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Design of H_∞ Robust Damping Controllers of FACTS Devices with Considering Time-delay of Wide-area Signals

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Abstract-- This paper proposed the design of wide-area robust damping (WARD) controller for multiple Flexible AC Transmission Systems (FACTS) devices to enhance the stability of power system with considering time delay of wide-area signals. Firstly, as power systems interconnect more and more to exchange large amounts, wide-area measurement system (WAMS) is widely applied to monitor and control the interconnected power systems, which can enable the use of measured signals from remote locations for centralized control purpose. In this trend, the impact of time delays introduced by remote signal transmission and processing in WAMS has not been ignored. So this paper describes the wide-area multiple FACTS robust damping controller design problem of power system as time-delay feedback control problem. Then based on the time-delay power system model, wide-area multiple FACTS robust damping controller is design free-weighting matrices method and pole placement method in the linear matrix inequality (LMI). Finally, the case study on 2 areas 4 machines system will show the robustness and effectiveness of this proposed controller.

***Index Terms*-- FACTS devices, damping controller, wide-area measurement system (WAMS), linear matrix inequality (LMI).**

I. Introduction

As power systems interconnect more and more to exchange large amounts, inter-area oscillation has become inherent, which leads to the bad control performance and the instability of power systems [1], [2]. Recently, wide-area measurement system (WAMS) technology is widely applied to monitor and control the large interconnected power systems to improve the stability of systems. Besides flexible AC transmission system (FACTS) are applied to modern power systems to implement power flow control, voltage stability control, power oscillation damping (POD) control, and so on. Up to now, based on the global information measured by WAMS, the FACTS damping controller design can be achieved with rapid advancement in power systems [3-7]. But most of them used a single FACTS device to damp the oscillations.

Therefore, the main aim of this paper is to analyze the design of multiple FACTS devices to enhance the stability of power system with considering time delay of wide-area signals. This paper is organized as follows: in Section II, the concept of wide-area robust damping control for multiple FACTS devices can be described. In Section III, the linearized open-loop plant model with consideration of time delay will be presented, then, based on the free-weighting matrices approach, we will design a wide-area robust damping controller as a state-feedback control for the oscillation damping of the power system. In Section IV, the detail nonlinear simulations on a 2 areas 4 machines system will be performed to evaluate the performance of the proposed wide-area robust damping control. Finally, in section V, we will give some conclusions.

II. Description of Multiple FACTS Wide-Area Damping Control

The basic concept of wide-area robust damping control for multiple FACTS devices can be described as shown in Figure 1. For the large-scale power systems including kinds of FACTS devices (e.g. shunt-type and series-type FACTS devices), the supplementary control functions associated to each FACTS devices can be available for the implementation of wide-area damping control to enhance the overall stability of large-scale power systems.

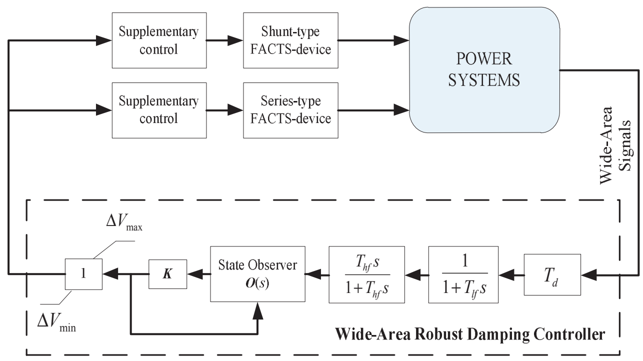

Fig. 1 Basic framework of robust wide-area damping control of multple FACTS devices

From the basic framework as shown in Figure 1, it can be seen that the wide-area control signals should be determined in

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advance before constructing wide-area damping control. Generally, kinds of operating variables such as line power flow, line current, rotor speed of remote generator, and so on, can be selected as the wide-area control input. The classic residue method can be used to choose the suitable control input. In addition, for the wide-area control, the effect of the time delay of the wide-area signals on the wide-area control performance should be considered carefully. In this paper, the Pade approximation is used to represent the time delay characteristic of the wide-area control signals, and the linear robust control theory and design method based on linear matrix inequality is used handle with the robust control problem of the time delay power system.

Furthermore, according to the structure of the wide-area robust damping controller as shown in Figure 1, it can be seen that the high-pass and the low-pass filters (HPF and LPF) are used to process the wide-area control signals. Besides this, it is worth to say that in this paper, the designed controller is the typical state-feedback controller, however, in practice, it could be impossible to realize the observation of all the operating states of the large-scale power systems, therefore, the state observer is introduced to converse such state-feedback control as one kind of output-feedback control. In this paper, the state observer is designed with the classic but practical pole-placement method.

III. Design of Wide-Area Robust Damping Controller for Multiple FACTS Devices

Generally, the dynamical behavior of the power systems with FACTS devices can be described by a set of first-order nonlinear ordinary differential equations and a group of nonlinear algebraic equations. When consider the disturbance of power system, the linearized power system with series-type FACTS device (TCSC) and shunt-type FACTS device (SVC) can be described as

$$\begin{cases} \dot{x}(t) = Ax(t) + B_1 u(t) + B_2 \omega(t) \\ z(t) = \begin{bmatrix} Cx(t) + D_2 \omega(t) \\ D_1 u(t) \end{bmatrix} \end{cases} \quad (1)$$

where $x(t)$ is the state vector, $u(t)$ is the control input, $\omega(t)$ is a disturbance signal, $z(t)$ is the control output. A, B_1, B_2, C, D_1, D_2 are constant matrices with appropriate dimensions.

For a given scalar $\gamma > 0$, the performance of the system is defined to be

$$J(\omega) = \int_0^\infty z^T(t)z(t) - \gamma^2 \omega^T(t)\omega(t)dt \quad (2)$$

Then the H_∞ Robust Controller design Problem addressed in this paper can be stated as described as: for a memory state-feedback controller, find a value for the gain $K \in \Re^{m\times n}$, in the control law

$$u(t) = Kx(t - \tau(t)) \quad (3)$$

Such that for any time-varying delay, satisfying $0 \le \tau(t) \le h$ and $\dot{\tau}(t) \le \mu$

- The closed-loop system (1) should be asymptotically stable under the condition $\omega(t) = 0$;
- $J(\omega) < 0$ for all non-zero $\omega(t)$ under the zero initial condition and a given $\gamma > 0$.

So the system (1) can be described as

$$\begin{cases} \dot{x}(t) = Ax(t) + BKx(t - \tau(t)) + B_2 w(t) \\ z(t) = \begin{bmatrix} Cx(t) + D_2 w(t) \\ BKx(t - \tau(t)) \end{bmatrix} \end{cases} \quad (4)$$

Based on the free-weighting matrices method [8] and Lyaponov stability theory, the following theorem can be obtained and used to design the H_∞ robust damping controllers for the FACTS devices with considering the time-varying delay of singles. For this purpose, the following lemmas will be employed in the proofs of our results. And the notion “ * ” stands for the symmetric matrix.

Lemma (Schur complement) [18] Given a symmetric matrix $S = S^T = \begin{bmatrix} S_{11} & S_{12} \\ S_{12}^T & S_{22} \end{bmatrix}$ ($S_{11} \in \Re^{r\times r}$), the following three conditions are equal.

(1) $S < 0$

(2) $S_{11} < 0, S_{22} - S_{12}^T S_{11}^{-1} S_{12} < 0$

(3) $S_{22} < 0, S_{11} - S_{12} S_{22}^{-1} S_{12}^T < 0$

Theorem For a given time delay, the closed-loop system (4) can keep on the internal stability and also the external disturbance rejection index γ, if there exist real matrices $L > 0$, $\hat{Q}_i > 0, i = 1,2$, $W > 0$, $L > 0$, $Y = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ * & Y_{22} & Y_{23} \\ * & * & Y_{33} \end{bmatrix}$, and any appropriate dimensions matrices, $\hat{N}_i, i = 1,2,3$, $\hat{M}_i, i = 1,2,3$, such that the following matrix inequalities are feasible. Moreover, the gain matrix of such H_∞ controller (3) can be obtained as $K = VL^{-1}$.