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Research article

The design of delay-dependent wide-area DOFC with prescribed degree of stability α for damping inter-area low-frequency oscillations in power system

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ABSTRACT

In this paper, the delay-dependent wide-area dynamic output feedback controller (DOFC) with prescribed degree of stability is proposed for interconnected power system to damp inter-area low-frequency oscillations. Here, the prescribed degree of stability α is used to maintain all the poles on the left of $s = -\alpha$ in the s-plane. Firstly, residue approach is adopted to select input-output control signals and the schur balanced truncation model reduction method is utilized to obtain the reduced power system model. Secondly, based on Lyapunov stability theory and transformation operation in complex plane, the sufficient condition of asymptotic stability for closed-loop power system with prescribed degree of stability α is derived. Then, a novel method based on linear matrix inequalities (LMIs) is presented to obtain the parameters of DOFC and calculate delay margin of the closed-loop system considering the prescribed degree of stability α. Finally, case studies are carried out on the two-area four-machine system, which is controlled by classical wide-area power system stabilizer (WAPSS) in reported reference and our proposed DOFC respectively. The effectiveness and advantages of the proposed method are verified by the simulation results under different operating conditions.

1. Introduction

With the increase of the scale and load ability of power systems, the inter-area low frequency oscillations become a serious problem and often suffer from poor system damping [1,2]. Many power systems in the world are affected by these electromechanical oscillations whose frequency varies between 0.1 and 2 Hz [3]. Traditionally, the damping of low frequency oscillations is provided by installing a power system stabilizer (PSS), which uses local measurements such as rotor speed and active power as feedback signals. Such PSSs can damp the local area modes effectively, while their effectiveness in damping inter-area modes is reduced because such modes are not observable/controllable directly from local signals of the generators.

With the wide application of synchronized phase measurement unit (PMU) in power system, the wide-area measurement system (WAMS) technology has enabled the use of measured information from remote location for enhancing transient stability [4–7]. The availability of remote signals can overcome the aforementioned shortcoming of lacking observability and provide flexibility to damp a special critical inter-area oscillation mode of power system [8]. Although wide-area PSS provides a great potential to improve the damping of inter-area oscillation modes, the delay caused by the transmission of remote signals will degrade the damping performance, or even cause instability of the closed-loop system [9,10]. Therefore, the influence of time delay must be fully taken into consideration in the controller design.

In the published works about the time delay issue of power system, three different strategies are often adopted. The first is to design controllers without considering time delay [5,11]. The second strategy is to make use of Pade approximation method, which can approximate time delay during model linearization [12–14]. It's obvious that the accuracy of Pade approximation changes with the change of order number and the higher the order number is, the higher the accuracy is. However, the amount of calculation will greatly increase. The third is to employ some robust control methods, which can keep the system stable within a certain delay [6,9,15–17]. Though the fore-mentioned controllers can ensure the stability of power systems, it may produce weakly damped inter-area oscillation mode, which is not acceptable in damping control of power system due to the larger oscillation amplitude and longer fluctuation time.

The idea of prescribed degree of stability is proposed in theory to deal with weakly oscillation mode [18]. This concept is applied

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to power system to damp low-frequency oscillations in [19,20], where [19] designs a nonlinear decentralized feedback controller and [20] presents a WAPSS design under the condition of given damping factor and required signal transmission delay. The literature [20], above mentioned [6,9] and [21] are dedicated to obtain the parameters of WAPSS by lead-lag compensation method, but this method is no more effective because the strong coupling between the local oscillation modes and the inter-area modes would make the tuning of PSSs for damping all modes nearly impossible and the only adjusted gain would make the control effect very limited [22,23].

The WAPSS described in the form of transfer function is a dynamic output feedback controller by nature. Recently, the DOFC design has received particular research interests owing to the partially known state information and inaccurate measurement information in practical application [24,25]. However, in many cases, the design methods of state feedback controller cannot be easily applied to those of dynamic output feedback controller, which makes output feedback control generally more difficult and involved [26–29]. Without considering the time delay of closed-loop systems, the continuous and discrete DOFC are respectively designed in [26] and [27,28]. Though [29] presents a novel DOFC design and acquires its parameter matrices for discrete-time Takagi-Sugenno fuzzy system with time-varying delays, it is still very difficult for continuous time-delay system to obtain these parameter matrices.

Motivated by the above investigation, the delay-dependent wide-area DOFC with prescribed degree of stability in this paper is developed to improve the damping inter-area oscillation, where the prescribed degree of stability guarantees all the poles of closed-loop power system on the left of $s = -\alpha$ in the s-plane. At first, the modal analysis of the linear model for power system excluding wide-area damping controller is applied to find out the low-frequency oscillation modes and identify the critical inter-area mode. Next, residue approach is utilized to select the most efficient input-output control signals. Then, the delay margin based on prescribed degree of stability and the parameters of DOFC are obtained by solving the derived LMIs. Finally, based on the full-order model of two-area four-machine power system, simulation studies are undertaken to verify the effectiveness and demonstrate the advantages of the proposed method. The main contribution of the paper can be summarized as follows.

1) The prescribed degree of stability realized by transformation operation in complex plane is introduced to deal with weakly damped inter-area oscillation modes.

2) The delay-dependent sufficient conditions of asymptotic stability for closed-loop power system with prescribed degree of stability are derived.

3) A novel method based on LMI is presented to solve parameters of dynamic output feedback controller and calculate the delay margin with prescribed degree of stability.

Notations. The superscript “T”, “H” and “−1” stand for matrix transposition, conjugate transpose and inverse, respectively; R^n denotes the n-dimensional Euclidean space; the notation $P > 0$ means that P is real symmetric and positive definite; I and 0 represent the identity matrix and zero matrix, respectively.

2. Problem formulation

2.1. Modal analysis and selection of wide-area signals

The nonlinear dynamic model of power system is usually described by a set of differential-algebraic equations. The whole power system excluding the local PSS and wide-area damping controller can be linearized at an equilibrium point as follows

$$\begin{cases} \dot{x}_0(t) = A_0 x_0(t) + B_0 u_0(t) \\ y_0(t) = C_0 x_0(t) \end{cases} \tag{1}$$

where $x_0(t) \in R^{n\times 1}$, $u_0(t) \in R^{m\times 1}$ and $y_0(t) \in R^{p\times 1}$ are the state, input and output vectors, respectively. $A_0 \in R^{n\times n}$, $B_0 \in R^{n\times m}$ and $C_0 \in R^{p\times n}$ are the state, input and output matrices, respectively.

An eigen analysis of matrix A_0 produces the distinct eigenvalues λ_k (assumed distinct for $k=1,\ldots,n$) and corresponding matrices of the right and left eigenvectors $E = \left[e_1^T \; e_2^T \; \cdots \; e_n^T\right]^T$ and $F = \left[f_1 \; f_2 \; \cdots \; f_n\right]$, respectively.

The transfer function of interconnected system associated with (1) is expressed by

$$H(s) = C_0\left(sI_n - A_0\right)^{-1}B_0 = \sum_{k=1}^{n} \frac{R_k}{s - \lambda_i} \tag{2}$$

where $R_k \in C^{p\times m}$ is the residue matrix associated with mode λ_k and

$$R_k = Ce_k f_k^H B \tag{3}$$

For $i=1,\ldots,p$ and $j=1,\ldots,m$, the element $r_k(i, j)$ of matrix R_k are given by

$$r_k(i, j) = C_i e_k f_k^H B_j \tag{4}$$

If the maximal value $r_k(i, j)$ of the residues associated with mode k is obtained, then control input $u_j(t)$ and feedback signal $y_i(t)$ are the most efficient signals to damp mode k.

2.2. Modeling of power system with time delay

For a large-scale power system, the order of the linearized model is comparatively high, which makes the design of a controller difficult or even infeasible. Moreover, the analysis of low frequency oscillation does not require the full-order model, as fast dynamic modes are not considered in this case. Hence, a model reduction method is always used to reduce the order of the whole power system. In this paper, the Schur balanced truncation model reduction method is used to find the reduced-order system and its details can be found in [30]. The reduced-order model of the open-loop power system excluding the wide-area damping controller can be linearized at an equilibrium point as follows

$$\begin{cases} \dot{x}(t) = A_1 x(t) + B_1 u(t) \\ y(t) = C_1 x(t) \end{cases} \tag{5}$$

where $x(t)$, $u(t)$ and $y(t)$ are the state, input and output vectors, respectively. A_1, B_1 and C_1 are the state, input and output matrices of the reduced-order power system.

The structure of the closed-loop power system, which includes the reduced-order power system, wide-area damping controller and transmission delay d of the wide-area signal, is shown in Fig. 1.

The wide-area damping controller adopted in the form of dynamic output feedback controller is shown in Fig. 1 as

$$\begin{cases} \dot{x}_W(t) = A_W x_W(t) + B_W u_W(t) \\ y_W(t) = C_W x_W(t) + D_W u_W(t) \end{cases} \tag{6}$$

where $x_W(t)$, $u_W(t)$, $y_W(t)$ are the state, input and output vectors of DOFC, A_W, B_W, C_W and D_W are the state, input, output and transmission matrices of DOFC to be determined.

The connection between the open-loop power system and WADC is represented as

$$\begin{cases} u(t) = y_W(t) \\ u_W(t) = y(t - d) \end{cases} \tag{7}$$