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Brief paper

Practical nonlinear excitation control for a single-machine infinite-bus power system based on a detailed model☆

Yong Wan [1], Bin Jiang

College of Automation Engineering, Jiangsu Key Laboratory of Internet of Things and Control Technologies, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

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ABSTRACT

In this paper, a new control scheme is proposed to achieve both stability and improvement of performances for a single-machine infinite-bus power system. A high-order power system model is presented and only measurable state variables are considered to be used in the feedback control. The continuous and discontinuous excitation controllers, which have different characteristics to be chosen by engineers to meet different practical needs and objectives of power system operation, are respectively designed. The stability analysis and simulation results all show that the developed controllers are effective.

1. Introduction

In recent years, with the rapid developments and widespread applications of electric power industry, human society has increasing requirements and dependencies on electric power energy. Once oscillations or breakouts of power systems occur, great economic losses and society confusion will be caused. Consequently, many research efforts have been devoted toward power system stability which is one of the most significant problems needed to be solved urgently in modern industries (Anderson & Fouad, 2003; Mei, Ni, Wang, & Wu, 2008). To this end, advanced control systems technologies are necessary and effective, which is a fact acknowledged by the scientists and engineers in both academia and industry (Grigsby, 2007; Isidori, 1995).

Due to the intrinsic nonlinear characteristics of power systems, the studies on nonlinear control methods have been paid attentions, and there are many successful applications for the design of power system controllers, such as generator excitation control (Galaz, Ortega, Bazanella, & Stankovic, 2003; Shen, Mei, Lu, Hu, & Tamura, 2003; Yan, Dong, Saha, & Majumder, 2010). To the best knowledge of the authors, most of the existing results are model-based nonlinear control strategies (Dimirovski, Jing, Li, & Liu, 2006; Fu, Zhao, & Dimirovsk, 2006; Mei, Shen, & Liu, 2008; Sun, Tong, & Liu, 2011; Sun, Zhao, & Dimirovski, 2009; Wan, Zhao, & Dimirovski, 2014), thus, the mathematical models of power systems play an important and fundamental role in the control design for power systems.

For improving power system stability, the usual way is to develop a control law by using a nonlinear control method based on the classical third-order power system model which is a simplified version of the detailed one. Although this reduced-order model has been validated and confirmed from both theoretical and experimental perspectives (Arjona, Escarela-Perez, Espinosa-Perez, & Alvarez-Ramirez, 2009; Kokotovic & Sauer, 1989), under complex operating conditions, the unmodeled dynamics often can induce power oscillations and even can cause system instability (Padiyar, 2008). Thus, if higher transient and steady-state performances of power systems are pursued to meet increasingly sophisticated power grids, the high-order model of power systems is necessary to be used for the design of an effective control law.

However, in the detailed model, system state variables are often not fully available for practical applications, for example, flux linkages are unmeasurable and they cannot be used to construct a

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E-mail addresses: wanyong17007@163.com (Y. Wan), binjiang@nuaa.edu.cn (B. Jiang).

[1] Tel.: +86 25 84892305x5070; fax: +86 25 84892300.

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feedback control law (Wang, Song, & Irving, 2008). This is one of reasons why the reduced-order model is so popular for the study of power system stability. In addition, usually, for a nonlinear control method, there is a matching condition on the system structure, for instance, the requirement of strict-feedback form for backstepping design (Wan & Zhao, 2013). As far as the authors know, the existing nonlinear control approaches could not directly solve the stabilization problem of power systems based on the high-order model. Therefore, it not only has practical significance, but also has theoretical challenge to design a nonlinear controller based on the detailed model using only feedback of measurable state variables.

Time-scale redesign is a methodology which was first proposed by Chakrabortty and Arcak (2009) for stabilization and performance recovery of nonlinear systems with unmodeled dynamics. The main advantages of the redesign technique are as follows: the state variables of unmodeled dynamics are not required for feedback; the nominal performance recovery can be achieved, that is, the closed-loop trajectories of the system with unmodeled dynamics can approach those of the nominal system. But there is a structure requirement for the nominal and the unmodeled parts, and thus, this method is not applicable for all nonlinear systems such as the high-order power system model. Thus, for this power system model, achieving the nonlinear control design by using only measurable variables is a challenging task.

In this paper, a high-order mathematical model that is highly nonlinearly coupled between measurable and unmeasurable states is considered, and based on this detailed model, a new nonlinear control design framework for generator excitation is developed by using only measurable states for feedback to ensure both the stability and performances of SMIB, which is an important problem, and almost no theoretical results are available in the control literature. Moreover, the following two points also belong to the main characteristics of the proposed method. First, the transient and steady-state performances are improved compared with existing results based on the simplified model. Second, this method is also applicable to other nonlinear systems with partially measurable state variables.

The paper is organized as follows. A detailed model of power system is described in Section 2. In Section 3, two kinds of nonlinear controller for generator excitation are designed. Section 4 gives stability analysis for the closed-loop system with the designed controllers. The simulation results are presented in Section 5. Conclusions are drawn in Section 6.

2. System dynamic model and problem statement

Most of the existing results for power system control are obtained based on the classical simplified third-order model which eliminates the effects of d-axis transient flux linkage, d- and q-axis sub-transient flux linkages, and the dynamics of the mechanical power and the exciter (Dib, Kenné, & Lamnabhi-Lagarrigue, 2009).

Different from that, this section presents a high-order dynamic model which is identified as the most detailed and representative in power system transient stability studies and is necessary for high-precision control requirements (Padiyar, 2008). For example, for the rotor, this model includes the transient effects of a field winding ‘f’ on the d-axis and a damper winding ‘g’ on the q-axis, and also the sub-transient effects of two damper windings ‘h’ and ‘k’ respectively on the d-axis and q-axis.

Next, Sections 2.1–2.5 provide basic equations of power systems such as the detailed generator model, network equation, etc. Then based on these equations, Section 2.6 derives a high-order power system model, and Section 2.7 gives some discussions on the differences between the presented and simplified model. The main problems to be solved in this paper are described in Section 2.8.

2.1. Mechanical equation

$$\begin{aligned} \dot{\delta} &= \omega, \\ \dot{\omega} &= -(D/H)\omega + v_s(P_e, P_m), \\ \dot{P}_m &= -(1/T_h)(P_m + P_T u_h), \end{aligned} \tag{1}$$

where δ is the power angle in rad; ω is the relative speed in rad/s; D is the damping coefficient in p.u.; H is the inertia constant in s; ω_0 is the synchronous speed in rad/s; P_m is the mechanical power in p.u.; P_e is the active power in p.u.; T_h is the time constant in s; P_T is the throttle pressure in p.u.; u_h is the governor value position in p.u.; $v_s(P_e, P_m) = (\omega_0/H)(P_m - P_e)$.

2.2. Stator equation

$$\begin{aligned} \boldsymbol{E}'' - \boldsymbol{Z_s}\boldsymbol{I} &= \boldsymbol{V}, \\ \boldsymbol{E}'' - \boldsymbol{C_s}\boldsymbol{\psi} &= \boldsymbol{0}, \end{aligned} \tag{2}$$

where E''_d and E''_q are the d- and q-axis stator sub-transient voltages in p.u., $\boldsymbol{E}'' = [E''_q \quad E''_d]^T$; i_d and i_q are the d- and q-axis stator currents in p.u., $\boldsymbol{I} = [i_q \quad i_d]^T$; V_d and V_q are the d- and q-axis stator voltages in p.u., $\boldsymbol{V} = [V_q \quad V_d]^T$; x_f is the d-axis field winding reactance in p.u., x_h and x_g, x_k are the d- and q-axis damper winding reactances in p.u., x_{fh} is the d-axis field-damper mutual reactance in p.u., x_{gk} is the q-axis mutual reactance in p.u., $d_1 = x_f x_h - x_{fh}^2$, $d_2 = x_g x_k - x_{gk}^2$; x_{df}, x_{dh} and x_{qg}, x_{qk} are the d- and q-axis stator–rotor mutual reactances in p.u., $c_1 = (x_{df}x_h - x_{dh}x_{fh})/d_1$, $c_2 = (x_{dh}x_f - x_{df}x_{fh})/d_1$, $c_3 = (x_{qg}x_k - x_{qk}x_{gk})/d_2$, $c_4 = (x_{qk}x_g - x_{qg}x_{gk})/d_2$, $\boldsymbol{c_1} = [c_1 \quad c_2]$, $\boldsymbol{c_2} = [c_3 \quad c_4]$, $\boldsymbol{C_s} = \begin{bmatrix} \boldsymbol{c_1} & 0 \\ 0 & -\boldsymbol{c_2} \end{bmatrix}$; x_d and x_q are the d- and q-axis synchronous reactances in p.u., x''_d and x''_q are the d- and q-axis sub-transient reactances in p.u., $x''_d = x_d - c_1 x_{df} - c_2 x_{dh}$, $x''_q = x_q - c_3 x_{qg} - c_4 x_{qk}$, r_a is the stator resistance in p.u., $\boldsymbol{Z_s} = \begin{bmatrix} r_a & -x''_d \\ x''_q & r_a \end{bmatrix}$; ψ_f and ψ_g are the d- and q-axis transient flux linkages in p.u., ψ_h and ψ_k are the d- and q-axis sub-transient flux linkages in p.u., $\boldsymbol{\psi} = [\psi_f \quad \psi_h \quad \psi_g \quad \psi_k]^T$.

2.3. Network equation

$$\boldsymbol{V_s}(\delta) + \boldsymbol{Z_e}\boldsymbol{I} = \boldsymbol{V}, \tag{3}$$

where V_s is the infinite bus voltage in p.u., $\boldsymbol{T_f}(\delta) = \begin{bmatrix}\cos\delta & -\sin\delta\end{bmatrix}^T$, $\boldsymbol{V_s}(\delta) = V_s \boldsymbol{T_f}(\delta)$; r_e and x_e are the external resistance and reactance viewed from generator terminal in p.u., $\boldsymbol{Z_e} = \begin{bmatrix} r_e & -x_e \\ x_e & r_e \end{bmatrix}$.

2.4. Rotor equation

$$\dot{\boldsymbol{\psi}} = \boldsymbol{A_0}\boldsymbol{\psi} + \boldsymbol{B_0}\boldsymbol{I} + \boldsymbol{E_f}, \tag{4}$$

where r_f, r_h, r_g and r_k are the rotor resistances in p.u., $a_1 = -\omega_0 r_f x_h/d_1$, $a_2 = \omega_0 r_f x_{fh}/d_1$, $a_3 = \omega_0 r_h x_{fh}/d_1$, $a_4 = -\omega_0 r_h x_f/d_1$, $a_5 = -\omega_0 r_g x_k/d_2$, $a_6 = \omega_0 r_g x_{gk}/d_2$, $a_7 = \omega_0 r_k x_{gk}/d_2$, $a_8 = -\omega_0 r_k x_g/d_2$, $\boldsymbol{A_{01}} = \begin{bmatrix} a_1 & a_2 \\ a_3 & a_4 \end{bmatrix}$, $\boldsymbol{A_{02}} = \begin{bmatrix} a_5 & a_6 \\ a_7 & a_8 \end{bmatrix}$, $\boldsymbol{A_0} = \begin{bmatrix} \boldsymbol{A_{01}} & 0 \\ 0 & \boldsymbol{A_{02}} \end{bmatrix}$; $b_1 = \omega_0 r_f/x_{df}$, $b_2 = \omega_0 r_f c_1$, $b_3 = \omega_0 r_h c_2$, $b_4 = \omega_0 r_g c_3$, $b_5 = \omega_0 r_k c_4$, $\boldsymbol{B_0} = \begin{bmatrix} 0 & 0 & b_4 & b_5 \\ b_2 & b_3 & 0 & 0 \end{bmatrix}^T$; E_{fd} is the field excitation voltage in p.u., $\boldsymbol{E_f} = \begin{bmatrix} b_1 E_{fd} & 0 & 0 & 0 \end{bmatrix}^T$.

2.5. Exciter equation

$$\dot{E}_{fd} = -(1/T_E)[(K_E + S_E)E_{fd} - V_F], \tag{5}$$