Neurocomputing 162 (2015) 1–8

Contents lists available at ScienceDirect

Neurocomputing

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

Robust stochastic stability of power system with time-varying delay under Gaussian random perturbations ☆

Yonghui Sun *, Xuemao Zhao, Ning Li, Zhinong Wei, Guoqiang Sun

College of Energy and Electrical Engineering, Hohai University, Nanjing 210098, China

ARTICLE INFO

Article history:
Received 6 December 2014
Received in revised form
28 January 2015
Accepted 29 March 2015
Communicated by Guang Wu Zheng
Available online 16 April 2015

Keywords:
Power system
Gaussian random perturbations
Robust stochastic stability
Linear matrix inequality

ABSTRACT

In this paper, by taking into account the stochastic perturbations, the power system with time-varying delay under Gaussian random perturbations is formulated into the stochastic differential equation, then the robust stochastic stability is discussed in detail. Based on Lyapunov stability theory, some improved robust stability and robust stochastic stability criteria are developed, where the restrictions on the derivative of time-varying delay are removed so as to reduce the conservatism. The obtained results formulated in the form of linear matrix inequalities (LMIs) can be effectively solved by the LMI toolbox. Finally, one machine and infinite system under random perturbations is provided to demonstrate the effectiveness and usefulness of the developed results.

1. Introduction

Since the origin of the electrical power industry, system stability is assumed to be the most important thing in the planning, operation and control of power system [1]. Nowadays, with the development of power grid interconnection, power systems are becoming larger and more complex, therefore stability problem for power system has attracted an increasing interest in the past several decades, a variety of results have been developed for this problem.

It should be noted that time delays caused by transmission of remote signals are one of the key factors influencing the whole system stability and damping performance [2,3]. As time delays are mainly derived from the local measurement device, for traditional power system, time delays are too small to be usually ignored [3]. However, with the development of the wide-area measurement system (WAMS), remote signals have become available as the feedback signals to design wide-area damping controllers (WADCs) for FACTS devices [4]. Time delays are becoming more and more ubiquitous in modern power systems, which become a source of instability and performance deterioration in system. Therefore, the last decade has shown an increasing research activity on stability analysis and control for power system with time delays [5,6]. In [7], the authors considered the robust stability of power system with constant time delay, several delay-dependent stability conditions were derived. In [8], the authors considered the impact of time delay on power system by numerical simulation. Recently, wide measurement areas and applications of phasor measurement unit (PMU) devices make necessary remote measures, which has gained some considerations on the effect of measurement delays. In [3], the authors presented a robust control approach for wide-area power system with time delays. In [9], by using the characteristic roots method, the authors discussed time delay issues of power systems. In [10], the power system stabilizers for small-signal stability using phasor measurements were designed based on optimal control with structural constraints, where time delays were included.

For the other related results considering load frequency control (LFC) of power system, by incorporating communication delay, the authors presented a load frequency control method based on linear matrix inequalities (LMIs) in [11]. In [12], the authors investigated the delay-dependent stability of the load frequency control scheme based on Lyapunov theory, and a delay-dependent criterion has been developed in the form of LMIs. The authors in [13] improved the results reported in [12], where a less conservative delay-dependent stability criterion of LFC emphasizing on multi-area environment has been proposed. In [14], the authors considered H_∞ robust control for analysis/synthesis of a PID-type LFC scheme with time delays. In [15], by using the model reduction technique, the delay-dependent stability of a power system equipped with a wide-area damping controller (WADC) has been investigated. However, all the aforementioned results are dependent on the differentiability of time-varying delay and the derivatives of it to be less than a constant.

☆The work was supported in part by the National Natural Science Foundation of China under Grants 61104045, 51107032 and 51277052, in part by the 111 Project (B14022), and in part by the Fundamental Research Funds for the Central Universities of China under Grant 2014B08014.

* Corresponding author. Tel.: +86 25 58099077; fax: +86 25 58099077.
E-mail address: sunyonghui168@gmail.com (Y. Sun).

http://dx.doi.org/10.1016/j.neucom.2015.03.073
0925-2312/

On the other hand, any physical systems, power system cannot be exempted, contain randomness and uncertainties, such as stochastic loads, the inherent randomness in wind power generation, the random vibration of original motivation, random harmonics and fault in interconnected power grid, and the random small oscillation of power angle [16,17]. In addition, with the integration of more and more renewable energy generations, such as wind power generation, photovoltaic power and electric vehicles into the power system, much more random components are operating with the power system, so the potential stability of power system will become more and more important. Due to the rapid process of stochastic system [18–24], in recent years, there have been some results considering modeling and control of power systems in the framework of stochastic system. In [25], both load and wind power production were modeled with stochastic differential equations to address the problem of power system balance management in an hourly time frame. In [26], the authors considered the stability of power system under small Gauss random excitations. In [27], the authors considered the simulation of stochastic transition stability. In [28], the authors proposed a systematic stochastic modeling approach for power system and considered the stability by numerical simulation. However, to the best of the authors' knowledge, there are few results considering stability and control of delayed power system with stochastic perturbations. Based on the above discussions, the motivation of this paper is to study the robust stochastic stability of power system with stochastic perturbations, and some less conservative stability results will be developed.

The remainder of the paper is organized as follows. Section 2 gives the dynamic model of power system with time-varying delay under Gaussian random perturbations. Section 3 presents the robust stochastic stability and robust stability results for stochastic power systems. In Section 4, simulation results based on one machine and infinity system are provided, where the random excitation amplifying coefficient is considered and the influences of stochastic noise are also discussed. At last, this paper is completed with a conclusion.

2. Preliminaries

2.1. One machine and infinite bus system

In this subsection, one machine and infinite bus (OMIB) system is introduced in advance [1], under the deterministic circumstance, that is in the noise-free conditions, the dynamic motion of the OMIB system can be formulated as

$$M\frac{d^2\delta}{dt^2}+D\frac{d\delta}{dt}=P_m-P_e, \tag{1}$$

where δ is the rotor angle, ω is the rotating speed, P_m is the mechanical power and is assumed to be a constant, $P_e=(E'U/X_\Sigma)\sin\delta$ is the electrical power, E' is the internal voltage, X_Σ is the total reactance, and U is the infinite bus voltage. The OMIB model can be found from Fig. 1.

It is worth pointing out that with the penetration of renewable energy power, such as wind power and photovoltaic power, these inherit randomness and uncertainties would affect the stability of power system, such as the direct influence of wind power is the fluctuations of the frequency. Following the same way [26], taking into account the random loads, adding a random excitation term to the right of (1), then the noise-perturbed model can be given by

Fig. 1. One machine and infinite bus system.

$$M\frac{d^2\delta}{dt^2}+D\frac{d\delta}{dt}=P_m-P_e+\sigma W(t), \tag{2}$$

where $W(t)$ is the Gauss process, and σ is the intensity of random excitation.

For simplicity, the linearization of the nonlinear system (2) could be derived:

$$\begin{cases}\dfrac{d\Delta\delta}{dt}=\Delta\omega,\\[2mm] \dfrac{d\Delta\omega}{dt}=-\dfrac{E'U\cos\delta_0}{MX_\Sigma}\Delta\delta-\dfrac{D}{M}\Delta\omega+\dfrac{\sigma}{M}W(t),\end{cases} \tag{3}$$

then rewrite (3) into the following compact form:

$$dx(t)=Ax(t)\,d(t)+HdB(t), \tag{4}$$

where

$$x(t)=\begin{bmatrix}\Delta\delta\\ \Delta\omega\end{bmatrix},\quad A=\begin{bmatrix}0 & 1\\ a & b\end{bmatrix},\quad H=\begin{bmatrix}0\\ \frac{\sigma}{M}\end{bmatrix},\quad a=-\frac{E'U\cos\delta_0}{MX_\Sigma},$$
$$b=-\frac{D}{M},$$

M is the inertia constant, and $B(t)$ is the n-dimensional Wiener process.

2.2. Stochastic power system with time-varying delay

Based on the above discussion, considering the time delay caused by transmission of remote signals [2,3], without loss of generality, one has the following general stochastic power system with time-varying delay:

$$dx(t)=[Ax(t)+Bx(t-\tau(t))]d(t)+H(x(t),x(t-\tau(t)))\,d\omega(t), \tag{5}$$

where $x(t)=[x_1(t),x_2(t),\dots,x_n(t)]^T\in R^n$ is the state vector, $\tau(t)$ is the time-varying delay satisfying $0\le\tau(t)\le\tau$, $\omega(t)$ is a Gauss process. $H(x(t),x(t-\tau(t)))$ is the noise intensity, without loss of generality, assume $H(x(t),x(t-\tau(t)))$ satisfying

$$H(x(t),x(t-\tau(t)))=Cx(t)+Dx(t-\tau(t)). \tag{6}$$

Considering the power system continuously experiencing different perturbations and changes of operating conditions [29], the uncertain stochastic power system can be formulated as

$$dx(t)=\left[(A+\Delta A)x(t)+(B+\Delta B)x(t-\tau(t))\right]d(t)+H(x(t),x(t-\tau(t)))\,d\omega(t), \tag{7}$$

where ΔA and ΔB are taken as the unknown constant systemic parameter uncertainties, which are assumed to be of the following form:

$$[\Delta A,\Delta B]=WF_0[E_a,E_b]. \tag{8}$$

Here, W,E_a and E_b are the known real constant matrices with appropriate dimensions and F_0 satisfy

$$F_0^TF_0\le I. \tag{9}$$

The following lemma will be used in the proof of the main results.

Lemma 1 (Xie [30]). *Given matrices $Q=Q^T,H,E$ and $0<R=R^T$ of appropriate dimensions,*

$$Q+HFE+E^TF^TH^T<0, \tag{10}$$

for all F satisfying $F_0^TF_0\le R$, if and only if there exists some $\lambda>0$ such that

$$Q+\lambda HH^T+\lambda^{-1}E^TRE<0. \tag{11}$$