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Decentralized nonlinear coordinated excitation and steam valve adaptive control for multi-machine power systems

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ABSTRACT

In this paper, a decentralized nonlinear coordinated excitation and steam valve adaptive control combined with a modified high-order sliding mode differentiator is designed for multi-machine power system stability enhancement. The proposed control scheme is based on Lyapunov's direct method and requires only local information on the physically available measurements of relative angular speed, active electric power and terminal voltage with the assumption that the power angle and mechanical power input are not available for measurement. Each synchronous generator is considered as a classical fifth order model that includes turbine dynamics. The simplicity of the proposed scheme and its robustness with respect to large perturbations, change in operating point and parameter uncertainties constitute the main positive features. Simulation results in the case of the Kundur 4-machines 2-area power system show the effectiveness, robustness and superiority of the proposed scheme over the classical AVR/PSS.

Introduction

The high complexity and nonlinearity of modern power systems together with their almost continuously time varying nature requires the application of advanced control techniques to improve the dynamic performance and stability of the power system. Since a power system is a large scale system consisting of many generator subsystems, decentralized control is preferred because it does not require the full state feedback and communication between different subsystems, which makes the controller implementation more feasible and simpler [1–3].

After decades of theoretical studies and field experiments, AVR/PSS techniques have made a great contribution in enhancing the operating quality of the power system [4–8]. But, with the development of power systems and increasing demand for quality electricity, it is worthwhile looking into the possibility of using modern advanced control techniques.

As one of the most effective and economical decentralized control technique, excitation control of large synchronous generators has attracted many researchers' attention for improving the dynamic performance and transient stability of power systems [9–12]. Nevertheless, the improvement of transient stability is limited due to the physical limits of the excitation voltage. In order to further improve the transient stability, it has been shown in [12–15] that a decentralized control should also be applied to the valve opening of steam turbines or hydroturbines.

More recently, various advanced nonlinear control technologies have been applied to excitation and steam valve control design of single machine and multi-machine power systems [2,9,10,14,15]. However, in most cases, the turbine and excitation controls are considered as independent and decoupled processes characterized by different time scales, which is unsuitable for modern power systems since the appearance of advanced governors, such as digital governors, results in tight mutual interaction between excitation and governor loops [13,14]. Furthermore, most of these nonlinear control schemes are based on the Direct Feedback Linearization (DFL) technique and differential geometric tools which reduces or cancels the inherent system nonlinearities in order to obtain a feedback equivalent linear system.

Some recent results can be found in [2,9,10,14–16]. In [2], a nonlinear decentralized scheme was developed to solve the problem of general nonlinear bounds of interconnections. Both excitation and steam valve control were developed to enhance the transient stability. Nevertheless, DFL is used and the problem of voltage regulation has not been addressed. In [9], a sliding mode controller based on a time-varying sliding surface is used to control the rotor speed and terminal voltage simultaneously in order to enhance the transient stability and to ensure good post-fault voltage regulation. But in practice, the selection of a time-varying

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sliding surface is a difficult task. Also, the case of a multi-machine power system has not been investigated. In [10], a multi-variable nonlinear controller is proposed to achieve simultaneously rotor angle stability and good quality post-fault regulation of the generator terminal voltage, taking into account the automatic voltage and speed regulators dynamics in the control design. However, the problem is formulated as a tracking problem based on differential geometric tools which linearizes the system.

A nonlinear decentralized excitation and governor coordinated controller design for hydraulic power plants is proposed in [14] to enhance power system transient stability. But the excitation and hydro-governor controllers, are developed based on differential geometric theory and the problem of voltage regulation has not been investigated. It has been shown in [15] that a robust coordinated excitation and steam valve control produce better results when a large fault occurs close to the generator terminal. However, DFL is used and the coordination between the two control laws is done using a switching algorithm which causes a discontinuity of system behavior. Hence the control laws cannot achieve satisfactorily both transient stability enhancement and voltage regulation simultaneously. In [16], the stabilization of generalized Hamiltonian control system with internally generated energy is considered using passivity-based control. Both steam valve control and super-conducting magnetic energy storage (SMES) control were developed to enhance the transient stability. However, the problem of voltage regulation has not been investigated.

In order to satisfy some recent objectives and constraints imposed by the evolution of large scale interconnected power systems, a new methodology for the synthesis of power system stabilizers (PSSs) and speed governors using a third level of coordination is proposed in [17]. Both Standard PSSs and improved governors were developed and tuned simultaneously in a coordinated way in order to achieve the desired performance. However, the control model is obtained by linearizing the nonlinear power system around a given operation point. In [18], generators based on steam turbines with asymmetrical dq inductances were used to develop an observer based nonlinear controller to improve the stability of a multimachine power system. However, feedback linearization is used in designing the control law. In addition, most of the above control algorithms assumes that the mechanical power input and power angle are available. But these parameters or variables are physically not available for measurement in practice.

Due to the above mentioned issues and by exploiting the concepts developed in [11,19], in this paper we propose:

- A simplified nonlinear decentralized coordinated excitation and steam valve adaptive control based on Lyapunov's direct method to simultaneously enhance the transient stability and voltage regulation of a multi-machine power system with unknown power angle and mechanical power input.
- A modified high-order sliding mode differentiator to estimate in finite time, the time derivatives of unmeasurable variables and states.
- Numerical simulations to test and compare the performance of the new nonlinear adaptive control scheme during a large disturbance, change in operating point and parameter uncertainties with a classical AVR/PSS.

The paper is organized as follows. In Section "Plant system dynamic model and control objectives", the dynamic model of the multi-machine power system is described. The design procedure of the formulation of the proposed control algorithms is presented in Section "Design procedure of adaptive nonlinear controller for multi-machine power systems". Simulation results are presented in Section "Simulation results" to demonstrate the performance of the proposed controllers. Finally, in Section "Conclusion", some concluding remarks end the paper.

Plant system dynamic model and control objectives

Multi-machine dynamic model

The full mathematical details and physical assumptions of the classical dynamic model of a large scale power systems can be found in [4–6,13]. In this work, we use the following dynamics and electrical equations.

Mechanical dynamics:

$$\dot{\delta}_i = \omega_i, \tag{1}$$

$$\dot{\omega}_i = -\frac{D_i}{H_i}\omega_i - \frac{\omega_s}{H_i}(P_{ei} - P_{mi}). \tag{2}$$

Generator electrical dynamics:

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}(E_{fi} - E_{qi}). \tag{3}$$

Turbine dynamics:

$$\dot{P}_{mi} = -\frac{1}{T_{mi}}P_{mi} + \frac{K_{mi}}{T_{mi}}X_{ei}. \tag{4}$$

Turbine valve control:

$$\dot{X}_{ei} = -\frac{K_{ei}}{T_{ei}R_i\omega_s}\omega_i - \frac{1}{T_{ei}}X_{ei} + \frac{1}{T_{ei}}P_{ci}. \tag{5}$$

Electrical equations:

$$E_{qi} = x_{adi}I_{fi} = E'_{qi} + (x_{di} - x'_{di})I_{di}, \tag{6}$$

$$E_{fi} = K_{ci}u_{fi}, \tag{7}$$

$$P_{ei} = \sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\sin(\delta_i - \delta_j), \tag{8}$$

$$Q_{ei} = -\sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\cos(\delta_i - \delta_j), \tag{9}$$

$$I_{di} = -\sum_{j=1}^{n} E'_{qj}B_{ij}\cos(\delta_i - \delta_j), \tag{10}$$

$$I_{qi} = \sum_{j=1}^{n} E'_{qj}B_{ij}sin(\delta_i - \delta_j), \tag{11}$$

$$V_{ti} = \sqrt{(E'_{qi} - x'_{di}I_{di})^2 + (x'_{di}I_{qi})^2}. \tag{12}$$

The notation for the multimachine power system model is given in Appendix section "Power systems nomenclature".

Control objectives

We design independently two controllers based on local measurements for each machine, i.e., E_{fi} for the excitation control loop and P_{ci} for the steam valve control loop and coordinate their actions in order to cooperatively achieve both transient stability enhancement and voltage regulation simultaneously in the presence of a large perturbation.

Design procedure of adaptive nonlinear controller for multi-machine power systems

Direct Lyapunov method is a powerful tool for transient stability assessment and control of power systems. In the following analysis, the Lyapunov theory is used to design an adaptive