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CIGRE US National Committee
2015 Grid of the Future Symposium

Demonstration of Measurement Derived Model-Based Adaptive Wide-Area Damping Controller on Hardware Testbed

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SUMMARY

One of the main drawbacks of the existing oscillation damping controllers that are designed based on offline dynamic models, is adaptivity to the power system operating condition. With the increasing availability of wide-area measurements and the rapid development of system identification techniques, it is possible to identify a measurement-based transfer function model online that can be used to tune the oscillation damping controller. Such a model could capture all dominant oscillation modes for adaptive and coordinated oscillation damping control.

This paper proposes a measurement derived model-based adaptive wide-area damping controller. Firstly, the system model in the form of multiple-input multiple-output AutoRegressive Moving Average with eXogenous inputs (ARMAX) is identified online by using ambient data or ringdown data. Secondly, the frequency and residue angle of the target oscillation mode are derived from the identified model to update the controller parameters. Thirdly, a time delay compensator employing the lead-lag structure is proposed to compensate for random time delay. Assuming constant time delay in one control cycle, the parameters of the time delay compensator are updated based on the measured time delay in each control cycle. Finally, the proposed adaptive wide-area damping controller is implemented on a hardware testbed, which emulates a two-area four-machine system. The testing on the hardware testbed demonstrates the feasibility of practical realization of a measurement derived model-based wide-area damping control system for small and large disturbances over a wide range of operation conditions.

KEYWORDS

Adaptive Wide-Area Damping Controller, Wide-Area Measurement System, System Identification, Hardware Testbed, Time Delay Compensation

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1. Introduction

In today's interconnected power grids, low-frequency oscillation is a significant issue limiting the power transfer capability and even deteriorating the power system security. Local and wide-area power system stabilizers (PSSs) are installed or proposed to provide supplementary damping control through generator excitation systems [1], flexible alternating current transmission systems (FACTS) devices [2], and high-voltage direct current (HVDC) links [3] to suppress these low-frequency oscillations. However, one of the main drawbacks of the existing oscillation damping controllers that are designed based on offline dynamic models, is adaptivity to the power system operating conditions. If the actual operating condition is significantly different from the typical operating conditions considered in the offline design procedure, the controller's performances may degrade. In some extreme cases, they even provide negative damping.

A robust control scheme can be utilized to improve adaptivity. 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 [4], [5]. The variations of operating condition are reflected in the additive and/or multiplicative uncertainty of the system model. Nevertheless, it is not easy to determine the uncertainty boundary of the system model, and the controller performance may not be optimal when the actual operating condition deviates from the dominant one.

With the increasing availability of wide-area measurements and the rapid development of system identification techniques, it is possible to identify a measurement-based transfer function model in an online environment. Since the system model can depict all the dominant oscillation modes, it is feasible to optimize the controllers' parameters at the control center, and remotely configure the parameters of dispersed damping controllers. In this way, the controller parameters can be updated online to track the continuous variations in operating conditions. For instance, a self-tuning adaptive PSS based on artificial neural networks is proposed in [6]. In [7], the parameters of phase lead-lag compensators are updated based on the online modal analysis.

This paper presents a Wide-area Damping Controller (WADC) based on a measurement derived model. The entire power system is represented by a linear transfer function in the form of multiple-input multiple-output (MIMO) AutoRegressive Moving Average with eXogenous inputs (ARMAX), and the controller parameters are updated based on the identified model to improve adaptivity. Additionally, an adaptive time delay compensator employing a lead-lag structure is utilized to reduce the impact of random time delay. 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.

2. Design of adaptive measurement model-based WADC

2.1 Overview of the WADC

Fig. 1 shows the overall architecture of the adaptive WADC. The adaptive WADC is designed to damp a critical inter-area oscillation mode by providing supplementary damping control signal through generator excitation system. The adaptive WADC consists of two parts: conventional controller employing lead-lag structure, and a time delay compensator. The entire power system is represented by a MIMO ARMAX model with generator bus frequency as output signal. The identified system model will be used to calculate the eigenvalues of the oscillation modes, which can be used to update the parameters of the wide-area PSS. The time delay compensator is used to reduce the impact of random time delay due to communication.

2.2 System identification

In the discrete-time domain, the entire system can be represented by a MIMO ARMAX model as [8]

$$\alpha(z)y(t) = \beta(z)u(t) + \gamma(z)e(t) \tag{1}$$

where $y(t)$ is the vector of m outputs, $u(t)$ is the exogenous part which is the vector containing the known p excitations, and $e(t)$ is the moving average part which is the vector with q unknown noise. $\alpha(z)$, $\beta(z)$ and $\gamma(z)$ are the autoregressive polynomial matrix, the exogenous polynomial matrix, and the moving average polynomial matrix, respectively. z is the shift operator.The matrices $\alpha(z)$, $\beta(z)$ and $\gamma(z)$ in (1) can be expanded as (2)-(4). The coefficient matrix can be calculated by using two-stage least square algorithm [8].

$$\alpha(z) = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} + \begin{bmatrix} {\alpha_{11}}^{(1)} & \cdots & {\alpha_{1m}}^{(1)} \\ \vdots & \ddots & \vdots \\ {\alpha_{m1}}^{(1)} & \cdots & {\alpha_{mm}}^{(1)} \end{bmatrix} \times z^{-1} + \cdots + \begin{bmatrix} {\alpha_{11}}^{(n_\alpha)} & \cdots & {\alpha_{1m}}^{(n_\alpha)} \\ \vdots & \ddots & \vdots \\ {\alpha_{m1}}^{(n_\alpha)} & \cdots & {\alpha_{mm}}^{(n_\alpha)} \end{bmatrix} \times z^{-n_\alpha} \quad (2)$$

$$\beta(z) = \begin{bmatrix} {\beta_{11}}^{(0)} & \cdots & {\beta_{1p}}^{(0)} \\ \vdots & \ddots & \vdots \\ {\beta_{m1}}^{(0)} & \cdots & {\beta_{mp}}^{(0)} \end{bmatrix} + \begin{bmatrix} {\beta_{11}}^{(1)} & \cdots & {\beta_{1p}}^{(1)} \\ \vdots & \ddots & \vdots \\ {\beta_{m1}}^{(1)} & \cdots & {\beta_{mp}}^{(1)} \end{bmatrix} \times z^{-1} + \cdots + \begin{bmatrix} {\beta_{11}}^{(n_\beta)} & \cdots & {\beta_{1p}}^{(n_\beta)} \\ \vdots & \ddots & \vdots \\ {\beta_{m1}}^{(n_\beta)} & \cdots & {\beta_{mp}}^{(n_\beta)} \end{bmatrix} \times z^{-n_\beta} \quad (3)$$

$$\gamma(z) = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} + \begin{bmatrix} {\gamma_{11}}^{(1)} & \cdots & {\gamma_{1q}}^{(1)} \\ \vdots & \ddots & \vdots \\ {\gamma_{m1}}^{(1)} & \cdots & {\gamma_{mq}}^{(1)} \end{bmatrix} \times z^{-1} + \cdots + \begin{bmatrix} {\gamma_{11}}^{(n_\gamma)} & \cdots & {\gamma_{1q}}^{(n_\gamma)} \\ \vdots & \ddots & \vdots \\ {\gamma_{m1}}^{(n_\gamma)} & \cdots & {\gamma_{mq}}^{(n_\gamma)} \end{bmatrix} \times z^{-n_\gamma} \quad (4)$$

where n_α, n_β and n_γ are the orders of the outputs, exogenous inputs, and noise, respectively. $\alpha(z)$ is an $m \times m$ matrix, $\beta(z)$ is an $m \times p$ matrix, and $\gamma(z)$ is an $m \times q$ matrix.

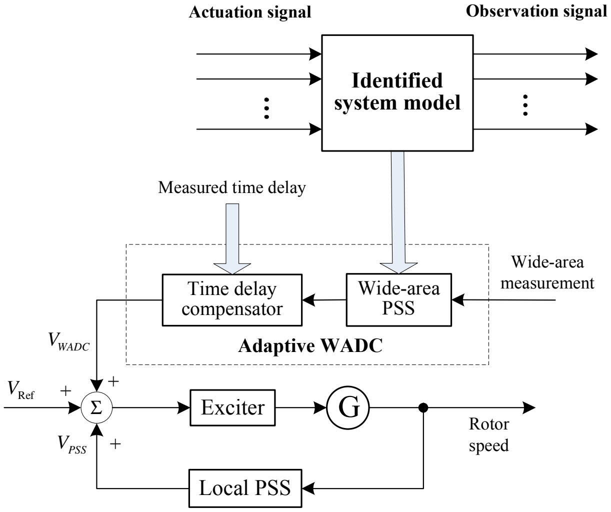


Fig. 1. Adaptive WADC considering time delay

The online model identification is triggered by system events including generation trip, load shedding, and topology changes due to line trip, etc. and the model will be updated. In addition, the identification procedure can be triggered by a predefined timer (periodical trigger). If there is no system events, the model will be updated using collected ambient data every 5 minutes.

After identifying the ARMAX model, it is necessary to validate whether the model is good enough to describe the system oscillatory characteristics [9]. The identified ARMAX model is validated in both time domain and frequency domain. In time domain, the response of the identified model is compared with actual system response. In frequency domain, the eigenvalues calculated by the denominator polynomial of the MIMO ARMAX model are compared with results of Matrix Pencil (MP) analysis of the measurement data. MP is a modal extraction technique (similar to Prony method), which effectively estimates the dominant modes' information in a response [10].

2.3 Parameter update of wide-area PSS

As shown in Fig. 1, the transfer function of a classical wide-area PSS is

$$H_{WADC}(s) = K_{WADC} \frac{T_w s}{1 + T_w s} \left(\frac{1 + sT_1}{1 + sT_2}\right)^2 \quad (5)$$

where T_1 and T_2 are the lead and lag time constants, respectively. T_w is the washout constant, K_{WADC} is the gain of the WADC.

$$T_1 = \frac{1}{\omega\sqrt{\alpha}}, T_2 = \alpha T_1, \alpha = \frac{1 - \sin\frac{\phi_{NMk}}{2}}{1 + \sin\frac{\phi_{NMk}}{2}} \quad (6)$$

where ω is the oscillation frequency of the mode λ_{NMk}, ϕ_{NMk} is the residue angle of the mode λ_{NMk}.

The system model identified by using ambient data or ringdown data is used to calculate the eigenvalue of target oscillation mode, and residue angle of the selected control loop. Then, the time constants T_1 and T_2 can be updated to track continuous variations of operating condition.

2.4 Parameter update of time delay compensator

In order to eliminate the effects of the time delay, the following transfer function will be used to compensate the phase lead/lag and the gain drift:

$$H_c(s) = K_c\left(\frac{1+sT_{c1}}{1+sT_{c2}}\right)^2 \tag{7}$$

where $T_{c1} = \dfrac{1}{\omega\sqrt{\alpha_c}}$, $T_{c2} = \alpha_c T_{c1}$, $\alpha_c = \dfrac{1-\sin\frac{\omega\tau}{2}}{1+\sin\frac{\omega\tau}{2}}$, $K_c = \beta\dfrac{1}{\gamma}$, $0<\beta<1$.

where ω is the oscillation frequency of the mode λ_{NMk}, τ is the measured time delay, and β can be adjusted according to the performance of the compensation.

Assuming the delay is constant in one control cycle, the parameters of the time delay compensator could be updated to reduce the impact of random time delay. Accurate time from the global positioning system (GPS) would be received locally in both the PMUs and the time delay compensator. Wide-area phasors measured by the PMUs at time ta are collected and resynchronized by the Phasor Data Concentrator (PDC) and in turn processed by the adaptive WADC to generate the wide-area damping control signal with a time stamp [ta]. When the local time delay compensator, which is installed close to the generator exciter, receives the control signal [tb], the signal will be re-labelled with a new time stamp [tb] also obtained from GPS and the exact time delay can be calculated accurately as τ = tb-ta because of the high-resolution time service provided by the GPS.

3. Demonstration on hardware testbed

3.1 Implementation of WADC on hardware testbed

The hardware testbed in the National Science Foundation and Department of Energy (NSF/DOE) engineering research center-Center for Ultra-wide-area Resilient Electric Energy Transmission Networks (CURENT), is a platform built for power grid control methodology test and demonstration. The two-area four-machine system as shown in Fig. 2 is now emulated on the hardware testbed, which provides a perfect environment for WADC implementation, testing, and demonstration. The configuration of the hardware testbed is shown in Fig. 3. A LabVIEW-based control system has been developed to emulate some functions of an actual power system control center. It gathers the measurement data from monitoring devices in the HTB and sends control commands to virtual generators through Ethernet. MATLAB code of an adaptive WADC was integrated into the HTB control software using standard LabVIEW interface. The configuration and parameters of this two-area four-machine system are described in [11].

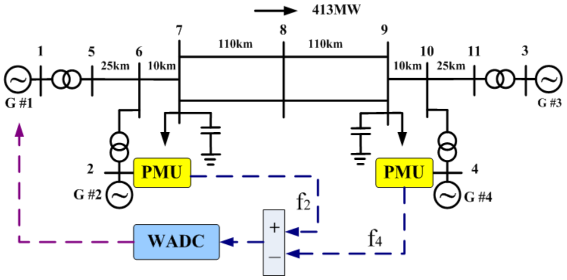


Fig. 2. Two-area four-machine system.

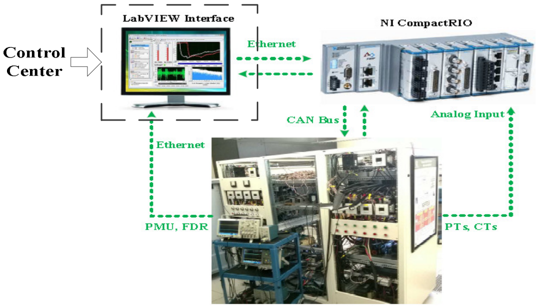


Fig. 3. HTB configuration.

3.2 Controller performance

In order to test the effectiveness and robustness of the proposed adaptive WADC, the following four typical scenarios and the captured dominant mode during different operating conditions are shown in Table 1. The parameters of the adaptive WADC in each case are listed in Table 2. The time delay in the communication channel of HTB is 100ms to 300ms.

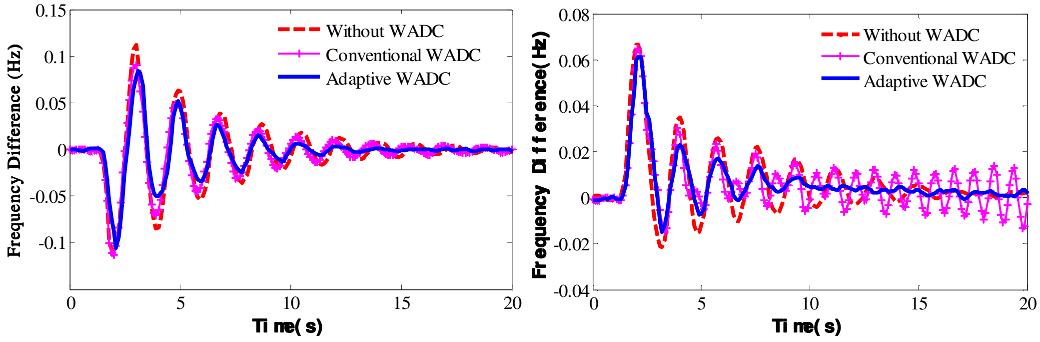
Table 1 Case Study Details

No.	PSS Location	Event Type	Event Location	Change (p.u.)	Frequency (Hz)	Damping Ratio
1	G1,G3	Load Increase	L2	0.4 to 0.7	0.58	4.2%
2	G1,G3	Generation Increase	G1	0.3 to 0.7	0.56	4.8%
3	G1	Load Increase	L1	0.4 to 1.0	0.56	0.38%
4	G1	Generation Trip	G3	0.4 to 0.05	0.65	1.67%

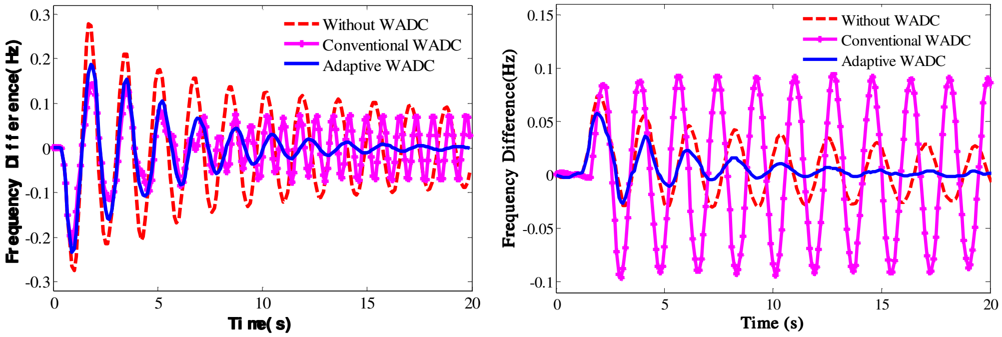
Table 2 Parameters of Adaptive WADC

No.	T_w	T_1	T_2	K_{WADC}
1	10	0.3624	0.2077	0.322
2	10	0.3324	0.2430	0.331
3	10	0.4408	0.1832	0.329
4	10	0.2889	0.2076	0.328

The proposed adaptive WADC is compared to the conventional WADC proposed in [1]. Under the operating condition in Case1 shown in Fig. 4 (a), both the adaptive WADC and traditional WADC can suppress the oscillation. However, when the operating condition is changed from Case 1 to Case 2 or Case 3, the conventional WADC not only cannot suppress the oscillation but also triggers unstable oscillation while the adaptive WADC still has good control performance. From Fig. 4(d), it can be found that the conventional WADC even becomes an oscillation source. Note that the conventional WADC is tuned and tested in a similar operating point as Case 1, but the control performance degrades when the operating condition changes, while the adaptive WADC updates the parameters with the identified SISO model that can track the changes of the operation condition. For Cases 1 and 2, the oscillation can be damped even without control actions, but the settle-down time was shortened after the adaptive WADC was implemented. In Cases 3 and Case 4 there is a poor damping without control. Therefore, the WADC can adapt to a wide range of operating conditions and improve the stability of the power system.



(a) Case 1 (b) Case 2



(c) Case 3 (d) Case 4

Fig. 4 Controller performances comparison in different cases

4. Conclusion

In this paper, an adaptive wide-area damping control system fully based on measurement signals of the power system is proposed and verified. An adaptive WADC and local time delay compensation system was designed that can update the parameters online with the prediction of the dominant mode and compensate the time delay locally. The implementation on the hardware testbed demonstrates the feasibility of practical implementation of a measurement derived model-based wide-area damping control system for small and large disturbances over a wide range of operating conditions.

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