig.5 respectively, which are marked with "2".

Fig.2 shows that in this case the active power output in the steady state will not be disturbed from the given operation value by the voltage regulation.

Fig.3 indicates that the terminal voltage can also follow the regulation requirement to the new setting value.

Fig.4 indicates that with the increasing of the terminal voltage, the rotor angle of the generator will decrease. The reason is that in order to remain the active power output constant, increasing the terminal voltage will strengthen the electromagnetic relations between the stator and the rotor. This results in the rotor angle decrease.

Fig. 5 shows that increasing of the terminal voltage requires the increase of the excitation voltage accordingly.

The simulation results also show that the proposed control scheme integrates two kinds of generator control very well. Both the terminal voltage and the active power output are precisely controlled as desired. The influence of generator terminal voltage regulation on its active power output and the influence of the generator active power output regulation on its terminal voltage are investigated. No conflict is found from the simulation results.

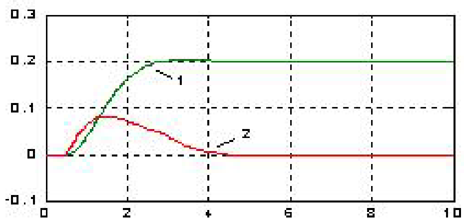

Fig.2 Simulation results of active power output

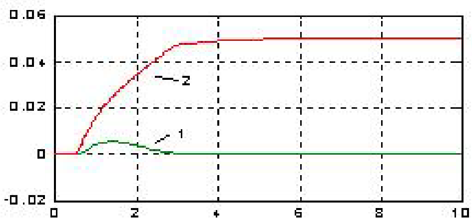

Fig.3 Simulation results of terminal voltage

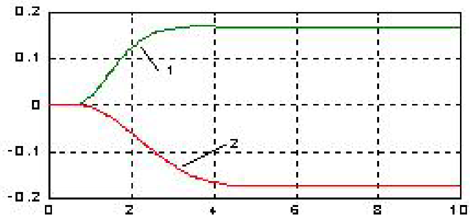

Fig.4 Simulation results of power angle

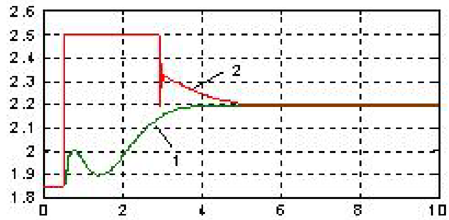

Fig.5 Simulation results of excitation voltage

4.3 A Three-Phase Short-Circuit

In this case, a 0.2 second three-phase short-circuit happens at the high-voltage side of the step-up transformer of the generator. The circuit is reclosed successful after the fault is cleared. The dynamic responses of the state variables $U_f, P_e, \Delta\omega, \delta$ and the control variables E_{qe}, P_m are shown in Fig.6 to Fig.9.

Fig.6 and Fig.7 show that the terminal voltage and the active power output recover soon after the fault is cleared. Fig.8 indicates that the proposed controller can damp out the mechanical oscillation of the generator unit effectively. Fig.9 gives the change of the excitation voltage and the input mechanical power during the transient procedure.In the simulation, the lower and the upper limits for the excitation voltage are set at -2.5 and 2.5 respectively, and those for the input mechanical power are set at 0 and 1 respectively.

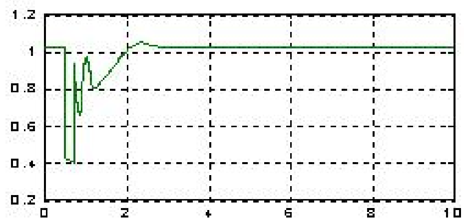

Fig.6 Simulation result of terminal voltage to a three phase fault

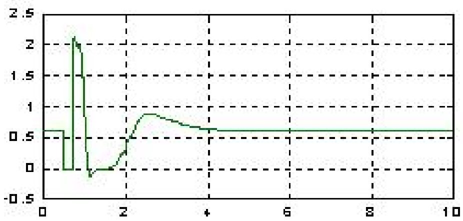

Fig.7 Simulation result of active power output to a three phase fault

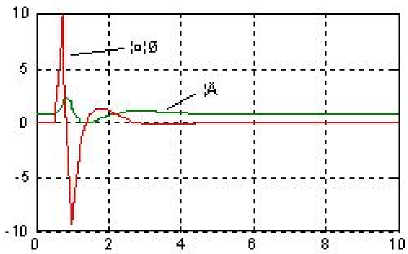

Fig.8 Simulation results of angular velocity and power angle to a three phase fault

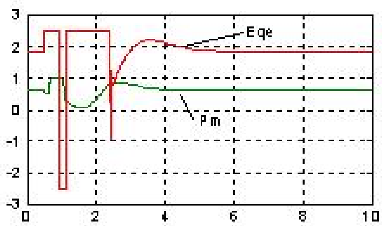

Fig.9 Simulation results of excitation voltage and input mechanical power to a three phase fault

CONCLUSIONS

The research of this paper indicates that, in designing a nonlinear controller, selection of the output functions will greatly influence the performances of the controlled system. Changing of the state variables contained in the output functions and their combination will alter the performance of the system. Based on this idea, a kind of multi-objective nonlinear control and its design method are proposed. In the proposed control, satisfactory performance of the closed-loop system can be obtained by appropriate selection of multiple state variables contained in the output functions. Applying the proposed control into the turbine generator unit, a nonlinear integrated control is proposed. Simulation results of applying the proposed control in a single-machine-infinite-bus power system show that the control integrates two kinds of generator control very well. Both the terminal voltage and the active power output are precisely controlled as desired. In addition to this, the dynamic performance of the generator is extensively improved, which results in an enhancement of the system stability. The nonlinear control for turbine generator presented in this paper is of great potential in practical industrial application.

Acknowledgements

This work was supported by the Chinese National Key Basic Research Special Foundation (Grant G1998020319), the Project Fund (Grant PD9521907) and in part by the Natural Science Foundation of Guangxi, China (Grant T98101).

References

1. [1] Tarek Lahdhiri, Ali T. Alouani, "Nonlinear excitation control of a single machine infinite-bus power system," IEEE, Proceedings of the Twenty-Seventh Southeastern Symposium on System Theory, pp. 61-65, 1995.
2. [2] Dulpichet Rerkpreedapong and Ali Feliachi, "Decentralized control of nonlinear electric power systems thru. excitation and governor systems using local measurements and feedback linearization," Proceedings of the 43rd IEEE Midwest Symposium on Circuits and Systems, Vol. 2, pp. 626-629, 2000.
3. [3] Xin Zhang and Jin Jiang, "Nonlinear excitation control in electrical power systems," IEEE Canadian Conference on Electrical and Computer Engineering, Vol.1, pp. 229-232, 1998.
4. [4] D. Cheng, T. J. Tan, A. Isidori, "Global Linearization of nonlinear systems via feedback," IEEE Trans. On AC, Vol. 30, No. 8, pp808-811, 1985.
5. [5] Q. Lu, Y. Z. Sun, Z. Xu, T. Mochizuki, "Decentralized Nonlinear Optimal Excitation Control," IEEE Transactions on Power Systems, Vol.11, No.4, pp. 1957-1962, Nov. 1996.
6. [6] Qiang Lu, Shengwei Mei, Wei Hu, Felix F. Wu, Yixin Ni, Tielong Shen, "Nonlinear Decentralized Disturbance Attenuation Excitation Control via New Recursive Design for Multi-Machine Power Systems," IEEE Transactions on Power Systems, Vol. 16, No. 4, pp. 729-736, Nov. 2001.

Biographies

Xiaocong Li received his B.S. degree from Kunming University of Science and Technology, China, in 1982, and his M.S. degree from Wuhan University of Hydraulic and Electrical Engineering, China, in 1992, all in electrical engineering. He is an associate professor, working in Dept. of Electrical Engineering of Guangxi University, China. Now, as a doctor candidate, he studies in Huazhong University of Science and Technology, Wuhan, China.

Shijie Cheng (M'1986, SM'1987) graduated from the Xi'an Jiaotong University, Xi'an, China in 1967 and received his Master of Engineering Degree from the HUST, Wuhan, China in 1981 and his Ph.D. from the University of Calgary, Calgary, Canada in 1986, all in the Electrical Engineering. He is now a full professor at the HUST. His research interests are power system control, stability analysis of power system and application of AI in power systems.