Electric Power Systems Research 89 (2012) 204–214

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

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

Multi-machine power system stability improvement using an observer-based nonlinear controller

A.E. Leon[a,*], J.M. Mauricio[b], J.A. Solsona[a]

[a] Instituto de Investigaciones en Ingeniería Eléctrica (IIIE) "Alfredo Desages" (UNS-CONICET), Universidad Nacional del Sur (DIEC-UNS), Avenida Alem 1253, 8000 Bahía Blanca, Argentina

[b] Department of Electrical Engineering, University of Seville, 41092 Seville, Spain

ARTICLE INFO

Article history:
Received 8 November 2011
Received in revised form 20 January 2012
Accepted 23 January 2012
Available online 6 April 2012

Keywords:
Decentralized excitation control
Nonlinear observer
Multi-machine power system
Nonlinear control
Power system stability

ABSTRACT

Control and operation of electric networks undergo several changes due to growing energy coming from renewable sources and demanding power quality standards. New dynamic load features also pose a challenge to grid designers. In addition, economic reasons, an increasing demand and remote generation push transmission lines to their stability limits causing oscillation modes to become more lightly damped. In this context, controllers and devices are used to enhance the performance of the new power systems. In this work, an observer-based controller to improve stability in power systems, by using the excitation of synchronous generators, is introduced. The strategy goal is to attain maximum damping injection and to increase the transient stability, while good voltage regulation performance is maintained. The proposed strategy presents two important features from the implementation point of view. First, the controller only needs sensing currents and rotor speed, and second, previous knowledge of network parameters and topology is not required. Several comparisons in multi-machine scenarios with current power system stabilizers are presented. These studies confirm the viability and the performance improvement when conventional solutions are replaced by the proposed approach.

1. Introduction

Currently, both planning and operation of power systems are changing due to several reasons. New technologies based on power electronics, such as flexible ac transmission systems (FACTS) (high-voltage direct current transmissions, static synchronous compensators, etc.) and distributed generation are being introduced [1–3]. The installed capacity on renewable energies (wind energy, photo-voltaic generation, etc.) is also increasing in a fast way [4–6]. In many power networks exist great distances between places where the energy is generated and where it is consumed. Consequently, groups of generators behave like areas and oscillations among them can produce great blackouts [7,8]. Besides, power systems operate close to stability limits due to transport and economic reasons. In this context, multi-machine power system stability arises as a very important subject to be deeply analyzed by engineers and researchers. Classical control schemes needed to be updated, and new and enhanced strategies to improve transient stability and voltage regulation in current and future power system scenarios must be found.

Control using the excitation of synchronous generators is a viable option to improve the stability margin, when economic constraints do not allow to use FACTS equipment. In this way, a cheaper solution based on the existing power facilities is obtained. The improvement of excitation controllers is also important because it is expected that future smart grids include both excitation controllers and FACTS equipments, working in a coordinated way.

One of the first studies on excitation control for stabilizing power systems is reported in [9]. There, oscillations are damped by using a power system stabilizer (PSS). This kind of controllers adds a stabilizing signal in the excitation system, and they are based on robust transfer functions to be tuned via linear techniques around an operating point. However, due to the generator behavior is nonlinear, this technique is not completely appropriate for large disturbances such as topology changes and short circuits. In such cases, PSS performance could vary causing stability problems. Taking into account this negative aspect of PSS controllers, nonlinear control techniques were introduced to improve performance in the presence of large disturbances which push the machine states out of

* Corresponding author at: Instituto de Investigaciones en Ingeniería Eléctrica (IIIE) "Alfredo Desages" (UNS-CONICET), Departamento de Ingeniería Eléctrica y de Computadoras, Universidad Nacional del Sur (UNS), Avenida Alem 1253, 8000 Bahía Blanca, Argentina. Tel.: +54 291 459 5101x3338; fax: +54 291 459 5154.

E-mail addresses: aleon@ymail.com (A.E. Leon), j.m.mauricio@ieee.org (J.M. Mauricio), jsolsona@uns.edu.ar (J.A. Solsona).

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doi:10.1016/j.epsr.2012.01.022

its nominal operating point. Strategies based on feedback linearization can be found in the following pioneer works [10–14], being those proposals continued in [15,16]. A design based on a Lyapunov technique, named L_gV control, was presented in [17]. Stabilization by energy-shaping was proposed in [18]. Adaptive and discrete predictive controllers were reported in [19–22]. Back-stepping and sliding mode techniques can also be found in [23–25]. All previously cited works present decentralized controllers because they only use local measurements. On the other hand, nonlinear centralized controllers have been proposed in [26–28]. In order to construct nonlinear controllers, feedback linearization is often preferred, because it presents high-performance and it allows tuning the controller through several ways. For example, in [27,29] an adaptive control based on feedback linearization was presented. In [30] feedback linearization was used and gains were set via optimal control; whereas, in [31,32] the tuning was made by using robust control techniques.

A power network is a complex system and there are many specifications to be satisfied. For these reasons, many times controllers are developed under several simplifications and/or they partially satisfy the specifications. An often used assumption considers symmetrical dq inductances (i.e. $L_q = L'_q = L'_d$), for instance, in Refs. [17,18,27,28,30,31,33]. Sometimes, only load angle control is considered without taking into account the voltage regulation [22,27,28,30]. Other works address the problem assuming an infinite bus in the system [10,14,16,17,19,29,34–36]. Some authors assume that generator internal states are available (load angle δ or transient electromotive force voltages (EMF) e'_q, e'_d) [13,15–17,27,28,34,36–40], or they build observer-based controllers measuring the load angle δ [25,34,38,39]. Nevertheless, it must be considered that load angle and dq-axis transient EMFs are not measurable in generating stations. A nonlinear observer to estimate the load angle from the generator electrical power, currents and rotor speed was proposed in [41,42]. However, the observer gains were calculated using a Taylor linearization around a particular equilibrium point, reducing the observer performance beyond the point of tuning.

In order to obtain a more precise and easily implementable control strategy, the above aspects should be reconsidered. Generators based on steam turbine could be better modeled with asymmetrical dq inductances. The requirement of good post-fault voltage regulation must also be included. Besides, regarding the implementation aspects, the availability of sensors of the variables to be fed back must be taken into account. Robustness against parameters; network topology uncertainties; and large disturbances must also be provided by the control law.

Due to the above-mentioned issues, this paper proposes a controller to improve the stability margin in a multi-machine power system via nonlinear decentralized excitation control of synchronous generators. Its design is based on the feedback linearization technique; considers asymmetrical dq inductances ($L_q \neq L'_q \neq L'_d$); and only easily measurable variables are used to construct the controller (current and rotor speed states are fed back). In order to obtain the generator internal states, needed in the control stage, a nonlinear observer is used. The nonlinear observer gains are calculated by using the Lyapunov theory. Not only the strategy increases the transient stability in multi-machine power systems, but also it provides good post-fault voltage regulation. Besides, it is robust against parameter uncertainties and large disturbances, being the network knowledge not needed.

The rest of the paper is organized as follows. Section 2 describes the model of power system components. In Section 3 the control strategy is presented. In Section 4 a static open-loop technique to obtain the generator internal states is introduced. In Section 5 the proposed nonlinear observer used to estimate the generator internal states is designed. In Section 6 the controller performance evaluation, discussions and multi-machine tests are presented. Finally conclusions are drawn in Section 7.

Table 1
State variable definitions.

Description	Symbol
Load angle of the generator i referred to the bus r	δ_{ir}
Generator rotor speed	ω
d, q axis transient EMF	e'_d, e'_q
d, q axis generator stator current	i_d, i_q
D, Q axis generator stator current	i_D, i_Q
d, q axis high-side transformer voltage	v_d, v_q
D, Q axis high-side transformer voltage	v_D, v_Q
Electromagnetic and mechanical torque	T_e, T_m
Exciter output voltage	e_{fd}

2. Multi-machine power system model

2.1. Local model of synchronous generators

The local model presents the synchronous generator with its step-up transformer connected to a generic bus “r” of the power system network. Because steam and hydraulic generators are to be included, a two-axis dynamic model, widely used in transient stability studies [16,18,26], is considered [43],

$$\dot{\delta}_{ir} = \Omega_B(\omega_i - \omega_{ri}), \tag{1}$$

$$2H_i\dot{\omega}_i = T_{mi} - T_{ei} - D_{bi}\omega_i - K_{di}(\omega_i - \omega_{ri}), \tag{2}$$

$$T'_{d0i}\dot{e}'_{qi} = -e'_{qi} + (L_{di} - L'_{di})i_{di} + e_{fdi}, \tag{3}$$

$$T'_{q0i}\dot{e}'_{di} = -e'_{di} - (L_{qi} - L'_{qi})i_{qi}, \tag{4}$$

and $T_{ei} = e'_{qi}i_{qi} + e'_{di}i_{di} + (L'_{di} - L'_{qi})i_{qi}i_{di}$, where “i”-subindex stands for the ith generator of the system. The stator algebraic constraints are,

$$0 = R_{sri}i_{di} + L'_{qri}i_{qi} - e'_{di} + v_{di}, \tag{5}$$

$$0 = R_{sri}i_{qi} - L'_{dri}i_{di} - e'_{qi} + v_{qi}, \tag{6}$$

where the following definitions apply,

$$\begin{aligned} &L_{dri} \triangleq L_{di} + L_{ri}, && L_{qri} \triangleq L_{qi} + L_{ri},\\ &L'_{dri} \triangleq L'_{di} + L_{ri}, && L'_{qri} \triangleq L'_{qi} + L_{ri},\\ &R_{sri} \triangleq R_{si} + R_{ri}. \end{aligned} \tag{7}$$

Dynamic states and model parameters are in the per unit system. They are defined in Table 1 and 2. In both tables, notation to be used in the rest of the article has also been included.

A synchronous DQ reference frame is defined by synchronizing with the high-side transformer voltage $v_{ri}e^{j\theta_{ri}}$. In this synchronous DQ reference frame, the high-side transformer voltage is expressed as $v_{ri}e^{j0^\circ} = v_{Qi} + jv_{Di}$. The high-side transformer voltage, in the local dq reference frame, is given by $v_{ri}e^{-j\delta_{ir}} = v_{qi} + jv_{di}$. Therefore,

$$v_{di} = -v_{ri}\sin\delta_{ir}, \tag{8}$$

$$v_{qi} = v_{ri}\cos\delta_{ir}. \tag{9}$$

Current $i_ie^{j(\theta_{ri}-\phi_i)}$ can also be expressed in the synchronous DQ reference frame as $i_ie^{-j\phi_i} = i_{Qi} + ji_{Di}$ and in the local dq reference frame as $i_ie^{-j(\delta_{ir}+\phi_i)} = i_{qi} + ji_{di}$. These reference frames are shown in Fig. 1. In this point must be remarked a very important implementation issue. Variables in the local dq reference frame are not available to be fed back, because they are referred to a frame which depends on the non-measurable load angle δ_{ir}. However, actual sensors can be used to measure currents and voltages when they are expressed in