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Improved synergetic excitation control for transient stability enhancement and voltage regulation of power systems

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ABSTRACT

This paper proposes decentralized improved synergetic excitation controllers (ISEC) for synchronous generators to enhance transient stability and obtain satisfactory voltage regulation performance of power systems. Each generator is considered as a subsystem, for which an ISEC is designed. According to the control objectives, a manifold, which is a linear combination of the deviation of generator terminal voltage, rotor speed and active power, is chosen for the design of ISEC. Compared with the conventional synergetic excitation controller (CSEC), a parameter adaptation scheme is proposed for updating the controller parameter online in order to improve the transient stability and voltage regulation performance simultaneously under various operating conditions. Case studies are undertaken on a single-machine infinite-bus power system and a two-area four-machine power system, respectively. Simulation results show the ISEC can provide better damping and voltage regulation performance, compared with the CSEC without parameter adaptation scheme and the conventional power system stabilizer.

Introduction

The power system stability is a critical problem that needs to be handled to ensure a reliable and secure supply of electricity [1]. The excitation control of synchronous generators has attracted lots research efforts, as an economic and effective way to enhance power system stability [2–5]. Traditionally, the power system stabilizers (PSSs) or linear optimal excitation controllers are employed to improve transient stability and suppress low frequency oscillations of power systems [2,3]. However, these controllers cannot always guarantee a satisfactory performance over a wide range of operating conditions, because they are designed based on a linearized model obtained from a specific operating condition.

For this aforementioned reason, numerous advanced control techniques have been proposed to design the excitation controllers, such as, feedback linearization control [4–7], fuzzy logic control [8], adaptive control [9,10], nonlinear predictive control [11], sliding mode control [12], and robust control [13]. Many of them employ the state feedback technique and usually only consider the transient stability and ignore the voltage regulation [4,5]. This would lead to the generator terminal voltage deviating from its scheduled value after a permanent fault or a change of the network topology. As power system stability and voltage regulation are two major issues, they are desired to be considered in the stage of designing the excitation controllers [6]. To solve this problem, a nonlinear variable structure excitation controller is proposed in [14] and a new load angle reference is calculated from a dynamic term given by a PI voltage regulator in [15] to maintain the voltage profile. However, it is usually difficult to fulfil the global asymptotic stability of rotor angle while achieving satisfactory voltage profile due to the high nonlinearity and complexity of the power systems.

In recent years, the synergetic control theory, which has the advantages of order reduction and is similar to sliding mode control but without its disadvantage of chattering [16,17], has been successfully applied in designing controllers for power electronics devices [18,19] and synchronous generator [20–24]. The conventional synergetic theory-based PSS is designed for a single-machine infinite-bus system in [20] and a multi-machine power system to enhance its stability in [21], respectively. Moreover, a decentralized synergetic damping controller, which employs reinforcement learning to update the controller parameters online in order to improve the damping performance, is proposed for a multi-machine system in [22]. In [23,24], an adaptive synergetic PSS is designed, in which a type-2 fuzzy logic system is used to approximate the unknown system dynamics. Since the synergetic control can provide asymptotic stability of rotor angle by selecting the suitable manifold, these synergetic controllers have excellent

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performance in damping oscillations for power systems. However, the outputs of these controllers are added as a supplementary signal to the exciter of the generator and the dynamic of voltage regulation is not considered. Therefore, these controllers must be carefully tuned to avoid interaction with the automatic voltage regulator (AVR). In our previous work [25], the synergetic control theory is applied to design a conventional synergetic excitation controller (CSEC) for the generator to enhance transient stability and voltage regulation performance for a single-machine infinite-bus system. However, the CSEC is lack of robustness to different disturbances and its regulation speed of terminal voltage is slow when it is applied in a multi-machine power system.

In this paper, an improved synergetic excitation controller (ISEC) for synchronous generator is proposed to obtain satisfactory rotor angle stability and voltage regulation performance simultaneously over a wide range of operating conditions. The deviation of terminal voltage and rotor speed are both included in the manifold explicitly for achieving global asymptotic stability and voltage regulation by the excitation control simultaneously. To deal with the drawback of the CSEC proposed in [25], an online parameter adaptation scheme is proposed for the ISEC to improve both the voltage regulation and transient stability performance. In addition, it is easily implemented in a practical power system as only local measurements are required. Case studies are undertaken based on a single-machine infinite-bus power system and a two-area four-machine power system, respectively. Simulation results verify the effectiveness of the proposed ISEC.

This paper extends our work reported in [25] and its main contributions are summarized as follows:

- This paper proposes an improved synergetic excitation controller (ISEC) for both the single-machine infinite-bus system and multi-machine power systems. The parameter scheme is adapted to the ISEC to improve the control performance especially under the change of the system operating conditions, while [25] which only uses the synergetic control theory to design a conventional synergetic excitation controller (CSEC) without parameter scheme for the generator of a single-machine infinite-bus system.
- This paper generalizes the CSEC proposed in [25] to ISEC and extends its application from a single-machine infinite-bus in [25] to a multi-machine power system.
- Applications of the proposed ISEC have been verified on not only a single-machine infinite-bus power system but also a four-machine two-area power system, while the reference [25] only investigates the proposed CSEC only on a single-machine infinite-bus power system. Moreover, the ISEC has been compared with CSEC proposed in [25] to validate its superiority.

The rest of the paper is organized as follows: the synergetic control theory is briefly recalled in 'Synergetic control theory'. Then the proposed synergetic excitation controller is designed for the power system in 'Design of improved synergetic excitation controller'. In 'Case studies', the control performance of the proposed ISEC is verified based on a single-machine infinite-bus power system and a two-area four-machine power system, respectively. Conclusions are given in the last section.

Synergetic control theory

Suppose the controlled nonlinear system can be represented as the following differential equation

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{d}, t) \tag{1}$$

where $\boldsymbol{x}$ is the state vector, $\boldsymbol{d}$ is the control input vector, and t is time.

The design procedure based on synergetic control theory starts by defining a macro-variable as a function of the state variables

$$\psi = \psi(\boldsymbol{x}) \tag{2}$$

The macro-variable should be chosen according to control objective and the requirement of the dynamic performance. If there are multiple control channels, the same amount of macro-variables should be defined.

The synergetic controller will force the system state variables to evolve on the manifold $\psi = 0$, enabling for desired performance to be achieved despite uncertainties and disturbances. The desired dynamic evolution of the macro-variables is

$$T\dot{\psi} + \psi = 0 \quad T > 0 \tag{3}$$

where T is a controller parameter that indicates the converging speed to the manifold specified by the macro-variable. Since the macro-variable ψ is a function of the state variables, the chain rule of differentiation gives

$$\dot{\psi} = \frac{d\psi}{d\boldsymbol{x}}\dot{\boldsymbol{x}} \tag{4}$$

Combining Eqs. (1), (3) and (4), we can obtain

$$T\frac{d\psi}{d\boldsymbol{x}}\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{d}, t) + \psi = 0 \tag{5}$$

Solving Eq. (5) for $\boldsymbol{d}$, the control law can be obtained. Under the control of $\boldsymbol{d}$, the close-loop system converges to the manifold at a speed determined by T from any initial positions.

According to Eq. (3), we can get the solution of macro-variable:

$$\psi = e^{-\frac{t}{T}} \tag{6}$$

Since $T > 0$, the macro-variable ψ will decay exponentially with a speed determined by T. The smaller the value of T is, the faster the macro-variable decays. When ψ reaches zero, the system converges to the manifold and then operates on the manifold without leave. In this way, the manifold introduces a new constraint in the state space domain and reduces the order of the system. Therefore, it is important to build a manifold carefully to ensure the system stability.

Design of improved synergetic excitation controller

In this paper, a multi-machine power system is considered. Each generator is considered as a subsystem, for which a decentralized excitation controller is designed.

Multi-machine power system model

Considering some standard assumptions, the dynamical model of an n-machine power system consisting of n interconnected subsystems can be described as follows [11]

$$\begin{cases} \dot{\delta}_i = \omega_0(\omega_i - 1) \\ \dot{\omega}_i = (P_{mi} - P_{ei} - D_i(\omega_i - 1))/2H_i, \quad i = 1, 2, \cdots, n \\ \dot{E}'_{qi} = (E_{fdi} - E_{qi})/T'_{d0i} \end{cases} \tag{7}$$

where δ_i is the rotor angle, ω_i is the rotor speed, ω_0 is the synchronous speed, P_{mi} is the mechanical input power, P_{ei} is the active electrical power, E_{fdi} is the field voltage, E_{qi} and E'_{qi} is the q-axis and its transient electromotive force (EMF) voltage, respectively, T'_{d0i} is the d-axis transient open circuit time constant, H_i is the generator inertia constant, D_i is the damping coefficient of the generator.

The related algebraic equations are given as follows

$$E_{qi} = E'_{qi} + (x_{di} - x'_{di})I_{di} \tag{8}$$