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Decentralized multi-machine power system excitation control using continuous higher-order sliding mode technique

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ABSTRACT

A new decentralized continuous higher-order sliding mode (HOSM) excitation control scheme is proposed to enhance transient stability and robustness of multi-machine power system. Power angle deviations are chosen as sliding variables. The HOSM control for uncertain nonlinear multi-machine power system is equivalently transformed into finite time stability problem of uncertain integrator chains. The alleged continuous HOSM excitation controller is composed of geometric homogeneous continuous control and super-twisting second-order sliding mode control law to achieve finite time convergence and overcome power system uncertainties. An adaptive gain, constructed for the super-twisting control item, enables reducing the switching control amplitude of excitation voltage to the minimum possible value along with a finite time convergence. The first-order and second-order time derivatives of power angles are estimated by the exact robust differentiators. Finite time stability of closed-loop power system is strictly proved. Simulation results for a three-machine system and 10-machine 39-bus New England power system demonstrate the effectiveness of the proposed decentralized continuous HOSM excitation control approach.

Introduction

Modern power system is incessantly getting larger and larger in size and becoming more complexes with increasing interconnection [1]. It consists of a serial of synchronous generators having the different inertia constants, which are weakly connected through large transmission lines [2]. One of the most crucial tasks is to maintain the system transient stability, i.e., to reach an acceptable steady-state behavior after a major contingency occurs [3]. When a major accident takes place, e.g., the three-phase short circuit fault, power grid parameters and structure will be changing greatly. The power balance of each relevant generator set will be destroyed and the synchronism among the power system generators could be lost, which can lead to large-scale blackout [4]. Power system stabilizer (PSS) plus automatic voltage regulator (AVR) is widely adopted [5] as the most effective and economic means to enhance power system stability. The earliest attempts in improving transient stability are based on linearized model obtained from a specific operating condition [6]. Such linear control scheme generally provides stability in a small region and only deals with small disturbances around an operating point. When some large perturbations transpire, the synchronism among the power system generators can be lost.

Maintaining modern power system transient stability encounter new challenge in recent years, since the number of elements connected to the system, e.g., the generators, the lines, the loads, etc., has increased dramatically. Meanwhile, since the power system is subject to variations like the changes in system configuration and the loading, it is a highly nonlinear dynamic system [7]. Therefore, many advanced control approaches, such as feedback linearization control [1,8], nonlinear predictive control [9], fuzzy control [10,11], neural networks [12], synergetic control [13] and chaotic optimization algorithm [14] have been designed to achieve high dynamic performance under large and unexpected contingencies. These advanced controls enable operating region to be extended and transient stability to be partly improved, yet the control systems are still sensitive to the plant parameter variations and external disturbances. Since there exist various kinds of uncertainties such as measuring errors of the generator synchronous speed, the damping constant, the active electrical power, the quadrature-axis transient voltage, direct-axis synchronous reactance and the direct-axis transient reactance [15], as well as unknown external disturbances, it is quite important to achieve

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robust control for multi-machine power system while enhancing transient stability.

An effective approach for improving system robustness under parameter uncertainties and external disturbances is by using sliding mode control (SMC). SMC has also been reported as one of the most effective control method in improving power system stability, due to its invariance properties and robustness [4,16,10,17,18]. Though improved oscillations damping and fast transient dynamic behavior are received, these classical first-order SMCs [4,16,10,17,18] may lose robustness when considering the exciter's dynamics, and the unexpected chattering phenomenon of excitation control voltage is rather serious. The chattering effect may excite the electrical unmodeled dynamics, and is manifested as vibration in the mechanical parts and undesirable heat losses, which can lead to a low control accuracy and cause mechanical loss. Therefore, the design of a robust excitation controller for the synchronous generator, keeping insensitivity with respect to uncertainties, and reduction of the excitation voltage chattering effect, becomes a challenging task.

Retaining the main advantages of the classical first-order SMC, high-order sliding mode (HOSM) control has been proposed to reduce the chattering effect and enhance sliding accuracy thanks to the application of the discontinuous sign-function on high-order time derivative of the sliding variable and eventually on time derivative of the control input [19,20]. As modern power system is not only large-scale, but also geographically dispersed and complex interconnected system with distributed generators, it is necessary to develop decentralized control methods which require the only local information for each local controller [21–24]. The decentralized HOSM control scheme has been applied to stability enhancement of power system in recent years [21,7,25,26]. Paper [21] combines block control technique with a novel HOSM approach to the PSS design for a single synchronous machine connected to an infinite bus in the presence of the exciter system dynamics. A second-order sliding mode super-twisting excitation control method for multi-machine power system is proposed in [7]. A nonlinear observer is designed to estimate the rotor fluxes of the synchronous machines. The designed decentralized control scheme requires the only local information for each local controller. Yet it is necessary to implement obscure control logic in order to fulfill control objectives, and the system stability is not formally proved. For multi-machine power system, papers [25,26] get rid of the control logic via optimize the control objectives based on decentralized quasi-continuous HOSM method. Simulations in [25] show the decentralized excitation controller can guarantee the overall stability under extreme conditions (short-circuit). However, a mistake occurs at the beginning of feedback linearization. The excitation method in [26] is also designed based on output feedback quasi-continuous HOSM control. The transient stability and robustness with respect to parameter variations and noise are greatly improved. Yet, the chattering of actual control input, i.e., the excitation voltage chattering is still serious.

It is necessary to take the chattering attenuation into theoretic consideration in excitation controller design. In the above mentioned methods, excitation control effects are not continuous because the HOSM orders are the same as power system orders. Moreover, the upper bound of power system uncertainties are supposed to be known in advance, which make the parameter choice of excitation controller conservative and thus result in relatively big excitation voltage chattering. In this paper, a new decentralized continuous HOSM control approach is proposed, i.e., for each subsystem, a local continuous HOSM controller is designed. The effects from other subsystems are considered as external disturbances. Firstly, aiming at the third-order model of multi-machine power system, the HOSM excitation control is converted to finite time stabilization of uncertain system. Then the new continuous HOSM excitation controller is presented based on geometric homogeneity control law and second-order sliding mode super-twisting algorithm. An adaptive gain method is developed for searching the minimum possible value of switching control based on equivalent control by a low-pass filter. The homogeneous continuous control part realizes finite time convergence of power angle, rotor speed and transient electromotive force. The system robustness is guaranteed by adaptive gain super-twisting control part. The finite time stability of the whole closed-loop system is strictly proved. Exact robust differentiator [27] is employed to estimate the missing derivatives of power angles. The performance of the newly designed continuous HOSM excitation controller is evaluated first in a three-machine power system and then in a 10-machine 39-bus New England power system in comparison with the homogeneous HOSM excitation controller [26] and conventional AVR + PSS method. Simulation results show the effectiveness and robustness of the proposed continuous HOSM excitation method in improving transient stability when suffering from three-phase short circuit fault.

The paper is organized as follows. In section 'Multi-machine power system', the third-order model of multi-machine power system is described. The design procedure of the proposed continuous HOSM excitation controller is presented in section 'Continuous HOSM excitation control'. Section 'Simulation results' presents simulation results to demonstrate the performance of the proposed excitation control method. Finally, in section 'Conclusion', some concluding remarks end the paper.

Multi-machine power system

In a multi-machine power system, each area contains several generators, as shown in Fig. 1. The power generation system is interconnected by means of power grids equipped with excitation controller. The control task is to regulate exciting voltage via these decentralized excitation controller, and then enhance multi-machine power system stability. Under some standard assumptions [3], the dynamical representation of the ith subsystem in an n-machine power system can be represented by the classical third-order model [1,3]:

$$\begin{cases} \dot{\delta}_i = \omega_i - \omega_s \\ \dot{\omega}_i = -\frac{D_i}{2H_i}(\omega_i - \omega_s) + \frac{\omega_s}{2H_i}(P_{mi} - P_{ei}) + d_{1i} \\ \dot{E}'_{qi} = \frac{1}{T'_{di}}(E_{fi} - E_{qi}) + d_{2i} \end{cases} \tag{1}$$

where $i = 1, 2, \ldots, n$, δ_i is the power angle of the ith generator (rad), ω_s is the generator synchronous speed (rad/s), D_i and H_i are the damping constant and the inertia constant of the ith generator (p.u.), P_{mi} is the mechanical power which is assumed to be constant (p.u.), P_{ei} is the active electrical power (p.u.), E_{qi} is the quadrature-axis electromotive force, E'_{qi} is the quadrature-axis transient voltage (p.u.), T'_{di} is the direct-axis open-circuit transient time constant (p.u.), X_{di} and X'_{di} represent the direct-axis synchronous reactance and the direct-axis transient reactance of the ith generator respectively (p.u.), I_{di} is direct-axis current (p.u.), E_{fi} is the exciting voltage which is the control input (p.u.). d_{1i} and d_{2i} are the lumped uncertainties. d_{1i} include measuring errors of ω_i, D_i, P_{mi}, P_{ei}, I_{qi}, interconnected terms and some external disturbances. d_{2i} are composed of measuring errors of E'_{qi}, I_{di}, X_{di}, X'_{di}, interconnected terms, and the modeling errors.

The relevant electrical equations [1,3] are:

$$I_{qi} = G_{ii}E'_{qi} + \sum_{j=1, j\neq i}^{n} E'_{qj}[G_{ij}\cos(\delta_i - \delta_j) - B_{ij}\sin(\delta_i - \delta_j)] \tag{2}$$

$$I_{di} = -B_{ii}E'_{qi} - \sum_{j=1, j\neq i}^{n} E'_{qj}[G_{ij}\sin(\delta_j - \delta_i) - B_{ij}\cos(\delta_j - \delta_i)] \tag{3}$$