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ORIGINAL ARTICLE

Resilient guaranteed cost control of a power system

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A B S T R A C T

With the development of power system interconnection, the low-frequency oscillation is becoming more and more prominent which may cause system separation and loss of energy to consumers. This paper presents an innovative robust control for power systems in which the operating conditions are changing continuously due to load changes. However, practical implementation of robust control can be fragile due to controller inaccuracies (tolerance of resistors used with operational amplifiers). A new design of resilient (non-fragile) robust control is given that takes into consideration both model and controller uncertainties by an iterative solution of a set of linear matrix inequalities (LMI). Both uncertainties are cast into a norm-bounded structure. A sufficient condition is derived to achieve the desired settling time for damping power system oscillations in face of plant and controller uncertainties. Furthermore, an improved controller design, resilient guaranteed cost controller, is derived to achieve oscillations damping in a guaranteed cost manner. The effectiveness of the algorithm is shown for a single machine infinite bus system, and then, it is extended to multi-area power system.

Introduction

Power system stability is the property of a power system that describes its ability to remain in a state of equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after a disturbance. However, it is observed, all around the world, that power system stability margins decrease. This feature is due to many reasons among which we point out the following three main ones [1]:

1. The inhibition of further transmission or generation constructions by economic and environmental restrictions. Consequently, power systems must be operated with smaller security margins.
2. The restructuring of the electric power industry. Such a process decreases the stability margins due to the fact that power systems are not operated in a cooperative way anymore.
3. The multiplication of pathological characteristics when power system complexity increases. These include the following: large scale oscillations originating from nonlinear phenomena, frequency differences between weakly tied power system areas, interactions with saturated devices, and interactions among power system controls.

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Beyond a certain level, the decrease in power system stability margins can lead to unacceptable operating conditions and/or to frequent power system. One way to avoid this phenomenon and to increase power system stability margins is to control power systems more efficiently.

Synchronous generators are normally equipped with power system stabilizers (PSSs), which provide supplementary feedback stabilizing signals through the excitation system. The stability limit of power systems can be extended by PSS, which enhances system damping at low-frequency oscillations associated with electromechanical modes [2]. The conventional PSS (CPSS) is designed as outlined in kundur [1]. The problem of PSS design has been addressed in the literature using many techniques including, but not limited to, fuzzy control, adaptive control, robust control, pole placement, H∞ design, and variable structure control [3–8]. The method of Jabr et al. [9] is implemented through a sequence of conic programming runs that define a multivariable root locus along which the eigenvalues move. The powerful optimization tool of linear matrix inequalities is also used to enhance PSS robustness through state and output feedback [2,8–11]. The availability of phasors measurement units was recently exploited [12] for the design of an improved stabilizing control based on decentralized and/or hierarchical approach. Furthermore, the application of multi-agent systems to the development of a new defense system, which enabled assessing power system vulnerability, monitoring hidden failures of protection devices, and providing adaptive control actions to prevent catastrophic failures and cascading sequences of events was previously proposed [13]. Attempts to enhance power system stabilization in case of controllers' failure are given in the literatures [14,15].

None of the above references tackled the problem of controller inaccuracies. Continuous-time control is implemented using operational amplifiers and resistors that are characterized by tolerances. So, the uncertainties exist not only in the plant, due to the continuous load variations, but also in the controller. It can be shown that the controllers designed using robust synthesis techniques can be very sensitive or fragile with respect to errors in the controller coefficients, which might lead even to system instability. Therefore, it is required that there exists a nonzero (possibly small) margin of tolerance around the controller parameters, within which the closed loop system stability is maintained. A control synthesis ensuring this property is known in the literature as resilient control [16].

Electric power systems are composed of new power stations, equipped with discrete-time digital PSSs, and old ones with continuous-time PSSs. Although digital PSS is precise, still it has uncertainties. Some sources of uncertainties are finite word length, impression in analog to digital and digital to analog conversions, finite resolution measurements, and round-off errors in numerical computations. In the present manuscript, we consider the worst-case, old power stations equipped with continuous-time PSS.

The present work proposes a design methodology of resilient excitation controller for a single machine infinite bus power system. The system is comprised of state feedback power system stabilizer (PSS) through the excitation system of the generator. Generally, it is acceptable for system operators to achieve a damping of the transient oscillations following small disturbances within a settling time of 10–15 s [17]. Expressing the settling time as a desired degree of stability, the proposed design methodology optimizes the controller parameters using an iterative LMI technique such that the degree of stability is kept within the desired range under both controller parameter inaccuracies and plant uncertainties.

The developed controller is tested under extreme load conditions and controller uncertainties. The results indicate evident effectiveness of the proposed design in maintaining robust stability with the desired settling time. Extension to multi-area power system is also given.

The paper is organized as follows: Section 2 briefly describes the power system under study and formulates the problems. In section 3, a sufficient LMI condition is derived for the design of a resilient PSS that achieves robust stability with prescribed degree of stability, under controller and plant perturbation. Adding the constraint of guaranteed cost, a better controller design is developed. Section 4 provides numerical simulation to verify the results. Finally, conclusions are made in Section 5.

Notations and a fact [16]

In this paper, W', W^{-1}, and $||W|| \leqslant 1$ will denote, respectively, the transpose, the inverse, and the induced norm of any square matrix W. $W > 0$ ($W < 0$) will denote a symmetric positive (negative)-definite matrix W, and I will denote the identity matrix of appropriate dimension.

The symbol $\bullet$ is as an ellipsis for terms in matrix expressions that are induced by symmetry, e.g.,

$$\begin{bmatrix} L+(W+N+W'+N') & N \\ N' & R \end{bmatrix} = \begin{bmatrix} L+(W+N+\bullet) & N \\ \bullet & R \end{bmatrix}$$

Fact

For any real matrices W_1, W_2, and $\Delta(t)$ with appropriate dimensions and $\Delta'\Delta \leqslant I$, $\leftrightarrow ||\Delta|| \leqslant 1$, it follows that

$$W_1\Delta W_2 + W_2'\Delta' W_1' \leqslant \varepsilon^{-1} W_1 W_1' + \varepsilon W_2' W_2, \ \varepsilon > 0$$

where $\Delta(t)$ represents system bounded norm uncertainty. The usefulness of this fact lies in bounding the uncertainties.

Methodology

The system under study consists of a single machine connected to an infinite bus through a tie-line as shown in the block diagram of Fig. 1. It should be emphasized that the infinite bus could be representing the Thévenin equivalent of a large interconnected power system. The machine is equipped with a solid-state exciter.

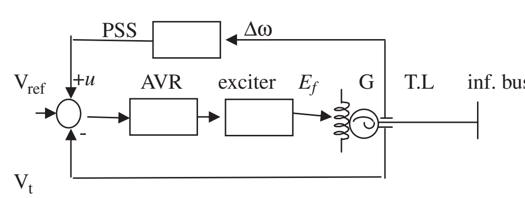

Fig. 1 Basic components of a single machine infinite bus power system.