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Brief paper

Decentralized adaptive controller design for large-scale power systems[☆]

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ABSTRACT

This paper proposes a novel decentralized adaptive excitation control scheme to globally stabilize large-scale power systems and enhance the transient stability. Two smooth functions are introduced to counteract the effect of unknown time-varying interactions, then a completely decentralized adaptive controller is constructed on the basis of the adaptive backstepping approach. The proposed controller utilizes only local measurements and has no requirement for the bounds of interconnections in the power system. All signals of the overall closed-loop large-scale power system are proved to be globally uniformly bounded. The proposed control scheme is tested on a two-area benchmark power system in the face of a symmetrical three-phase short circuit fault. Simulation results have showed better transient performances in comparison with existing controllers.

1. Introduction

Power systems are one of the most important and complex large-scale nonlinear systems, operating in a constantly changing environment (Lu, Sun, & Mei, 2001; Pan, Yuan, Sandberg, Goncalves, & Stan, 2015). As an effective tool for improving transient performances, excitation control of power systems has long been an active research topic in the control community. System stability, robustness and decentralized structure are three important issues that need to be considered for excitation control design. In the early stage of the research, based on approximately linearized models, conventional excitation controllers such as linear power system stabilizer (PSS) (Kamwa, Grondin, & Trudel, 2005; Larsen & Swann, 1981), were developed to primarily deal with small disturbances about an operating point. However, this type of control may not preserve stability if severe contingencies occur or the operating point of the power system is changed away from the equilibrium point (Lu et al., 2001).

Practical demands of handling sudden operating point deviations and large disturbances lead researchers to approach nonlinear excitation control by taking into consideration the entire operation region of the generators in the power system. Numerous decentralized nonlinear excitation controllers have been developed based on nonlinear control techniques such as differential geometrical control (Lu & Sun, 1989), energy function analysis (Hao, Wang, Chen, & Shi, 2002; Shen, Mei, Lu, Hu, & Tamura, 2003; Shen, Sun, Ortega, & Mei, 2005; Xi, Cheng, Lu, & Mei, 2002), sliding-mode control (Huerta, Loukianov, & Canedo, 2010; Majid-abad, Shandiz, & Hajizadeh, 2015; Soto-Cota, Fridman, Loukianov, & Canedo, 2006), and direct feedback linearization (Guo, Hill, & Wang, 2000; Wang, Guo, & Hill, 1997). In spite of the progress, it should be pointed out that, most of the aforementioned control schemes need either the exact information of system parameters or *priori* knowledge of the dynamic system to achieve the desired control objectives. For instance, the nonlinear decentralized excitation controller developed in Guo et al. (2000) is based on the known bounds of parameters. Nevertheless, some of the system parameters are unknown in practice especially when serious disturbances occur.

To circumvent the obstacle caused by unknown parameters, investigations have been extended to adaptive nonlinear

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Nomenclature

$\delta_i(t)$	The power angle of the ith generator, in rad
$\omega_i(t)$	The relative speed of the ith generator, in rad/s
ω_0	The synchronous machine speed, in rad/s
P_{mi0}	The mechanical input power, in p.u.
$P_{ei}(t)$	The active electrical power, in p.u.
$Q_{ei}(t)$	The reactive electrical power, in p.u.
D_i	The per unit damping constant
H_i	The inertia constant in seconds
$E'_{qi}(t)$	The transient EMF in the quadrature axis, in p.u.
$E_{qi}(t)$	The EMF in the quadrature axis, in p.u.
$E_{fi}(t)$	The equivalent EMF in the excitation coil, in p.u.
T'_{d0i}	The direct axis transient short circuit time constant, in seconds
$I_{di}(t)$	The direct axis current, in p.u.
$I_{qi}(t)$	The quadrature axis current, in p.u.
k_{ci}	The gain of the excitation amplifier, in p.u.
$u_{fi}(t)$	The input of the Silicon Controlled Rectifier amplifier of the generator, in p.u.
$V_{ti}(t)$	The terminal voltage of the ith generator
B_{ij}	The ith row and jth column element of nodal susceptance matrix at the internal nodes after eliminating all physical buses, in p.u.
x_{di}	The direct axis reactance, in p.u.
x_{qi}	The quadrature axis reactance, in p.u.
x'_{di}	The direct axis transient reactance, in p.u.
x'_{qi}	The quadrature axis transient reactance, in p.u.

excitation control of multimachine power systems in Jain, Khorrami, and Fardanesh (1994), Karimi and Feliachi (2008), Nechadi, Harmas, Hamzaoui, and Essounbouli (2012), and the references therein. One interesting result in Karimi and Feliachi (2008) showed that a totally decentralized adaptive backstepping excitation controller can be constructed for stability enhancement. However, this control scheme may be invalid if the interactive terms cannot be expressed as a polynomial function of local electric power deviation. More recently, based on the adaptive backstepping method (Krstic, Kanellakopoulos, & Kokotovic, 1995), a novel excitation control has been designed for improvement of transient stability of power systems in Yan, Dong, Saha, and Majumder (2010). Nevertheless, the result developed in Yan et al. (2010) is only partially decentralized since information exchange among generators is required. It is common that the generators are interconnected in wide geographical areas. Physical limitation on the system structure makes information transfer among subsystems unfeasible. Therefore, the problem of designing completely decentralized adaptive excitation controller for multimachine power systems with unknown parameters has not been fully explored, and to the best of our knowledge, remains unclear and open.

In this paper, the objective is to revisit the decentralized adaptive excitation control for multimachine power systems with three goals in mind:

- handling uncertain interactions among subsystems without the utilization of remote information;
- relaxing the assumption that the bounds of interactive terms and plant parameters are known;
- preserving transient stability when a major fault occurs.

To this end, a novel decentralized adaptive excitation control scheme based on backstepping method and a bound estimation strategy is proposed, which achieves all three goals. Although the design and analysis follow a step-by-step procedure in the general framework of backstepping, the details involved vary a lot in solving our problem. Compared with the previous works (Guo et al., 2000; Karimi & Feliachi, 2008; Yan et al., 2010), the highlighted features of this novel decentralized adaptive control scheme are twofold. Firstly, the requirement of the known bounds of interconnection parameters has been relaxed. Secondly, the adaptive controllers are completely decentralized, i.e., global stability of the overall closed-loop system is guaranteed without using remote information.

The remainder of this paper is organized as follows. In Section 2 we give the dynamic model of a power system with excitation control loop. Section 3 gives the decentralized adaptive controller design, followed by the stability analysis in Section 4. To illustrate the effectiveness of the proposed control scheme, simulation results performed on a two-area benchmark power system are presented in Section 5 and the conclusion is drawn in Section 6.

2. Power system dynamical model

For a large-scale power system consisting of n generators interconnected through a transmission network, we apply the classic dynamic model (Kundur, 1994; Lu et al., 2001). In the model, the generator is modeled as the voltage behind direct axis transient reactance; the angle of the voltage coincides with the mechanical angle relative to the synchronously rotating reference frame. The network has been reduced to internal bus representation. The dynamical model of the ith machine with excitation control can be written as follows:

Mechanical equations:

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

$$\dot{\omega}_i(t) = -\frac{D_i}{2H_i}\omega_i(t) + \frac{\omega_0}{2H_i}(P_{mi0} - P_{ei}(t)). \tag{2}$$

Generator electrical dynamics:

$$\dot{E}'_{qi}(t) = \frac{1}{T'_{d0i}}(E_{fi}(t) - E_{qi}(t)). \tag{3}$$

Electrical equations:

$$E_{qi}(t) = E'_{qi}(t) + (x_{di} - x'_{di})I_{di}(t), \tag{4}$$

$$E_{fi}(t) = k_{ci}u_{fi}(t), \tag{5}$$

$$P_{ei}(t) = \sum_{j=1}^{n} E'_{qi}(t)E'_{qj}(t)B_{ij}\sin(\delta_i - \delta_j), \tag{6}$$

$$Q_{ei}(t) = -\sum_{j=1}^{n} E'_{qi}(t)E'_{qj}(t)B_{ij}\cos(\delta_i - \delta_j), \tag{7}$$

$$I_{di}(t) = -\sum_{j=1}^{n} E'_{qj}(t)B_{ij}\cos(\delta_i - \delta_j), \tag{8}$$

$$I_{qi}(t) = \sum_{j=1}^{n} E'_{qj}(t)B_{ij}\sin(\delta_i - \delta_j), \tag{9}$$

$$E_{qi}(t) = V_{ti} + \frac{Q_{ei}x_{di}}{V_{ti}}. \tag{10}$$

The notation for the multimachine power system model is given in the Nomenclature. Let δ_{mi0}, ω_{mi0} and P_{mi0} be the desired values for the power angle $\delta_i(t)$, relative speed $\omega_i(t)$ and the active power $P_{ei}(t)$ of the ith generator at the operating point. Define $\tilde{\delta}_i(t) = \delta_i(t) - \delta_{mi0}$, $\tilde{\omega}_i(t) = \omega_i(t) - \omega_{mi0} = \omega_i(t)$ for $\omega_{mi0} = 0$ and $\tilde{P}_{ei}(t) = P_{ei}(t) - P_{mi0}$. Based on the calculation in Wang et al. (1997),