Electrical Power and Energy Systems 84 (2017) 76–86

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Robust nonlinear adaptive backstepping excitation controller design for rejecting external disturbances in multimachine power systems

T.K. Roy [a], M.A. Mahmud [a,*], Weixiang Shen [b], A.M.T. Oo [a], M.E. Haque [a]

[a] School of Engineering, Deakin University, Waurn Ponds, VIC 3216, Australia
[b] School of Software and Electrical Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

ARTICLE INFO

Article history:
Received 14 September 2015
Accepted 12 April 2016

Keywords:
Excitation system
External disturbances
Lyapunov function
Multimachine power systems
Robust adaptive backstepping controller
Stability sensitive parameters

ABSTRACT

This paper proposes a new approach to design a robust adaptive backstepping excitation controller for multimachine power systems in order to reject external disturbances. The parameters which significantly affect the stability of power systems (also called stability sensitive parameters) are considered as unknown and the external disturbances are incorporated into the power system model. The proposed excitation controller is designed in such a way that it is adaptive to the unknown parameters and robust to external disturbances. The stability sensitive parameters are estimated through the adaptation laws and the convergences of these adaptation laws are obtained through the negative semi-definiteness of control Lyapunov functions (CLFs). The proposed controller not only provides robustness property against external disturbances but also overcomes the over-parameterization problem of stability sensitive parameters which usually appears in some conventional adaptive methods. Finally, the performance of the proposed controller is tested on a two-area four machine 11-bus power system by considering external disturbances under different scenarios and is compared to that of an existing nonlinear adaptive backstepping controller. Simulation results illustrate the robustness of the proposed controller over an existing one in terms of rejecting external disturbances.

Introduction

Modern power networks are widely dispersed, large-scale, complex and interconnected systems. When such power systems are subjected to any kind of external disturbances such as changes in load demands, tripping out of generators, short-circuit faults, or noises due to measurements, the tasks to maintain system stability become more difficult and challenging. In such situations, the excitation controllers of synchronous generators should have the capability to reject these external disturbances and stabilize the whole power system by providing additional damping [1–5]. However, when the large external disturbances occur, the conventional excitation controllers which are designed based on the linear approximation around an operating point of power system do not work properly [6,7] because the operating point can vary as the result of inherent nonlinearities of power system components and continuously changing characteristics of loads.

Recently, various advanced nonlinear excitation controllers are designed to maintain the stability of power systems for different operating conditions under large external disturbances [8,9]. Feedback linearizing excitation controllers (FBLECs) are the mostly used nonlinear techniques [10–12]. They have an ability to decouple the disturbances from the system but require the exact parameters of the system which is extremely difficult in practice.

To overcome the effects of parametric uncertainties in power system, an adaptive FBLEC is proposed in [3] where adaptation laws are used to take care of these parametric uncertainties. The uncertainties in power systems are not only parametric but also state dependent. A robust partial FBLEC is proposed in [13] by considering both parametric and state dependent uncertainties in a structured way. It provides robust performance within the upper bound of the uncertainties. But the control law is very conservative when the characteristics of the system are outside beyond the bounded uncertainties. In addition to the uncertainties, the practical operation of power systems is also significantly affected by the stability sensitive parameters which are mostly the parameters of the synchronous generators such as damping coefficients, inertia constants and direct-axis open-circuit time constant in the presence of external disturbances such as measurement noises. Thus,

---

* Corresponding author.

E-mail addresses: tkroy@deakin.edu.au (T.K. Roy), apel.mahmud@deakin.edu.au (M.A. Mahmud), wshen@swin.edu.au (W. Shen), aman.m@deakin.edu.au (A.M.T. Oo), enamul.haque@deakin.edu.au (M.E. Haque).

http://dx.doi.org/10.1016/j.ijepes.2016.04.040
0142-0615/

a nonlinear controller needs to be designed in such a way that the effects of external disturbances and stability sensitive parameters should be included.

Nonlinear adaptive backstepping technique is one of the promising techniques to design excitation controllers for power systems when the exact parameters of synchronous generators are not known. The excitation controllers based on adaptive backstepping approaches can estimate the unknown parameters through the adaptation laws which are derived by guarantying the convergence of different physical properties of power systems such as speed and power. The convergence of these properties is ensured through the negative definiteness of Lyapunov function [14,15]. An adaptive backstepping controller is proposed in [16] for a single machine infinite bus (SMIB) system by considering the infinite bus voltage and the transmission line parameters as unknown. Similar control approaches are used in [17,18] to design excitation controllers where the damping coefficient is considered as an unknown parameter. However, external disturbances which usually exist in power systems are not taken into account during the controller design process.

In order to address the problems, a robust adaptive backstepping controller is proposed in [19,20] where the external disturbances have been incorporated into the power system model and some stability sensitive parameters such as the damping coefficient and transient reactances of synchronous generators are considered as unknown. The other stability sensitive parameters such as inertia constants and direct-axis open-circuit time constants are not used to design the controller. A robust adaptive H_∞ controller with unknown damping coefficients and external disturbances is proposed in [21] where the controller is designed based on the modified adaptive backstepping sliding mode control method. The main problem with the sliding model control approach is the determination of the sliding surface with the consideration of external disturbances. Another robust adaptive transient stabilizing scheme is proposed in [22] where the main emphasis is on parametric uncertainties rather than other external disturbances. Therefore, the design of excitation controllers by considering all the stability sensitive parameters of synchronous generators and mechanical power inputs to the generators along with external disturbances is worthwhile as these aspects are still uncovered for multimachine power systems though recently a similar concept is presented in [23] to evaluate the performances of an SMIB system.

This paper focuses on the design of a robust adaptive backstepping excitation controller where all stability sensitive parameters and mechanical power inputs are considered as unknown along with external disturbances in a multimachine power system. The stability of the whole power system is ensured through the formulation of control Lyapunov functions (CLFs) and the robustness of the designed controller is analyzed against the rejection of external disturbances. At the end, a two-area four-machine 11-bus interconnected power system is used to evaluate the effectiveness and robustness of the proposed design scheme under different operating scenarios. The performance of the proposed scheme is compared with that of an existing adaptive excitation controller where the external disturbances are neglected.

Power system model

It is well-known that a simplified one-axis third-order synchronous generator model can be used in excitation controller design for multimachine power systems. Let, n numbers of synchronous generators are connected in a multimachine power system to supply power within the system. The dynamical model of the multimachine power system can be represented by the following differential equations [2]:

$$\dot{\delta}_i = \omega_i - \omega_{0i} \tag{1}$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + \frac{\omega_{0i}}{2H_i}(P_{mi} - P_{ei}) \tag{2}$$

$$\dot{E}'_{qi} = \frac{1}{T_{doi}}(E_{fdi} - E_{qi}) \tag{3}$$

where the symbols carry standard meanings [10]. The relevant electrical equations can be written as

$$E_{qi} = E'_{qi} - (x_{di} - x'_{di})I_{di} \tag{4}$$

$$P_{ei} = E'_{qi}I_{qi} \tag{5}$$

$$Q_{ei} = E'_{qi}I_{di} \tag{6}$$

$$I_{di} = -E'_{qi}G_{ii} - \sum_{\substack{j=1\\ j\neq i}}^{N} E'_{qj}B_{ij}\cos\delta_{ij} \tag{7}$$

$$I_{qi} = E'_{qi}G_{ii} + \sum_{\substack{j=1\\ j\neq i}}^{N} E'_{qj}B_{ij}\sin\delta_{ij} \tag{8}$$

$$V_{ti} = \sqrt{(E'_{qi} - x'_{di}I_{di})^2 + (x'_{di}I_{qi})^2} \tag{9}$$

where the symbols have their usual meanings which can be seen in [2]. Power systems are being subjected to several external disturbances such as measurement noises from the sensor which can be taken into account in the power system model, as represented by Eqs. (1)–(3), with the substitution of electrical Eqs. (4)–(9), they can be rewritten as

$$\dot{\delta}_i = \omega_i - \omega_{0i} + d_{1i} \tag{10}$$

$$\dot{\omega}_i = \frac{\omega_{0i}}{2H_i}(P_{mi} - E'_{qi}I_{qi}) - \frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + d_{2i} \tag{11}$$

$$\dot{E}'_{qi} = \frac{1}{T_{doi}}E_{fdi} - \frac{1}{T_{doi}}[E'_{qi} - (x_{di} - x'_{di})I_{di}] + d_{3i} \tag{12}$$

Eqs. (10)–(12) will be used to design the robust nonlinear adaptive excitation controller. Before the excitation controller is designed, the focus in the following section is on the problems when the stability sensitive parameters are not exactly known and there are external disturbances within the system.

Control problem formulation

Power systems exhibit very unpredictable characteristics when there are external disturbances within the systems and the parameters of systems are inaccurate. The variations of parameters are very common in the operation of power systems and these variations have significant impact on the stability of power systems. For example, the damping coefficient (D) and inertia constant (H) of the synchronous generator vary when a short-circuit fault occurs in power systems. Similarly, the reactance X_d and X'_d of synchronous generators may vary shortly due to the saturation effect which also affect the direct-axis open-circuit time constant (T_{do}) [24]. On the other hand, the loads in power systems are continuously changing which cause disturbances in the mechanical power inputs (P_m) to the generators. Excitation controllers are used to remedy these problems. However, the implementation of excitation controllers requires some physical properties of power systems as feedbacks to the controllers. These physical properties are speed deviations, terminal voltages and electrical power outputs of synchronous generators. The incorporation of these properties into the excitation controllers adds some additional sensor noises into the system which deteriorate the stability margin of the system. For example, in the test system as shown in Fig. 3,