ISA Transactions 91 (2019) 21–31

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Design of observer-based non-fragile load frequency control for power systems with electric vehicles

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HIGHLIGHTS

- A load frequency controller with multiple time delays is proposed for power systems.
- The proposed method does not require any information on states of the power system.
- Delay-dependent stability criterion is developed for the resulting closed-loop system.

ARTICLE INFO

Article history:
Received 24 January 2018
Received in revised form 23 December 2018
Accepted 24 January 2019
Available online 7 February 2019

Keywords:
Load frequency control
Finite-time stability
Power systems
Electric vehicles
Non-fragile control

ABSTRACT

This paper establishes an observer-based finite-time non-fragile load frequency control design using electric vehicles for power systems with modeling uncertainties and external disturbances. A state space representation of the addressed power systems together with dynamic interactions of electric vehicles is formulated. A full-order observer-based non-fragile controller is designed to ensure finite-time boundedness and satisfactory finite-time H_∞ performance of the considered system. By constructing an augmented Lyapunov–Krasovskii functional and employing Wirtinger-based integral inequality, the required conditions are obtained in terms of linear matrix inequalities. The desired non-fragile load frequency control law is presented via the observer-based feedback approach. Simulations are given to show the effectiveness of the proposed control scheme.

1. Introduction

The active power and frequency control is often referred to as load frequency control (LFC). In power systems, voltage and frequency deviations often exist due to oscillations and mismatch of generations, unexpected events and uncertainties. These factors could damage equipment, degrade the load performance and cause transmission lines to be over loaded, which ultimately leads to unstable conditions for the power systems. The primary objective of LFC method is to maintain zero steady state errors for frequency deviation and good tracking of load demands in power systems. Based on these facts, LFC design has received considerable research focus to obtain satisfactory performance of control systems [1–3]. In recent years, many LFC schemes have been proposed for various kinds of power systems, such as electric vehicles (EVs), smart grid systems, multi-area thermal systems and wind farms [4–7]. In particular, power systems with EVs have attracted considerable research interests due to their environmentally friendly characteristics, such as lower green house emission and noise pollution. Using bidirectional power electronic devices and vehicle-to-grid technology, an aggregation of EVs plays the role of generating power source to assist conventional power units to respond rapidly to attain the requirement of LFC. Therefore, EVs participate in LFC to assist power units to promptly suppress the variations of system disturbances. Due to the nonlinearity of various components in power systems, a linear model obtained by linearization around an operating point like LFC is usually adopted for the controller design. In most of the existing LFC design approaches for the EV models, it is assumed that all the states of the models could be measured by using sensors. However, because of the high cost and maintenance of sensors, it is not easy to consider this assumption for the actual EV models. To overcome this difficulty, observer-based approach is introduced and consequently, several important works are proposed to estimate the unmeasurable states of many real-time systems via observer-based control technique in recent years [8–12]. An observer-based non-fragile control scheme for stochastic time delay systems is proposed in [13], where a new set

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https://doi.org/10.1016/j.isatra.2019.01.031
0019-0578/

of linear matrix inequality (LMI)-based conditions is developed for designing observer-based non-fragile controller without assuming any constraints on system matrices. Miao and Li [14] derived a set of sufficient conditions in terms of LMIs for designing an observer-based controller for stochastic time delay systems with the aid of Lyapunov stability theory. A robust LFC design problem for multi-area interconnected power systems has been investigated in [15] and [16] according to the constrained population extremal optimization and the adaptive population extremal optimization, respectively. Similarly, few interesting works based on the extremal optimization method have been reported for some practical systems, for instance see [17,18] and references cited therein.

It should be pointed out that finite-time stability and asymptotic stability are totally different concepts. In addition, the design of finite-time control for real process has received much attention due to its practical importance. For the past few years, the concepts of finite-time stability and stabilization have received much attention for various classes of dynamical systems, such as Markov jump systems [19], stochastic systems [20], nonlinear systems [21] and power systems [22]. By using the average dwell-time approach, the problem of finite-time boundedness for switched neutral systems with unknown time-varying disturbance is studied in [23], where a set of sufficient conditions that guarantees finite-time boundedness with H_∞ disturbance attenuation level of the closed-loop system is derived. Shi et al. [24] developed a mode-dependent finite-time H_∞ controller that can guarantee the finite-time boundedness with a prescribed H_∞ performance of the switched systems. Following these seminal works, it is more interesting to study the concepts of finite-time stability and stabilization for power systems to effectively deal with uncertainties. Specifically, a system is finite-time stable if its state is not larger than the prescribed bounds in the fixed time interval for the given bound on the initial condition. Hence, it is possible to make all the signals in the power systems being experience better performance over a prescribed finite time period even the frequency oscillates widely from its scheduled value. Thus, the investigation of finite-time stability and stabilization of power systems is of great importance from the practical point of view.

On the other hand, in real-time process, it is not possible to obtain the controllers exactly because of existence of some unavoidable uncertainties in their coefficients due to aging of components, parameter's re-adjustment process and network environment circumstances. Precisely, small perturbations in the control coefficients may destabilize the systems [25–27]. Therefore, it is important to consider gain fluctuations during controller design. Recently, non-fragile control approaches are proposed to deal with the controller gain fluctuation issues, which can ensure the stability of the considered systems [28–32]. In many practical control systems, time delay often exists, which is an important source of instability and poor system performance. Further, the exact delay value is not known in advance, which can only be estimated via a controller design process. Thus, research on practical control systems with time delay has gained a remarkable attention from research communities. Following this concept, many results about LFC design for power systems with time delays have been reported. On the other hand, robustness of control systems subject to disturbances and uncertainties has always been a central issue in the feedback control design. The main advantage of the H_∞ control method is to design robust controllers with respect to disturbances and to obtain good system performances with respect to unstructured uncertainties. Therefore, the consideration of robust H_∞ performance in the study of non-fragile stabilization of power systems has potential benefit from both theoretical and practical perspectives.

However, to the best of our knowledge, the issue of observer-based non-fragile control design with gain fluctuation for an EV model with external disturbances and multiple time delays in the controller design over a finite domain has not yet been fully considered. Motivated by the above discussions, the aim of this paper is to investigate the finite-time stabilization issue for an EV model with external disturbances and multiple time delays in the controller design by using an observer-based non-fragile H_∞ control technique. Therefore, the problem under consideration can reflect more realistic dynamical behaviors. Moreover, the significant contributions of this study can be summarized in the following aspects:

(i) Inspired by the work in [6], the LFC problem of an isolated power system with multiple time delays in the control input is considered for which an observer-based non-fragile control strategy that can ensure the system stability fluctuated by the load demands within a desired finite-time period is proposed.
(ii) A state-space mathematical model of the considered power system integrated with EVs is formulated, which represents the dynamic interactions of EVs with multiple time delays. For this model, a full-order state observer is constructed since the states of power system are assumed to be unavailable for the stability analysis.
(iii) Based on the Lyapunov–Krasovskii stability theory and the LMI approach, a delay-dependent criterion for finite-time boundedness of the formulated system is established by using the Wirtinger-based integral inequality.
(iv) Compared with the traditional LFC schemes, the proposed scheme can offer the advantages of low complexity, ease of implementation, systems operating over a finite time interval and robust performance in the presence of multiple time delays, disturbance and controller gain fluctuations.

The result of this study reveals that the proposed LFC method guarantees that all the signals in the considered power systems experience better performance as the frequency oscillates widely from its scheduled value. Finally, numerical simulations are given to illustrate the effectiveness of the proposed control design.

2. Problem formulation

In this study, we consider an isolated power system model with two input delays as presented in [6], whose transfer function model is given in Fig. 1. In particular, we consider one input delay in the dynamics of EVs and the other in the dynamics of the plant involving reheated thermal turbine.

In this system model, the control signal is divided into two parts, namely P_{cg} and P_{ce}, from the power set-point P_c by the participation factors α_g and α_e. The divided control signals could regulate the outputs of the reheated thermal turbine and EVs to sustain the overall system frequency at the prescribed value. Within these setups, we first consider a time delay between the transmission of the control signal P_{cg} and the reheated thermal turbine. Then, the power command sent from the control center to the generator can be given as $\epsilon_g(t) = P_{cg}(t-d) = \alpha_g P_c(t-d)$, where d is the network-induced time delay and the dynamics of the reheated thermal generation can be expressed as

$$\begin{aligned}
\dot{X}_g(t) &= -\frac{1}{T_g}X_g(t) - \frac{1}{R_gT_g}f(t) + \frac{1}{T_g}\alpha_g P_c(t-d),\\
\dot{P}_r(t) &= -\frac{1}{T_t}P_r(t) + \frac{1}{T_t}X_g(t), \qquad (1)\\
\dot{P}_g(t) &= -\frac{1}{T_r}P_g(t) + \frac{K_r}{T_rT_t}X_g(t) + \frac{T_t-K_r}{T_tT_r}P_r(t),
\end{aligned}$$

where the system parameters are listed in Table 1.

In a similar way, we consider the second time delay in the EVs communication channel. Here, the power command received at the