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RESEARCH ARTICLE

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Observational linearization and tracking objective excitation control strategy based on phasor measurement unit

Abstract To improve the transient stability of multimachine power systems, observational linearization and tracking objective excitation control laws were derived from the phasor measurement unit (PMU), observational linearization, and tracking objective control theory based on synchronized coordinates and reference generator coordinates. The control strategies utilized real-time state variables obtained by PMU to linearize the state equations of the system, and then the linear optimal control strategy was used to design excitation controllers. The inaccuracy of the local linearization method and the complexity of the system models designed in the exact linearization method for nonlinear systems were avoided. Therefore, the control strategies were applied in real time. Simulation results show that the proposed method can improve the transient stability of power systems more efficiently than nonlinear optimal excitation control.

Keywords PMU, nonlinear optimal excitation control, observational linearization, tracking objective control

1 Introduction

Since the introduction of the global positioning system (GPS) and the phasor measurement unit (PMU), generator rotor angles and bus voltage phasors could be monitored and measured in real time with precision GPS-synchronized clock as synchronized signals. The actual operation states of the whole power networks could also be observed. Therefore, PMU provides a key measurement means for safe and stable operation of power networks [1–4].

The state equations of generators were local-linearized in a working point in the design of traditional nonlinear excitation controllers. But the control effects can become worse and wrong control might be produced when power systems subjected to a severe disturbance make the operation point change greatly or deviate from the selected working point. The nonlinear excitation controller designed by the exact linearization method can avoid these problems, but the system models in this method are complex; so, there are some problems of application in real time [5,6]. Reference [7] studied nonlinear excitation control based on the wide-area measurement technique; some global information was introduced in the nonlinear control strategy, and so, the performance of nonlinear excitation control was improved.

The basic principle of observational linearization and tracking objective control theory is tracking the nonlinear movement trajectory of a system and controlling system state approaching the postfault steady-state region based on linearization at an observational point [7]. The nonlinear characteristics of the system are considered in this control strategy. The nonlinear quantities in the system models are computed in terms of wide-area observational quantities measured by PMU. So the inaccuracy of the local linearization method and the complexity of the system models designed in the exact linearization method in nonlinear control are avoided, and closed loop feedback is formed. Therefore, the control strategy is applied in real time. Reference [8] studied the excitation control strategy of a single-machine infinite-bus system based on observational linearization and tracking objective control theory, and Ref. [9] designed a high voltage direct current (HVDC) supplementary controller according to observational linearization and tracking objective control theory. Both obtained better results.

Observational linearization and tracking objective control theory based on PMU were introduced in the nonlinear excitation control of multimachine power systems in two different coordinates. A new excitation control strategy of multimachine power systems based on PMU was proposed in this paper. Firstly, the system models for nonlinear excitation control in two different coordinates were founded. Then, the nonlinear excitation control strategies of multimachine power systems in two different coordinates based on PMU were designed according to observational linearization and tracking objective control theory. Finally, the control strategies

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were realized on a three-machine nine-bus system by power system analysis software package (PSASP) of Electric Power Research Institute in China (EPRI). Simulation results demonstrated that the control strategies could improve dynamic characteristics and enhance the transient stability of power systems effectively.

2 Observational linearization and tracking objective control theory based on phasor measurement unit

In observational linearization and tracking objective control theory, the quantities with nonlinear characteristics in the system state equation are transformed to high-precision constants, which are updated in real time by PMU online measurement and computation continuously. Consequently, the system state equation is linearized. On this basis, control laws are designed for the linear state equation.

The state equation and the output equation of a nonlinear system are

$$\dot{\boldsymbol{X}}(t)=\boldsymbol{f}\left[\boldsymbol{X}(t),\ \boldsymbol{u}(t)\right] \tag{1}$$

$$\boldsymbol{y}(t)=\boldsymbol{h}\left[\boldsymbol{X}(t)\right] \tag{2}$$

where $\boldsymbol{f}$ and $\boldsymbol{h}$ both are nonlinear functions.

Suppose at some equilibrium point $\boldsymbol{X}_0$, we have

$$\boldsymbol{X}(t)=\boldsymbol{X}_0+\boldsymbol{x}(t),\ \ \boldsymbol{f}(\boldsymbol{X}_0,0)=0 \tag{3}$$

where $\boldsymbol{x}(t)$ is the excursion to stable equilibrium point. Hence

$$\begin{aligned}\dot{\boldsymbol{x}}(t)&=\boldsymbol{A}\boldsymbol{x}(t)+\boldsymbol{B}\boldsymbol{u}(t)+\boldsymbol{f}\left[\boldsymbol{X}_0+\boldsymbol{x}(t),\ \boldsymbol{u}(t)\right]-\boldsymbol{A}\boldsymbol{x}(t)-\boldsymbol{B}\boldsymbol{u}(t)\\&=\boldsymbol{A}\boldsymbol{x}(t)+\boldsymbol{B}\boldsymbol{u}(t)+\boldsymbol{r}(t)\end{aligned} \tag{4}$$

$$\boldsymbol{y}(t)=\boldsymbol{C}\boldsymbol{x}(t)+\boldsymbol{h}\left[\boldsymbol{X}_0+\boldsymbol{x}(t)\right]-\boldsymbol{C}\boldsymbol{x}(t)=\boldsymbol{C}\boldsymbol{x}(t)+\boldsymbol{s}(t) \tag{5}$$

where $\boldsymbol{r}(t)=\boldsymbol{f}\left[\boldsymbol{X}_0+\boldsymbol{x}(t),\boldsymbol{u}(t)\right]-\boldsymbol{A}\boldsymbol{x}(t)-\boldsymbol{B}\boldsymbol{u}(t)$

$$\boldsymbol{s}(t)=\boldsymbol{h}\left[\boldsymbol{X}_0+\boldsymbol{x}(t)\right]-\boldsymbol{C}\boldsymbol{x}(t)$$

In the equations above, $\boldsymbol{x}(t)$ is the vector of state variables, $\boldsymbol{u}(t)$ is the vector of control variables, $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are coefficient matrices, and $\boldsymbol{r}(t)$ and $\boldsymbol{s}(t)$ are nonlinear quantities.

Because voltage magnitudes and angles of the buses can be measured directly by PMU, a synchronous operation state of power networks with high precision can be obtained and nonlinear quantities $\boldsymbol{r}(t)$ and $\boldsymbol{s}(t)$ can be obtained by computing in terms of the observational quantities measured by PMU. In this way, this control problem is transformed to the tracking problem in linear optimal control, which looks for tracking control $\boldsymbol{u}(t)$ to make output $\boldsymbol{y}(t)$ approach the expected output $\boldsymbol{y}_d(t)$. Thus, the nonlinear state equation of the system is linearized, and the linear optimal control theory can be used to design the controller.

To minimize the errors of state variables and input variables with respect to their expected values, the quadratic performance index is selected as follows

$$\begin{aligned}\boldsymbol{J}(\boldsymbol{u})=&\frac{1}{2}\left[\boldsymbol{e}^{\mathrm{T}}(t_f)\boldsymbol{F}\boldsymbol{e}(t_f)\right]\\&+\frac{1}{2}\int_{t_0}^{t_\mathrm{f}}\left[\boldsymbol{e}^{\mathrm{T}}(t)\boldsymbol{Q}\boldsymbol{e}(t)+\boldsymbol{u}^{\mathrm{T}}(t)\boldsymbol{R}\boldsymbol{u}(t)\right]\mathrm{d}t\end{aligned} \tag{6}$$

Here, $\boldsymbol{J}(\boldsymbol{u})$ is the aim function, $\boldsymbol{e}(t)=\boldsymbol{y}(t)-\boldsymbol{y}_\mathrm{d}(t)$ is the error vector, $\boldsymbol{F}$ is a symmetric non-negative definite constant matrix, $\boldsymbol{Q}$ and $\boldsymbol{R}$ are non-negative definite and positive definite matrices, respectively. t_0 and t_f are the start time and the stop time of the state observation respectively.

In terms of the optimal control theory, the tracking control law is obtained

$$\boldsymbol{u}^*(t)=-\boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\left[-\boldsymbol{g}^*(t)+\boldsymbol{P}^*\boldsymbol{x}(t)\right] \tag{7}$$

Here, $\boldsymbol{P}^*$ is obtained by solving the following Riccati equation offline

$$\begin{cases}\dot{\boldsymbol{P}}(t)=-\boldsymbol{P}(t)\boldsymbol{A}-\boldsymbol{A}^{\mathrm{T}}\boldsymbol{P}(t)+\boldsymbol{P}(t)\boldsymbol{B}\boldsymbol{R}^{-1}\boldsymbol{B}\boldsymbol{P}(t)-\boldsymbol{C}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{C}\\\boldsymbol{P}(t_f)=\boldsymbol{C}^{\mathrm{T}}\boldsymbol{F}\boldsymbol{C}\end{cases} \tag{8}$$

$\boldsymbol{g}^*(t)$ satisfies the following equation

$$\begin{cases}\dot{\boldsymbol{g}}(t)=-\left[\boldsymbol{A}^{\mathrm{T}}-\boldsymbol{P}(t)\boldsymbol{B}\boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\right]\boldsymbol{g}(t)\\\qquad\quad-\boldsymbol{C}^{\mathrm{T}}\boldsymbol{Q}\left[\boldsymbol{y}_d(t)-\boldsymbol{s}(t)\right]+\boldsymbol{P}(t)\boldsymbol{r}(t)\\\boldsymbol{g}(t_f)=\boldsymbol{C}^{\mathrm{T}}\boldsymbol{F}\boldsymbol{C}\end{cases} \tag{9}$$

Solving the equation above, we obtain

$$\boldsymbol{g}^*(t)=\left[\boldsymbol{A}^{\mathrm{T}}-\boldsymbol{P}^*\boldsymbol{B}\boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\right]^{-1}\left[\boldsymbol{C}^{\mathrm{T}}\boldsymbol{Q}\left(\boldsymbol{y}_d(t)-\boldsymbol{s}(t)\right)-\boldsymbol{P}^*\boldsymbol{r}(t)\right] \tag{10}$$

3 Observational linearization and tracking objective excitation control laws based on phasor measurement unit

3.1 Observational linearization and tracking objective excitation control based on synchronized coordinates

For interconnected power systems including n generators, the nonlinear excitation control model of the ith generator in synchronized coordinates is given by

$$\begin{cases}\dot{\delta}_i=\omega_N(\omega_i-1)\\\dot{\omega}_i=\dfrac{P_{\mathrm{m}i}-P_{\mathrm{e}i}-D_i\omega_N(\omega_i-1)}{T_{\mathrm{J}i}}\\\dot{E}'_{qi}=\dfrac{-E'_{qi}-(x_{di}-x'_{di})I_{di}+u_{fi}}{T'_{d0i}}\end{cases} \tag{11}$$

Here, δ_i and ω_i are the rotor angle and the angular velocity with respect to synchronous rotation reference coordinates respectively. T_{Ji} is the inertia time constant of the generator. D_i is the damping coefficient. P_{mi} is the mechanical power. P_{ei} is the electromagnetic power. T'_{d0i} is the d-axis open circuit transient time constant. u_{fi} is the excitation voltage. E_{qi} is the nonload potential. E'_{qi} is the q-axis transient potential. x'_{di} is the d-axis transient reactance. x_{qi} is the q-axis synchronous reactance. I_{di} and I_{qi} are the d-axis and the q-axis currents of the stator, respectively.

Let $\Delta\delta_i = \delta_i - \delta_{i0}$, $\Delta\omega_i = \omega_i - 1$, $\Delta E'_{qi} = E'_{qi} - E'_{qi0}$;
from Eq. (11), we obtain

$$\begin{bmatrix} \Delta\dot{\delta}_i \\ \Delta\dot{\omega}_i \\ \Delta\dot{E}'_{qi} \end{bmatrix} = \begin{bmatrix} 0 & \omega_N & 0 \\ 0 & -\dfrac{D_i\omega_N}{T_{Ji}} & 0 \\ 0 & 0 & -\dfrac{1}{T'_{d0i}} \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{qi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{T'_{d0i}} \end{bmatrix} u_{fi} + \begin{bmatrix} 0 \\ \dfrac{P_{mi} - P_{ei}}{T_{Ji}} \\ \dfrac{-\left(x_{di} - x'_{di}\right) I_{di}}{T'_{d0i}} \end{bmatrix} \tag{12}$$

$$\boldsymbol{y}(t) = \begin{bmatrix} \delta_i \\ \omega_i \\ V_{ti} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \delta_i \\ \omega_i \\ \sqrt{V_{tqi}^2 + V_{tdi}^2} \end{bmatrix} \tag{13}$$

Transform Eqs. (12) and (13) to the following forms, which are linearized by observational linearization

$$\begin{bmatrix} \Delta\dot{\delta}_i \\ \Delta\dot{\omega}_i \\ \Delta\dot{E}'_{qi} \end{bmatrix} = \begin{bmatrix} 1 & \omega_N & 1 \\ 0 & -\dfrac{D_i\omega_N}{T_{Ji}} & 1 \\ 0 & 0 & -\dfrac{1}{T'_{d0i}} \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{qi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{T'_{d0i}} \end{bmatrix} u_{fi} + \boldsymbol{r}(t) \tag{14}$$

$$\begin{bmatrix} \delta_i \\ \omega_i \\ V_t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{qi} \end{bmatrix} + \boldsymbol{s}(t) \tag{15}$$

where

$$\boldsymbol{r}(t) = \begin{bmatrix} -\Delta\delta_i - \Delta E'_{qi} \\ \dfrac{P_{mi} - P_{ei}}{T_{Ji}} - \Delta E'_{qi} \\ \dfrac{-\left(x_{di} - x'_{di}\right) I_{di}}{T'_{d0i}} \end{bmatrix}, \boldsymbol{s}(t) = \begin{bmatrix} \delta_i - \Delta\delta_i \\ \omega_i - \Delta\omega_i \\ \sqrt{V_{tqi}^2 + V_{tdi}^2} - \Delta E'_{qi} \end{bmatrix}$$

3.2 Observational linearization and tracking objective excitation control based on reference generator coordinates

In interconnected power systems including n generators, if the nth generator is selected as the reference generator, the nonlinear excitation control model of the ith generator is given by

$$\begin{cases} \dot{\delta}_{in} = \omega_N \omega_{in} \\ \dot{\omega}_{in} = \dfrac{P_{mi} - P_{ei} - D_i\omega_N(\omega_i - 1)}{T_{Ji}} - \dfrac{P_{mn} - P_{en} - D_n\omega_N(\omega_n - 1)}{T_{Jn}} \\ \dot{E}'_{qi} = \dfrac{-E'_{qi} - \left(x_{di} - x'_{di}\right) I_{di} + u_{fi}}{T'_{d0i}} \end{cases} \tag{16}$$

The meanings of the notation in Eq. (16) are the same as in Eq. (11).

Let $\Delta\delta_i = \delta_{in} - \delta_{in0}$, $\Delta\omega_i = \omega_{in}$, $\Delta E'_{qi} = E'_{qi} - E'_{qi\,0}$,
$\boldsymbol{x} = \left[\Delta\delta_i, \Delta\omega_i, \Delta E'_{qi}\right]$;
then, the standard observational linearization state equation and the output equation of the system are obtained, in which coefficient matrices are the same as in Eqs. (14) and (15). $\boldsymbol{r}(t)$ and $\boldsymbol{s}(t)$ are as follows

$$\boldsymbol{r}(t) = \begin{bmatrix} -\Delta\delta_i - \Delta E'_{qi} \\ R \\ \dfrac{-\left(x_{di} - x'_{di}\right) I_{di}}{T'_{d0i}} \end{bmatrix} \tag{17}$$

$$\boldsymbol{s}(t) = \begin{bmatrix} \delta_i - \Delta\delta_i \\ \omega_i - \Delta\omega_i \\ \sqrt{V_{tqi}^2 + V_{tdi}^2} - \Delta E'_{qi} \end{bmatrix} \tag{18}$$

where

$$R = \frac{P_{mi} - P_{ei} - D_i\omega_N\left(\omega_n - 1\right)}{T_{Ji}} - \frac{P_{mn} - P_{en} - D_n\omega_N\left(\omega_n - 1\right)}{T_{Jn}} - \Delta E'_{qi}$$

The parameters of $\boldsymbol{r}(t)$ and $\boldsymbol{s}(t)$ can be obtained by prediction and measurement in terms of historical and current state data measured by PMU; that is, the nonlinear quantities $\boldsymbol{r}(t)$ and $\boldsymbol{s}(t)$ become high-precision constants, which are updated in real time by PMU online measurement and computation continuously. Consequently, the system state equation and the output equation are linearized.

Because the coefficient matrices of the state equation and the output equation remain constant in different coordinates, $\boldsymbol{P}(t)$ in Eq. (8) is independent of state variables $\boldsymbol{x}(t)$. $\boldsymbol{P}^*$ can be obtained by solving Riccati equation offline; therefore, $\boldsymbol{P}(t)$ remains unchanged. $g^*(t)$ can be obtained online in terms of $\boldsymbol{P}^*$ and the observational quantities measured by PMU. Thereafter, observational linearization and tracking objective excitation control law of multimachine power systems based on the wide-area measurement technology can be obtained by Eq. (7).

From the above, the structures of observational linearization and tracking objective excitation control laws in two different coordinates are the same, but the values of $\boldsymbol{r}(t)$ are different.

4 Simulation analyses

The three-machine nine-bus system in PSASP is used as an example in this paper. Its structure is shown in Fig. 1.

Riccati equation can be solved directly by MATLAB functions.

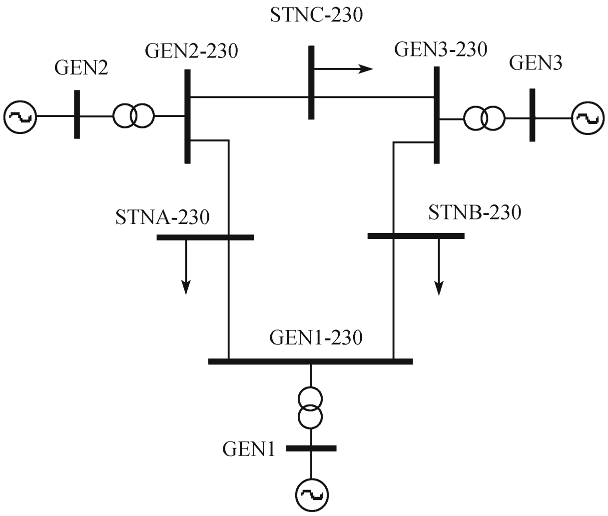

Fig. 1 The structure of PSASP three-machine nine-bus system

Let

$$\boldsymbol{Q}=\begin{vmatrix}0.1 & 0 & 0\\ 0 & 0.1 & 0\\ 0 & 0 & 0.1\end{vmatrix}, R=2.5$$

Substitute to the example system parameters, and yield

$$\boldsymbol{P}_1^*=\begin{vmatrix}2.705\,6 & 2.553\,7 & 4.571\,4\\ 2.553\,7 & 2.602\,9 & 4.476\,6\\ 4.571\,4 & 4.476\,6 & 8.283\,6\end{vmatrix},\ \boldsymbol{P}_2^*=\begin{vmatrix}1.998\,0 & 1.767\,2 & 3.086\,6\\ 1.767\,2 & 1.746\,5 & 2.861\,2\\ 3.086\,6 & 2.861\,2 & 5.273\,1\end{vmatrix}$$

$$\boldsymbol{P}_3^*=\begin{vmatrix}2.762\,0 & 2.295\,0 & 4.381\,2\\ 2.295\,0 & 2.083\,5 & 3.750\,0\\ 4.381\,2 & 3.750\,0 & 7.468\,9\end{vmatrix}$$

The control law can be obtained by substituting $\boldsymbol{P}_1^*$, $\boldsymbol{P}_2^*$, $\boldsymbol{P}_3^*$, in Eqs. (10) and (7). The control law changes with actual operation points.

To show the validity of observational linearization and tracking objective excitation control strategies in two different coordinates, simulations for various faults were done and compared with nonlinear optimal excitation control.

Simulation results are shown in Fig. 2 for the three-phase grounded short circuit at bus STNC-230 5% where is on the line (bus GEN2-230–bus STNC-230), the fault occurs at 0 seconds and is cleared at 0.1 s. From Fig. 2, we can see that observational linearization and tracking objective excitation control damps rotor angle oscillation better than nonlinear optimal excitation control. Hence, the transient stability of the system is improved and the transient response speed of the system is quickened. Moreover, the effect of observational linearization and tracking objective excitation control in reference generator coordinates is better than in synchronized coordinates, namely, control mode C has stronger ability to damp rotor angle oscillation compared to control mode B.

Simulations have been done for different faults, and the same results as above were obtained, that is, the performance

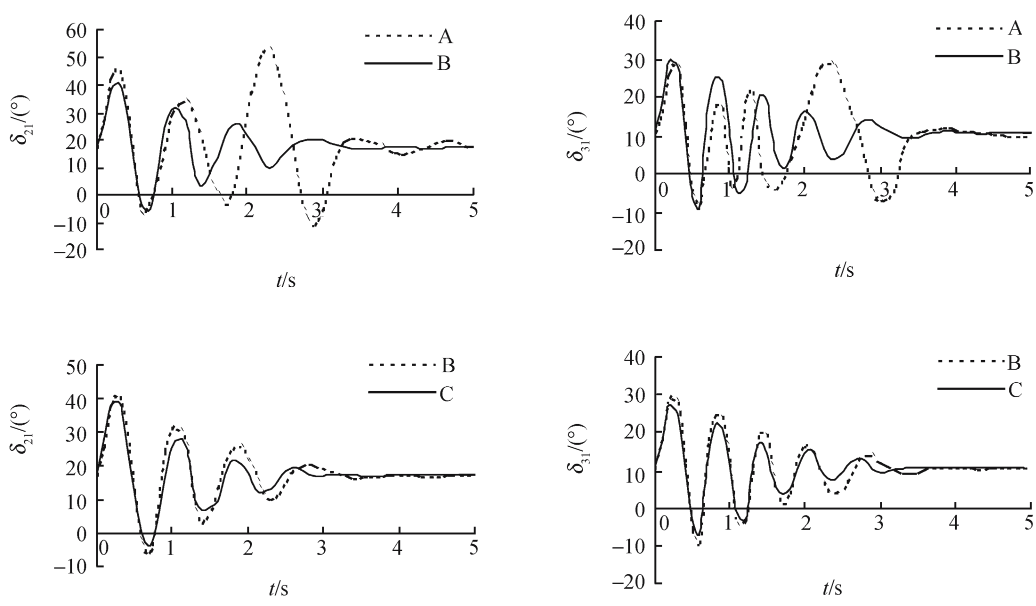

Fig. 2 Rotor angle transient responses for three-phase grounded short-circuit fault
A: Nonlinear optimal excitation control; B: Observational linearization and tracking objective excitation control in synchronized coordinates; C: Observational linearization and tracking objective excitation control in reference generator coordinates

of observational linearization and tracking objective excitation control is better than nonlinear optimal excitation control. It has stronger robustness for different faults. And the effect of observational linearization and tracking objective excitation control in reference generator coordinates is better than in synchronized coordinates.

5 Conclusions

1) Observational linearization and tracking objective excitation control laws of multimachine power systems in synchronized coordinates and in reference generator coordinates have been derived based on PMU and observational linearization and tracking objective control theory. The inaccuracy of local linearization and the complexity of the system models designed in exact linearization can be avoided in the control strategies, and closed loop feedback can be formed. Therefore, the control strategies are applied to engineering in real time.

2) Compared with nonlinear optimal excitation control, observational linearization and tracking objective excitation control can further improve dynamic characteristics and enhance the transient stability of power systems. Moreover, local observation is realized, which facilitates the hierarchical coordinated control of multimachine power systems.

3) For introducing global information of reference generator, the effect of observational linearization and tracking objective excitation control in reference generator coordinates is better than in synchronized coordinates, which have a stronger ability to damp rotor angle oscillation and can further enhance the transient stability of power systems.

4) Observational linearization and tracking objective excitation control based on PMU have stronger robustness.

In conclusion, observational linearization and tracking objective excitation control based on PMU are feasible and effective.

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References

1. Phadke A G. Synchronized phasor measurement in power systems. IEEE Computer Applications in Power, 1993, 6(2): 10–15
2. Ni H, Heydt G T, Mili L. Power system stability agents using robust wide area control. IEEE Trans on Power Systems, 2002, 17(4): 1 123–1 131
3. Kamwa I, Grodin R, Hebert Y. Wide-area measurement based stabilizing control of large power systems—a decentralized/hierarchical approach. IEEE Trans on Power Systems, 2001, 16(l): 136–153
4. Zhao Qingsheng, Liu Sheng, Chen Chen. Real time instability prediction based on energy approach and phasor measurement units. Automation of Electric Power Systems, 2003, 27(14): 9–12 (in Chinese)
5. Lu Qiang, Sun Yuanzhang. Nonlinear Control of Power Systems. Beijing: Science Press, 1993
6. Wang Xiaoyan, Qiu Xiaoyan. A decentralized nonlinear optimal excitation control strategy based on observation decoupled state space model for multi-machine power systems. Relay, 2005, 33(1): 38–41 (in Chinese)
7. Chang Naichao, Guo Zhizhong. Global nonlinear excitation control based on wide-area measurements. Proceedings of the CSEE, 2004, 24(2): 43–48 (in Chinese)
8. Liu Dong, Shan Yuanda. Linearization through observation and tracking objective excitation control. Automation of Electric Power Systems, 1997, 21(3): 17–20 (in Chinese)
9. Huang Ying, Xu Zheng, Yang Jingping. Observational linearization and optimal HVDC supplementary controller based on phasor measurement unit. Power System Technology, 2005, 29(3): 18–22 (in Chinese)