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Decentralized bounded input bounded output stabilization of perturbed interconnected time-delay power systems with energy storages

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ABSTRACT

This paper presents a new decentralized bounded input bounded output (BIBO) stabilization problem for a class of interconnected time-delay systems and its application to power systems with energy storages. We first provide conditions for the derivation of an ellipsoid that bounds a given linear functions of the state vector. Then, a design procedure is proposed to synthesize decentralized static output feedback controllers. The designed controllers guarantee that a given linear functions of the state vector, starting from any initial condition, converges exponentially to its prescribed zones. To deal with the time-delay issue, we use an improved weighted integral inequality recently reported in the literature to derive less conservative exponential stability conditions. Then, our presented control approach is applied to an interconnected power system integrated energy storages with multiple time delays. We synthesis decentralized static output feedback load frequency controllers to guarantee that the system frequency and interchanged power converge to their prescribed zones exponentially from any initial conditions. The controller's construction is simpler and easier for implementation due to only the local output measurements are required. In order to systematically obtain the controller gains, an effective procedure using linear matrix inequality based stabilisation criteria, which can be solved by various computation tools, is provided. Finally, the effectiveness of the proposed control scheme is verified by comprehensive simulations.

1. Introduction

Time-delay is paramount in the load frequency control (LFC) of power systems [1]. In particular, due to sudden congestion of communication channels, drop-out and disordering of data packets in the open communication infrastructure [2] such as networked control [3] or wide-area communication systems [4], the existence of time delays in smart grids is unavoidable and a source of oscillations, instability and poor performance [5]. Without proper control action, it leads to failures in maintaining the system frequency and interchanged powers to within acceptable tolerant levels [6]. The problem of LFC of time-delay power systems (TDPSs) has been the focus of considerable research attention (i.e., see [7–11] and references therein). In these works, Lyapunov-Krasovskii functional (LKF) method was deployed to design suitable controllers to restore the closed-loop system stability with an H_∞ attenuation level.

For interconnected TDPSs, both centralized and decentralized control strategies have been proposed to achieve the objectives of LFC. With respect to centralized control approaches, full state feedback [7,8] and full-order observer based feedback control schemes [9–11] were introduced for interconnected TDPSs with thermal turbine and reheated thermal turbines. However, proposed centralized controls of the aforementioned works [7–11] require a central facility with complex hardware/software for processing very large amount of information such as information of all state vectors and full-order state observers in real-time in order to achieve the closed-loop system stability and performance requirement within the overall systems. On the contrary, decentralized LFC strategies are essential in cost saving of data communication, in reducing computational and storage complexities for interconnected power systems [12,13]. In [14–16], decentralized PID [14], robust control [15] and decentralized control based on overlapped decomposition [16] were proposed for conventional interconnected power systems. Nontheless, the time-delays were not

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considered in these studies. In regards to the power systems taking time-delay into considerations, the authors in [17] proposed a decentralized state feedback controller which, however, requires full state variables to restore stability of TDPSs subject to load disturbances. For ease of implementation, it is more desirable that only the system outputs rather than the full state vector are utilized for the implementation of feedback controllers. Although decentralized output feedback (DOF) controllers for TDPSs were introduced in [18–21], on the one hand, the derived stabilization conditions in [18,19] were not formulated in the form of linear matrix inequality (LMI)-based conditions. Therefore, a non-linear trace minimization problem was alternatively deployed to obtain the controller gains. On the other hand, in [20,21], the controller gains were obtained according to the procedure of solving Riccati equation with iterative LMI algorithm. Besides that, in [22], an H_∞ feedback controller design was proposed for a power system with conventional thermal turbines. However, the studied model only has single power area without any interconnected links to other power areas so that the aim of LFC is only to handle the fluctuations of system frequencies.

In the past decades, the implementation of energy storages (ESs) [23] including superconducting magnetic energy storage (SMES) [24], battery energy storage systems (BESS) [25] and electric vehicles (EVs) [26] into power systems is an effective solution for the increasingly concerns on energy supply, environmental issues and high dependence on fossil fuels [27]. ESs can be used to enhance the reliability and flexibility of power grids such as in fast stabilizing the system stability. An aggregation of smart storage devices can participate in both the primary and secondary frequency controls of interconnected grids to support conventional power plants to quickly suppress the fluctuations in the system frequency and interchange powers resulted from load disturbances [9,28,29]. Motivated by the result of quasi-decentralized approach [29], a distributed functional observers based control method was developed for interconnected power systems with electric vehicles and diverse transmission links [26]. Although, in this study, the control task and the process of information are shared among local controllers, communication and computation resource are less than centralized control methods, nevertheless, the transference of augmented measured outputs between local control areas is still required. Along with that, LFC scheme for TDPSs with electric vehicles coordinated batteries state of change (SOC) control was investigated [28]. The authors of [28] primarily focused on the state of charge (SOC) control of electric vehicles and developed a robust model where the uncertainties imposed by the changes in the batteries' SOC can be taken into account. A robust static output frequency control scheme was proposed to ensure the closed-loop H_∞ performance of the system. The scope of studies in [28] was for isolated power systems (single area) and not for multi-area power systems.

Future power systems will have a high level of penetration of renewable energy (RE) such as wind and solar powers. Therefore, the instability (or fluctuations) of system frequency and interchange powers is not only caused by the contingent imbalance between the power generation and power consumption but also by the high intermittent of RE. In [7–11,17–22,28], H_∞ stability and stabilization conditions were derived for TDPSs to handle the issue related to disturbances. Due to the high level of penetration and intermittent of RE, it is meaningful and practical to consider the design of DOF controllers to bring the system frequency and tie-line powers to inside their prescribed safe zones, or in other words, inside their acceptable and allowable tolerant levels. In this regard, we draw our attention to some recent research works dealing with reachable set estimation (RSE) [30–34] of time-delay systems (TDSs) with bounded disturbances. The reachable set is a set of all reachable states starting from the origin under unknown but bounded disturbances [30,31]. By using the LKF method and its variants, the bounds of reachable set can be estimated by suitable regions of outer bounding convex shapes such as balls, ellipsoids or boxes (see, [32,33]). Hence, through a synthesized feedback controller, the system state vector can be brought into a pre-specified polyhedron or an ellipsoid [34,35]. On the other hand, the concept of BIBO stability and controller synthesis for TDSs has also been investigated [36–38]. Roughly speaking, BIBO means that any bounded input will result in an bounded output. By using LKF methods, the authors of [36–38] designed full-state feedback controllers to ensure the output of the closed-loop system converges to inside a bounded range. With regard to the LFC of TDPSs, it is therefore most desirable to design DOF controllers to ensure that the system frequency and interchanged powers converge into their prescribed safe zones whenever the system is subject to sudden changes in load demands and the intermittent of RE.

Motivated by the above discussions, in this paper, we present a new decentralized BIBO stabilization scheme for a class of perturbed TDSs and its applications to LFC of TDPSs. At first, by using RSE and BIBO results together with LKF method, we derive new exponential stability conditions to guarantee the existence of an ellipsoid that bounds a given linear function of the state vector. To deal with the time-delay issue, we use a recent weighted integral inequality [39] which encompasses the Jensen inequality [7,8,18–20,22] and its improvement based on Wirtinger integral inequality. Therefore, less conservative exponential stability conditions for TDSs can be achieved. The next contribution of this paper is the construction of DOF controllers for the studied system to ensure that a set of pre-specified linear functions of the state vector converges exponentially into its prescribed zone with a given convergent rate. The designed controllers only use the local output measurements and can be systematically obtained by solving some stabilization conditions expressed in terms of tractable LMIs together with a convex optimization algorithm. Then, we apply our proposed control scheme to an interconnected TDPSs integrating an aggregation of disperse energy storages (ESs) including storage devices and electric vehicle batteries. For this considered power system, we design effective DOF controllers which can restore the system frequency and interchange powers back to their prescribed zone after a finite time, with a given rate of convergence, which is different to the H_∞ control problem considered in [7–11,17–22,28]. It is also worth to mention that the problem of designing decentralized output feedback controllers for interconnected systems is more difficult than for centralized controllers [7–11] due to the constraint imposing upon the structure of the decentralized controllers.

The remaining of this paper is organized as follows: Section 2 introduces some definitions and the problem statement. Stability analysis and an effective design procedure to obtain DOF controllers are given in Section 3. The effectiveness of our method is verified in Section 4. Finally, Section 5 concludes the paper.

Notation: Throughout this paper, $\mathbb{R}^n$ and $\mathbb{R}^{m\times n}$ denote, respectively, the $n-$dimensional Euclidean space with standard norm $\|.\|$ and the set of $m \times n$ matrices. For $A \in \mathbb{R}^{n\times n}$, we denote $\lambda_{\max}(A)$ and $\lambda_{\min}(A)$ the maximal and minimal real part of all the eigenvalues of A. The symbol $\otimes$ denotes the Knonecker product of two matrices and others mathematical notations are well-known.

2. System description and problem statement

We consider the following class of TDSs