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Design and implementation of a measurement-based adaptive wide-area damping controller considering time delays

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ABSTRACT

Wide-area measurement systems enable the wide-area damping controller (WADC) to use remote signals to enhance the small signal stability of large scale interconnected power systems. System operating condition variations and signal transmission time delays are the major factors to worsen the damping effect and even deteriorate the system stability. This paper proposes a novel measurement-based adaptive wide-area damping control scheme using oscillation mode prediction and system identification techniques. These techniques adjust the parameters of WADC as well as the time delay compensation in an online environment. To achieve fast online implementation, an identified high order multi-input multi-output (MIMO) model is deformed into a low order single-input single-output (SISO) model according to the residue of MIMO model. The SISO model can accurately represent the power system dynamics in the form of a transfer function, capturing the dominant oscillatory behaviors in the frequency range of interest. Moreover, the WADC has been implemented on a hardware test-bed (HTB) by adding its output signal to the excitation system of a selected generator. The effectiveness of the proposed measurement-based adaptive WADC has been demonstrated in a two-area four-machine system on the HTB under various disturbance scenarios.

1. Introduction

With the increasing interconnection of large power grids, the power exchange among different areas via long distance transmission lines has significantly increased. The inter-area oscillations have been a critical issue limiting the power transfer capability and even deteriorating the security of the entire power system [1,2]. Therefore, damping of inter-area oscillations is one of the main concerns in the enhancement of power transmission and improving power system stability [3]. With the development of the wide-area measurement systems (WAMS), power system controllers can now utilize remote feedback signals from different locations of the power grid. The utilization of global signals can provide a better observation of inter-area modes, and overcome the shortcomings of local power system stabilizers (PSSs) [3–6]. However, most of wide-area damping controllers (WADCs) are tuned based on a number of typical operating conditions [3–7]. Although such methods are based on the exact model of power system and are well suited for off-line designing, the performances of designed WADCs may degrade if the actual operating condition is significantly different from what was considered in the offline design procedure. In some extreme cases, WADCs even provide negative damping.

The robust control technology is first utilized to solve the operating condition variation. In general, a robust oscillation damping controller is designed based on a detailed system model under a selected dominant operating condition with bounded model uncertainty [8–10]. The variations of the operating condition are reflected in the additive or multiplicative uncertainty of the system model. However, the number of operating conditions taken into consideration is limited due to computational complexity and increased chances of infeasibility. Additionally, in a real power system, the number of operating conditions is undoubtedly more than hundreds of thousands. Thus it is difficult to find a feasible solution for a polytope to accommodate the numerous operating conditions [11].

The adaptive control technology is another approach to improve the adaptivity of the controller. This technology can adjust the

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controller parameters based on the online estimated system model, and therefore, can adapt to the continuous variations in operating conditions. The adaptive control approach is more and more attractive as these technologies rely solely on PMU measurements since WAMS is capable to provide real-time measurements of the power system state with satellite-triggered time stamp in time intervals down to 20 ms [12–14].

On the other hand, although WADCs provide a great potential to improve the damping of inter-area oscillation, the signal time delays, mainly introduced by the long distance transportation of feedback signal, will degrade the damping performance and may even cause instability of the closed-loop system [15,16]. Those time delays can typically vary from tens to hundreds milliseconds, depending on the routines of signal transportation, communication protocols, and network load [17]. WADC design considering time delay has been addressed, such as applying a nonlinear bang-bang control method to deal with time delays [18] and designing robust controllers to handle the time delay as a part of the system uncertainties [19,20]. Although these methods could be used to design WADCs for various time delays offline, complex treatment of time delays would not only increase the processing time but also reduce the practicability of wide-area damping control online. Considering these disadvantages, a simple but practical local time delay compensator is designed to eliminate the influence of the signal transmission time delay.

This paper presents the design and implementation of an adaptive wide-area damping control system (WADCS) based on solely wide-area measurements: (1) fast Fourier transform (FFT) is employed to preselect remote signals in each area as the output signals of the transfer function model for identification; (2) the autoregressive exogenous model (ARX) identification technology [21–24] is adopted to identify the multi-input multi-output (MIMO) system model; (3) a control loop is selected based on the residue of the MIMO ARX model; (4) a SISO ARX prediction model is constructed according to the control loop for adjusting the WADC parameters online; (5) a practical time delay compensator is designed to eliminate the influence of the time delay; and (6) real-time implementation of the proposed WADC is applied on a two-area four-machine system on hardware test-bed (HTB), which is a converter based reconfigurable power grid emulator system serving as a platform for power system control methodology test and demonstration.

The remaining of this paper is organized as follows. The methodology of the adaptive WADC design is introduced in Section 2. In Section 3, the proposed WADC is validated by the case study in a two-area four-machine system on hardware test-bed (HTB). Discussion and future work are given in Section 4. Section 5 concludes this paper.

2. Methodology of adaptive WADC design considering time delay

The overall structure of an adaptive WADC design considering time delay is shown in Fig. 1(a). The WADC is designed to damp a critical inter-area oscillation mode by providing supplementary damping control signal for PSS as shown in Fig. 1(a). A classical lead-lag type WADC is considered. The time delay from the remote signals for the whole control loop is simplified as one single delay d at the feedback loop and represented by an e^{-sd} block in Fig. 1(b). An ARX model is used to predict the feedback signal and obtain the oscillation for adjusting the controller parameters.

As shown in Fig. 1(b), the transfer function of a classical WADC [3] is

$$H_{\mathrm{WADC}}(s) = K_{\mathrm{WADC}} \frac{T_w s}{1 + T_w s} \left(\frac{1 + sT_1}{1 + sT_2} \right)^m = K_{\mathrm{WADC}} H'_{\mathrm{WADC}}(s) \qquad (1)$$

where T_1 and T_2 are the lead and lag time constants, respectively, T_w is the washout constant usually as 5–10 s, K_{WADC} is the gain of the WADC, m is the number of the lead-lag block and m is usually given the value of 2 [4].

The details of the proposed adaptive WADCS design are described in the following subsections.

2.1. Signal detrending

Trend in a time series is a slow, gradual change in some property of the series over the whole study time window. For system identification, all signals should be detrended. There are different detrending methods, e.g., first differencing, curve fitting and digital fitting. First differencing is used in this paper for practical application. It is defined as

$$y(t) = y'(t) - y'(t-h) \qquad (2)$$

where $y'(t)$ is the original measurement signal, $y(t)$ is the detrended signal, and h is the sample time interval.

For dynamics study, we focus on the dynamics of the original signal $y'(t)$ instead of the detrended signal $y(t)$. To recover the original signal from the detrended signal, the inverse form of first differencing filter is

$$y'(t) = y(t) + y'(t-h) \qquad (3)$$

2.2. MIMO ARX model identification

Fast online identification of the system model to capture all critical modes of the power system is the prerequisite of the adaptive oscillation damping control. Two categories of measurement-based models can be used for system identification: state-space model [25–29], and transfer function model [30–33]. The state-space representation is concerned not only with input and output properties of the system but also with its complete internal behavior. In contrast, the transfer function representation is concerned with and specifies only the input/output behavior [1]. Hence, the transfer function model identification can be an alternative to overcome the drawback of high computation burden of state-space methods. The linear MIMO ARX model is adopted to construct the system model off-line both to determine the control loop for each critical mode and to deform the SISO ARX model for each critical mode by predicting the future mode ahead for adjusting the controller parameters.

With measured signal $y(t)$ as the model output signal, measured signals $u(t)$ as the model input signal, the mathematical structure of the single-input single-output (SISO) ARX model structure [21] is described as:

$$y(t) + a_1 y(t-1) + \cdots + a_{n_a} y(t-n_a) = b_0 u(t) + b_1 u(t-1) + \cdots + b_{n_b} u(t-n_b) + e(t) \qquad (4)$$

where t is the time index, and $e(t)$ is a white noise. n_a and n_b are the orders of the signal $y(t)$ and $u(t)$, respectively.

With the SISO ARX model structure (4) the multi-input single-output (MISO) ARX model structure can be derived:

$$y_i(t) + a_{i1} y_i(t-1) + \cdots + a_{in_a} y_i(t-n_{ai}) = \sum_{j=1}^{M} \left(b_{ij0} u_j(t) + b_{ij1} u_j(t-1) + \cdots + b_{ijn_{bij}} u_j\left(t - n_{bij}\right) \right) + e(t) \qquad (5)$$