Electric Power Systems Research 164 (2018) 39–46

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Delay-dependent supplementary damping controller of TCSC for interconnected power system with time-delays and actuator saturation

Maddela Chinna Obaiah, Bidyadhar Subudhi*

Department of Electrical Engineering, National Institute of Technology, Rourkela, Odisha 769008, India

A R T I C L E I N F O

Keywords:
Actuator saturation
Time-delays
Inter-area oscillations
Linear matrix inequalities
Sector conditions
Dead-zone nonlinearities
FACTS devices

A B S T R A C T

In this paper, a delay-dependent state feedback based supplementary damping controller of Thyristor Controlled Series Capacitor (TCSC) is designed to enhance the damping of inter-area oscillations of an interconnected power system. Although wide-area feedback signals are advantageous for damping enhancement of inter-area modes, but its usage as feedback signals in designing of a damping controller together with physical limitation of the actuator introduces time-delay and actuator saturation in the feedback loop. This results in degradation of the power system performance and even cause instability. The paper focuses on designing a damping controller considering the aforesaid time-delay and actuator saturation effects. Residue approach and Schur balanced truncation model reduction methods are used to obtain input-output control signals and reduced order power system model. The nonlinear effects of the actuator saturation are consider in the closed-loop system by using generalized sector condition. Based on Lyapunov–Krasovskii functional approach, a delay-dependent stability and stabilization conditions via linear matrix inequalities (LMIs) formulation are derived to guarantee the asymptotic stability of the closed-loop system. Then the problem of designing a state feedback control law which maximizes the region of attraction is formulated and solved as an optimization problem with LMI constraints. Simulation studies in the two-area four-machine power system demonstrate the effectiveness of the proposed controller for damping enhancement of the inter-area oscillations and compensating the effect of time-delays and actuator saturation.

1. Introduction

Low frequency inter-area oscillations are inherent in an interconnected power system due to the involvement of numerous generators and control areas. These oscillations with frequency range 0.1–0.8 Hz are found in an large interconnected power system when a group of alternators in one area oscillate against a group of alternators in another area. Inter-area oscillations are detrimental to the power system stability and the goal of maximum power transfer capability, if they are undamped or poorly damped [1]. Traditionally, conventional power system stabilizers (CPSSs) [2], and other power electronics controlling devices like HVDC, FACTS and wind farms with their supplementary damping controller (SDC) are used to damp inter-area oscillations [3–5]. As a common practice, the local measurable signals such as rotor speed and active power flow are used as feedback signals to the damping controllers. However, these controllers provide insufficient damping to inter-area oscillations due to lack of global observability capacity of the local feedback signals. From [4–7], it is observed that by using remote signals as feedback signals to design wide-area damping controllers (WADCs) rather than local measured signals, the system performance can be enhanced. With the development of the wide-area measurement systems (WAMS), it is easy to monitor the wide-area dynamic data of power system by using phasor measurement units (PMUs) [8].

WADCs designed by using remote signals improve the stability of an interconnected power system by damping the inter-area oscillations. But the delay caused by the transmission of remote signals and actuator saturation in the control loop may degrade the damping performance, or even cause instability of the closed-loop system [9,4,10]. In power system literature (see for instance [11–14], and references therein), substantial research has been undertaken to model and study the effect of time-delays on the power system stability, but a very few works are reported on the effect of actuator saturation on the power system stability [15–18].

Actuator saturation is an inevitable non-linear phenomenon in engineering applications due to the physical limitations or safety of the equipment. The actuator output signal is limited by minimum and maximum values. Most, if not all, the controllers employed for power

* Corresponding author.
E-mail addresses: chinnaobaiah.m@gmail.com (C.O. Maddela), bidyadhar@nitrkl.ac.in (B. Subudhi).

https://doi.org/10.1016/j.epsr.2018.07.031
Received 12 January 2018; Received in revised form 16 May 2018; Accepted 23 July 2018

system are subjected to actuator saturation, which are different from traditional magnetic saturation of generators. In order to limit the controller output, usually hard saturation is used, e.g. IEEE ST1A and IEEE DC2A, etc. excitation systems for synchronous generator, output of PSS and damping control of FACTS devices. If there exists a saturation, the performance of the damping controllers which is designed without considering actuator saturation may seriously deteriorate [15]. It is reported that the saturation function is handled by using two approaches, e.g. polytopic approach and sector bound approach in [19,10,20,21]. We use sector bound approach in this paper because of its applicability for both local and global stability analyses rather than polytopic approach which is only applicable for local stability analysis.

In this paper, we propose a delay-dependent supplementary damping controller design for FACTS devices to enhance the damping of inter-area oscillations of power system when time-delays and actuator saturation are simultaneously present. Series and shunt connected FACTS controllers are mainly used for dynamic compensation in power systems, these can provide improved voltage profile of the grid, enhanced transient stability and damping of power oscillations. Shunt connected controller controls the transmission voltage by reactive shunt compensation. Reactive shunt compensation is highly effective in maintaining the desired voltage along the transmission line but ineffective in controlling the transmitted power. By variable series compensation, the series connected controllers are highly effective for both controlling power flow in the line and improving stability. Therefore, if the purpose of the application is to control the current/power flow and damp oscillations, the series controller for a given MVA size is several times more powerful than the shunt controller [22]. Among the several series compensator devices, SSSC is a voltage source type and TCSC, TSSC, and GCSC are variable impedance type series compensators. Despite of numerous advantages of SSSC over TCSC, TSSC, and GCSC, the thyristor based device (TCSC) is still used as a practical option for the application of damping of inter-area oscillations and/or power flow control when the wide range of controllability of the SSSC is not necessary. There are relatively large number of various actual TCSC applications around the world due to the higher rating and lower cost of thyristors [23].

In our work, we chose to use a series connected controller i.e. thyristor controlled series capacitor (TCSC) as an actuator with supplementary damping controller to damp the inter-area oscillations among the various FACTS devices. The objective of the paper is to design a state feedback controller to achieve asymptotic stability and maximization of region of attraction of the closed-loop system in presence of time-delays and actuator saturation. The contributions of the paper are as follows.

- A generalized sector condition is used to derive the sufficient conditions for asymptotic stability of the closed-loop system based on Lyapunov–Krasovskii approach.
- The design of state feedback control law that maximizes the region of attraction is formulated in the form of a Linear Matrix Inequality (LMI) which is solved as an optimization problem to achieve damping of inter-area oscillations.
- A two-area four-machine benchmark power system model is used to evaluate the effectiveness of the proposed damping controller.

The remainder of the paper is organized as follows. Section 2 describes modeling of different components of interconnected power systems. Section 3 provides problem formulation. Delay-dependent stability criteria and stabilization of system with time-delay and actuator saturation are presented in Section 4. Section 5 provides the detailed description of the case study on benchmark model of four-machine two-area power system and non-linear simulations are presented in Section 6. Finally, Section 7 concludes the paper.

2. Dynamic model of interconnected power system

An interconnected power system consists of various components such as synchronous generators with their excitation systems (IEEE-ST1A), power system stabilizers (PSSs), FACTS controllers such as TCSC, SVC, and several loads. These different components are connected through the transmission network. In this section, the dynamic models of each component is developed using a set of non-linear differential and algebraic equations (DAEs) are described in [24].

2.1. Synchronous generator model

The dynamic model of the synchronous generator is described in terms of the following differential-algebraic equations.

2.1.1. Differential equations

The differential equations governing the sixth-order sub-transient model of the synchronous generator is given by.

$$\dot{\delta}_i = \omega_i - \omega_o = \Delta\omega_i \tag{1a}$$

$$\dot{\omega}_i = \frac{\omega_o}{2H_i}[T_{\mathrm{mi}} - (\psi_{\mathrm{di}}I_{\mathrm{qi}} - \psi_{\mathrm{qi}}I_{\mathrm{di}}) - D_i\Delta\omega_i] \tag{1b}$$

$$\dot{E}_{\mathrm{qi}}{}' = \frac{1}{T_{\mathrm{di0}}{}'}[E_{\mathrm{fdi}} - E'_{\mathrm{qi}} - \gamma_{\mathrm{dd}}[I_{\mathrm{di}} - \gamma_{d1}(\psi_{1\mathrm{di}} + \gamma_{\mathrm{dl}}I_{\mathrm{di}} - E'_{\mathrm{qi}})]] \tag{1c}$$

$$\dot{E}'_{\mathrm{di}} = \frac{1}{T'_{\mathrm{qi0}}}[-E'_{\mathrm{di}} + \gamma_{\mathrm{qq}}[I_{\mathrm{qi}} - \gamma_{q1}(\psi_{2\mathrm{qi}} + \gamma_{\mathrm{ql}}I_{\mathrm{qi}} + E'_{\mathrm{di}})]] \tag{1d}$$

$$\dot{\psi}_{2\mathrm{qi}} = \frac{1}{T''_{\mathrm{qi0}}}[-E'_{\mathrm{di}} - \gamma_{\mathrm{ql}}I_{\mathrm{qi}} - \psi_{2\mathrm{qi}}] \tag{1e}$$

$$\dot{\psi}_{1\mathrm{di}} = \frac{1}{T''_{\mathrm{di0}}}[E'_{\mathrm{qi}} - \gamma_{\mathrm{dl}}I_{\mathrm{di}} - \psi_{1\mathrm{di}}] \tag{1f}$$

where

$$\psi_d = -X''_{\mathrm{di}}I_{\mathrm{di}} + E'_{\mathrm{qi}}\gamma_{d2} + \psi_{1\mathrm{di}}\gamma_{\mathrm{dl}}\gamma_{d1}$$
$$\psi_q = -X''_{\mathrm{qi}}I_{\mathrm{qi}} - E'_{\mathrm{di}}\gamma_{q2} + \psi_{2\mathrm{qi}}\gamma_{\mathrm{ql}}\gamma_{q1}$$
$$I_{\mathrm{di}} = \frac{1}{R_{\mathrm{ai}} + \mathrm{j}X''_{\mathrm{di}}}[E'_{\mathrm{di}}\gamma_{q2} - \psi_{2\mathrm{qi}}\gamma_{\mathrm{ql}}\gamma_{q1} - V_{\mathrm{di}}]$$
$$I_{\mathrm{qi}} = \frac{1}{R_{\mathrm{ai}} + \mathrm{j}X''_{\mathrm{di}}}[E'_{\mathrm{qi}}\gamma_{d2} + \psi_{1\mathrm{di}}\gamma_{\mathrm{dl}}\gamma_{d1} - V_{\mathrm{qi}}]$$
$$V_{\mathrm{qi}} = V_i\cos(\delta_i - \theta_i), \qquad V_{\mathrm{di}} = V_i\sin(\delta_i - \theta_i)$$

i refers to ith generator, $1 \le i \le m$.

2.1.2. Algebraic equations

The algebraic equations consist of stator equations and network equations as follows. The stator algebraic equations are given by

$$V_{\mathrm{qi}} - \gamma_{d2}E'_{\mathrm{qi}} - \gamma_{d1}\gamma_{\mathrm{dl}}\psi_{1\mathrm{di}} + R_{\mathrm{ai}}I_{\mathrm{qi}} - X''_{\mathrm{di}}I_{\mathrm{di}} = 0 \tag{2a}$$

$$V_{\mathrm{di}} + \gamma_{q2}E'_{\mathrm{di}} - \gamma_{q1}\gamma_{\mathrm{ql}}\psi_{2\mathrm{qi}} - R_{\mathrm{ai}}I_{\mathrm{di}} - X''_{\mathrm{qi}}I_{\mathrm{qi}} = 0 \tag{2b}$$

Network equations for generator buses are given by

$$V_{\mathrm{qi}}I_{\mathrm{qi}} - V_{\mathrm{di}}I_{\mathrm{di}} - \sum_{k=1}^{k=n} V_iV_k[G_{\mathrm{ik}}\cos(\theta_{\mathrm{ik}}) + B_{\mathrm{ik}}\sin(\theta_{\mathrm{ik}})] = 0 \tag{3a}$$

$$-V_{\mathrm{di}}I_{\mathrm{qi}} - V_{\mathrm{qi}}I_{\mathrm{di}} - \sum_{k=1}^{k=n} V_iV_k[G_{\mathrm{ik}}\sin(\theta_{\mathrm{ik}}) - B_{\mathrm{ik}}\cos(\theta_{\mathrm{ik}})] = 0 \tag{3b}$$

Network equations for load buses are given by

$$P_{\mathrm{Li}}(V_i) + \sum_{k=1}^{k=n} V_iV_k[G_{\mathrm{ik}}\cos(\theta_i) + B_{\mathrm{ik}}\sin(\theta_{\mathrm{ik}})] = 0 \tag{4a}$$

$$Q_{\mathrm{Li}}(V_i) + \sum_{k=1}^{k=n} V_iV_k[G_{\mathrm{ik}}\sin(\theta_{\mathrm{ik}}) - B_{\mathrm{ik}}\cos(\theta_{\mathrm{ik}})] = 0 \tag{4b}$$