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Robust fault-tolerant control for power systems against mixed actuator failures

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ABSTRACT

This paper employs linear matrix inequality (LMI) based optimization algorithm to develop a method for designing fault-tolerant state feedback controller with mixed actuator failures for power systems subject to random changes. Meanwhile, the random abrupt changes are determined by a finite set Markov chain so the considered system is equivalently represented as a discrete-time Markov jump linear system (MJLS). Further, due to the variations of loading conditions in power system, an uncertainty term is incorporated to MJLS. For the proposed system, we construct a novel actuator fault model containing both linear and nonlinear terms which is more general than the conventional actuator fault models. The main purpose of this paper is to design the robust fault-tolerant controller such that for all possible actuator failures, time-varying delays and admissible parameter uncertainties, the closed-loop uncertain discrete-time MJLS is robustly stochastically stable. Based on free-weighting matrix approach and linear matrix inequality theory, a new set of sufficient conditions that guaranteeing the robust stochastic stability is presented by choosing an appropriate Lyapunov–Krasovskii functional candidate. In addition, a single-machine infinite-bus (SMIB) power system is considered as an application example and its simulation results demonstrate the effectiveness of the proposed design techniques.

1. Introduction

The past few decades have witnessed constant research interests on power systems because they are highly nonlinear and exhibit low frequency oscillations due to poor damping caused by high-gain, fast-acting automatic voltage regulator (AVR) employed in the excitation system [1–3]. Meanwhile, it is well-known fact that the damping of power system oscillation plays an important role in enhancing overall system stability. In order to increase the damping in power systems, there are several techniques such as high voltage direct current (HVDC) [4], static voltage condenser (SVC) [5] and power system stabilizers (PSSs) [6]. Among them, in recent years, PSSs with conventional industry structure have been extensively used by the research communities in modern power systems as an efficient means of damping power oscillations, for instant see [6,7]. Although power systems have a highly nonlinear behavior, the PSSs are designed by classical control techniques in the frequency domain, involving linearization around a nominal operating point, controller design over the linearized nominal model under various operating conditions [8].

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Moreover, it should be mentioned that abrupt changes often emerge in the structure and parameters of many real systems due to the phenomena such as component failures as well as repairs, changing subsystem interconnections and abrupt environmental disturbances. Considering these facts, power systems encountering abrupt changes may be treated as systems which contain finite modes and the modes may jump from one to another at different times so it is not wondering that these kinds of systems can be represented as Markov jump linear systems (MJLSs). Generally speaking, MJLS is a class of stochastic linear systems subject to abrupt variations. Therefore, researchers have used this class of systems to model the physical systems with abrupt structural changes such as failure prone manufacturing systems, power systems and communication systems. Over the last two decades, due to a large number of applications in control engineering, a great deal of effort has been devoted to the analysis and synthesis of MJLS. For some representative works on this general topic, one can refer to [9–13] and the references therein.

On the other hand, robustness of a control system is very important issue because uncertainties are commonly encountered in practical dynamical systems due to some unavoidable parameter variations, disturbance, component failures [14,15]. Furthermore, some recent interesting results on uncertain systems can be seen in [16–18]. Therefore, in order to make the performance of a PSS as robust, the design algorithm must take account of uncertainties for power system. Meanwhile, the changes in the power system caused by loading and varying operating conditions can be treated as a model uncertainty, which is described in terms of a structured perturbation [19]. Thus, the consideration of uncertainties in power systems during stability analysis and control design is of great importance for both theoretical and practical reasons.

Besides, in the existing literature, various control approaches have been applied to study the stability of power systems, for example see [20–22] and the references therein. Nevertheless, in recent years, fault-tolerant control is regarded as one of the major control techniques, which has received most remarkable attention by the research communities and has been successfully applied in industrial process control systems, see [23–27]. Because, in practice, the actuator failures often occur due to the component aging, data distortion and external disturbances so that the performance of controlled systems can no longer be guaranteed by the control scheme designed under the failure-free conditions. Therefore, it is of great necessity to redesign a controller which can achieve the specified system performance in a reliable way. In [23], by presenting a novel augmented sliding mode observer, the problem of fault-tolerant control for a class of stochastic systems with Markovian jump parameters, sensor and actuator faults, and output disturbances has been studied. Moreover, in [25], the problem of fault detection has been investigated for Takagi–Sugeno fuzzy system with sensor faults and time-varying delays via delta operator approach. By using Lyapunov stability theory, the authors in [27], addressed the issue of robust reliable H_∞ control for active vehicle suspension system with input delays and linear fractional uncertainties. Meanwhile, few of the researchers have been used control approaches to stabilize various kinds of nonlinear networked control systems, see [28,29].

However, to date and to the best of our knowledge, the problem of fault-tolerant control for power systems with abrupt changes against mixed actuator failures has not been reported in the literature and this motivates us to consider this interesting problem. Motivated by the aforementioned discussions, in this paper, we aim to cope with the fault-tolerant control problem of power systems against mixed actuator failures subject to random changes. The novelties of this paper lie in the following facts: (i) different from the existing literature, a new type of actuator fault model is considered in the control strategy, which may occur in many real-world situations; and (ii) the robust stabilization problem for discrete-time power systems via fault-tolerant control containing the newly considered fault model is presented. And the contributions of this paper contain the following aspects:

(1) With the aid of Markov chains, the power system model which containing abrupt variations and different pre-loading conditions is represented by uncertain discrete-time Markov jump linear systems.

(2) Being the occurrence of nonlinearity behavior circumstances like dead zone and relay in actuator fault model, a novel generalized fault-tolerant control strategy is proposed to the considered system.

(3) Based on the mode-dependent Lyapunov function approach and free-weighting matrix approach, the designed state feedback controllers can guarantee that the corresponding closed-loop system is stochastically stable.

Finally, the significance of the control law is demonstrated through by an application oriented numerical example.

The organization of the rest of this paper is as follows: In Section 2, system descriptions and some useful preliminaries are presented. In Section 3, nominal discrete-time MJLS without uncertainty is considered and stability results are obtained by using Lyapunov theory. In Section 4, sufficient conditions ensuring robust stochastic stability are derived for uncertain discrete-time MJLS under the fault-tolerant controller. A numerical example exploits the validity of the proposed method in Section 5. Section 6 presents the conclusion.

Notations: The notations used throughout this paper are standard. $\mathbb{R}^n$ and $\mathbb{R}^{m\times n}$ denote the n-dimensional Euclidean space and the space of all $m \times n$ real matrices, respectively. $\mathcal{P} > 0(\geq 0)$ means that $\mathcal{P}$ is real symmetric and positive definite (positive semi-definite); $\mathcal{I}$ refers to the identity matrix with compatible dimension; A' and A^{-1} mean the transpose and the inverse of a matrix A; $*$ denotes the symmetric terms in a symmetric matrix. The block diagonal matrix is specified by $\mathrm{diag}\{\cdots\}$. In addition, $\mathbb{E}\{x\}$ and $\mathrm{Prob}\{\alpha\}$ represent the expectation of the stochastic variable x and the occurrence probability of the event α, respectively. Matrices are assumed to be compatible for algebraic operations if their dimensions are not explicitly stated.