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Coordinated excitation and steam valve control for multimachine power system using high order sliding mode technique

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ABSTRACT

This paper presents a decentralized coordinated excitation and steam valve adaptive control combined with a high-order sliding mode differentiator. The aim is to obtain high performance for the terminal voltage and the rotor speed simultaneously under a sudden fault and a wide range of operating conditions. The methodology adopted is based on second order sliding mode technique using the supper twisting algorithm. The proposed scheme 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. It can be implemented locally and dispersedly for individual generators and is convenient for industrial applications. 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 controller and steam valve PI regulator.

1. Introduction

Power systems are becoming increasingly more complex due to the interconnection of regional subsystems, deregulations and the operation of associated electricity markets. As a result, they require the application of advanced control techniques to improve their dynamic performance and stability. Since the generator subsystems are interconnected in wide geographical areas, 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].

Recently, to cope with the increasing demand for quality electric power, much attention has been given to the application of nonlinear control techniques to solve the transient stability problem. Nonlinear control techniques such as feedback linearization [4,5], Hamiltonian techniques [6], passivity base approach [7], singular perturbation [8], and sliding mode control [9–12] have been successfully applied to achieve high dynamic performance under large sudden faults.

Amongst these nonlinear techniques, sliding mode control has been recognized as one of the efficient tools to design robust controllers for complex high order nonlinear dynamic systems operating under various uncertainty conditions. The main advantage of sliding mode is the low sensitivity to plant parameter variations and disturbances which relaxes the necessity of exact modeling [13]. Despite this advantage, the usage of standard sliding mode is restricted due to the chattering effect caused by the control switching. High order sliding mode (HOSM) technique generalizes the basic sliding mode idea by acting on the higher order time-derivative of the sliding manifold, instead of influencing the first time-derivative as it is the case in the standard sliding mode [14]. The operational feature of HOSM allows mitigating the chattering effect while keeping the main properties of the original approach.

Nonlinear control using the excitation of synchronous generators [4,11,15,16] is a viable option to improve the stability margin when economic constraints do not permit the use of FACTS equipments. In this way, a cheaper solution based on the existing power system facilities is obtained. 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 [4,17–19] that a decentralized control should also be applied to the valve opening of steam turbines or hydroturbines. The problem of frequency control is also very important in all power systems. The system is in equilibrium when the generated power is equal to the consumed power. This equilibrium is maintained by the control of the power generated by the prime movers (steam turbines) [20].

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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 [2,11,15,18,19]. 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 [17,18]. 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 [2,11,15,18,19,6,21]. 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 [11], 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 sliding surface is a difficult task. Also, the case of a multi-machine power system has not been investigated. In [15], 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 [18] 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 [19] 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 [6], 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 [21]. 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 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 [16,22], in this paper we propose:

- A simplified nonlinear decentralized coordinated excitation and steam valve adaptive control based on the supper twisting algorithm to simultaneously enhance the transient stability and voltage regulation of a multi-machine power system with unknown power angle and mechanical power input.
- A high-order sliding mode differentiator to estimate the time derivatives of unmeasurable variables and states.
- Numerical simulations to test the interaction and compare the performance of the new nonlinear adaptive control scheme with the classical AVR/PSS controller and steam valve PI regulator.

The paper is organized as follows. In Section 2, 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 3. Simulation results are presented in Section 4 to demonstrate the performance of the proposed controllers. Finally, in Section 5, some concluding remarks end the paper.

2. Plant system dynamic model and control objectives

2.1. 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 [23–25,17]. 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 A.1.