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Robust wide-area TCSC controller for damping enhancement of inter-area oscillations in an interconnected power system with actuator saturation

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ABSTRACT

Actuator saturation is an inevitable phenomenon in control system which degrades the system performance if it is not considered in the controller design. In this paper, a robust wide-area damping controller is designed for a thyristor controlled series capacitor (TCSC) to enhance the damping of inter-area oscillations when the power system is subjected to actuator saturation. A generalized sector condition is used to represent the nonlinear effects introduced by the actuator saturation in the closed-loop system. By using these conditions, the stabilization conditions for ensuring asymptotic stability of the closed-loop system are derived based on an quadratic Lyapunov criterion. The design of damping controller that maximizes the region of attraction is formulated in the form of linear matrix inequality (LMI) and solved as an optimization problem to achieve damping of inter-area oscillations. In addition to the damping controller, further, a robust pole placement approach is employed to place the closed-loop poles in a prescribed stability region. Two case studies, namely, a two-area four-machine power system and 16 machine 68 bus power system are considered to evaluate the performance of the proposed damping controller.

1. Introduction

Inter-area low-frequency oscillations (0.2–1.0 Hz) have severe influence on the operation of an interconnected power system due to the involvement of numerous generators. These oscillations are detrimental to the maximum power transfer between areas of the interconnected power system and power system security. These oscillations grow in magnitude within few seconds if they are undamped or poorly damped, that can lead to voltage collapse or generators may lose synchronism, ultimately resulting in system separations and blackouts. A famous example of a blackout caused by these oscillations is Western Electricity Coordination Council Region on August 10, 1996 [1]. Traditionally, these inter-area low-frequency oscillations are suppressed by using Power System Stabilizers (PSSs) by providing additional supplementary control to the Automatic Voltage Regulators on the generators. In addition to providing power flow, Flexible Ac Transmission System (FACTS) controllers are provided with supplementary controllers to effectively damp out inter-area oscillations [2]. These damping controllers which use local measured signals provide sufficient damping to the local modes only, but not to the inter-area modes because these modes are not observable/controllable directly from local signals.

The aforesaid problem can be overcome by using wide-area signals as feedback inputs to the PSSs and FACTS controllers [3]. Recently developed Wide-Area Measurement System (WAMS) technology allows the wide-area signals available at different areas in the control center [4,5]. Various methods have been proposed for designing a wide-area controller. In [6], wide-area control problems are formulated for damping of oscillations, voltage control, wide-area protection, disturbance localization and presented the benefits of wide area control in power systems. In [7], a supplementary controller for a Static VAr Compensator (SVC) is designed to damp the inter-area oscillations by using a reduced-order model. In [8], a FACTS-based controller has been designed by using control inversion approach to damp the inter-area oscillations in large power systems which are facilitated by aggregate models. In [9], a decentralized/hierarchical control architecture is presented with operational flexibility, and in [10], a new control has been designed for existing SVC and thyristor controlled series capacitor (TCSC) to improve the pacific inter-tie stability.

Although wide-area PSSs and FACTS controllers provide sufficient damping to the inter-area modes, but the delay caused by the transmission of wide-area signals and actuator saturation in the control loop may degrade the damping performance, or even cause instability of the closed-loop system [11–13]. Most, if not all, the controllers employed for power systems are subjected to actuator saturation. Actuator saturation is different from traditional magnetic saturation of generators. The amplitude of the control signal is restricted intensionally with hard

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saturation limits for safety reasons and limitations of the equipment. The limitations of the actuator are inevitable when the actuator performs the control action. This leads to the actuator saturation when it is driven by the signals resulting from the designed controller. Ignoring the actuator saturation in the controller design may lead to the performance degradation of the control system and even cause instability of the closed-loop system. These saturation limits will reduce the damping capabilities of the designed controller by restricting the actual damping controller outputs within the range of permissible output values. This will reduce the control signal needed for damping the oscillations [14]. Hence, it is necessary to consider the actuator saturation in the damping controller design to reduce the effect of actuator saturation on the damping of inter-area oscillations.

In literature, substantial research has been undertaken to model and study the effect of time-delays on the power system stability by designing FACTS devices based wide-area damping controllers [12,15–22], but very few works have considered the effect of actuator saturation on the power system stability [23–27]. In [23,24], the performance of the PSS controller with saturation nonlinearity and disturbance rejections are studied by estimating the stability region. In [25], an anti-windup compensator is designed for energy storage based damping controller to improve the stability of the power system. In [26], a saturated control scheme is developed for the uncertain power system to achieve the dynamic performance measures by placing the closed-loop poles in the desired region. A new approach is presented in [27] to enlarge the region of attraction of power system by considering the saturation limits in the control design. Though the aforesaid controllers can ensure the power system stability, it may provide weakly damped inter-area oscillation modes in the presence of actuator saturation.

Actuator saturation is inevitable in a control system since the actuator output signal has its minimum and maximum limits. If a controller designed without considering actuator saturation, the controller may ”wind up” the actuator, possibly resulting in degradation of performance or even the stability may be lost. Thus, a substantial amount of research has been directed to the design of control systems subjected to actuator saturation in control literature [13,28,29]. Two approaches for studying the effect of actuator saturation have been reported in the literature i.e. direct approach and indirect approach. In the direct approach, the actuator saturation is considered in the beginning of controller design process [30,31]. But in the indirect approach, first, a conventional controller is designed without considering saturation and then add-on anti-windup compensator designed to minimize the adverse effects caused by any control input nonlinearities [32,33]. The direct approach is applied with anti-windup compensator in this paper to reduce the effect of actuator saturation.

In this work, a robust wide-area TCSC controller is proposed to enhance the damping of inter-area oscillations in the presence of saturating actuator in a dynamic output feedback (DOF) form. In the present work, we only consider the effect of actuator saturation and assume that no time-delay occurs in the process of wide-area signal transfer. A generalized sector nonlinearity condition is used to obtain stabilization criterion. The proposed wide-area TCSC control algorithm is taken from Preposition 3.20 in [34]. To place the closed-loop poles in a prescribed stability region, further, a robust pole placement approach is applied to preposition 3.20. The contributions of the paper are as follows.

- Designed a dynamic output feedback controller along with an anti-windup compensator for TCSC device to mitigate the effect of actuator saturation and improve the damping of inter-area oscillations.
- A generalized sector condition is used to take the nonlinear effect of actuator saturation in the closed-loop system formulation.
- A robust pole-placement approach is applied to place the closed-loop poles in the prescribed stability region which ensure the transient small-signal performance of the closed-loop system.
- By employing an quadratic Lyapunov criterion, sufficient conditions for ensuring asymptotic stability of the closed-loop power system is obtained in the form of LMIs.
- To ensure the maximization of the region of the attraction of the closed-loop system by the designed controller, the formulated LMIs are solved as an optimization problem.
- The effectiveness of the proposed controller is demonstrated considering two benchmark power system models.

The rest of the paper is organised as follows. Sections 2 describes preliminaries and problem statement. Section 3 provides the detailed description of the stabilization with actuator saturation. In Section 4, different optimization problems are described. Detailed design procedure of the proposed controller is presented in Section 5. Section 6 provides the detailed description, simulation, and evaluation of case studies on benchmark models of four-machine two-area and 16 machine 68 bus power system. Section 7 concludes the paper.

Notation: Throughout this paper, $\Re^n$ denotes the n dimensional Euclidean space. $\Re^{n\times m}$ is the set of all $n \times m$ real matrices. The superscripts $\{'\}$ and -1 are stands for the transpose and the inverse of a matrix, respectively. $P = P^T > 0(\geqslant 0)$ denotes that P is a real symmetric positive-definite (positive semi-definite) matrix. diag{...} denotes a block-diagonal matrix. I denotes the identity matrix with appropriate dimensions. .

2. Preliminaries and problem formulation

An interconnected power system consists of various components such as synchronous generators with their excitation systems, PSSs, and FACTS controllers such as TCSC, SVC, and several loads. The above components are interconnected through a transmission network. An interconnected power system with aforesaid components is represented by a set of nonlinear Differential and Algebraic Equations (DAEs) [1].

Consider the following nonlinear differential algebraic equations to describe the dynamics of the interconnected power system.

$$\left.\begin{aligned} \dot{x}_p &= f(x_p(t), z(t), u(t)) \\ 0 &= g(x_p(t), z(t), u(t)) \\ y_p &= h(x_p(t), z(t), u(t)) \end{aligned}\right\} \tag{1}$$

where $x_p(t) \in \Re^{n_p}$, $u(t) \in \Re^m$, $z(t) \in \Re^r$ and $y_p(t) \in \Re^p$ denote the vectors of state variables, inputs, algebraic variables and outputs of power system respectively and f, g and h are vectors of differential, algebraic and output equations respectively.

The nonlinear model (1) is linearized around an equilibrium point to obtain the state space form of the open-loop interconnected power system. The linearized state space form of the pre-fault open-loop power system by excluding wide-area damping controller (WADC) at an equilibrium point is given by

$$\left.\begin{aligned} \dot{x}_p(t) &= A_p x_p(t) + B_\omega \omega(t) + B_p u(t) \\ y_p(t) &= C_p x_p(t) \end{aligned}\right\} \tag{2}$$

where A_p, B_p, B_ω and C_p are constant real matrices with appropriate dimensions. $\omega(t) \in \Re^{n_\omega}$ is an exogenous input which consists of different disturbances, bounded by some scalar δ with limited in energy, i.e. $\omega(t) \in L_2$ and it is represented as follows

$$\|\omega(t)\|_2^2 = \int_0^\infty \omega'(t) R \omega(t) dt \leqslant \frac{1}{\delta}, \quad 0 \leqslant \frac{1}{\delta} \leqslant \infty. \tag{3}$$

In low-frequency inter-area oscillation studies, the fast dynamics is not considered. Hence, the full-order model of the system is not necessary to be considered for controller design. To simplify and speed up the controller design procedure, it is necessary to reduce the system order. By employing *Schur* model reduction method [35], only the poorly damped electromechanical modes are obtained in the reduced