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Time-varying delays and their compensation in wide-area power system stabilizer application

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ABSTRACT

The processing of time delays is one of the key challenges in the use of wide-area power system stabilizer (WPSS) in engineering. In this study, the various time delays and their sources in WPSS applications are analyzed and measured. Strategies to reduce these time delays and the data transmission delay jitter of phasor measurement unit (PMU) used in WPSS closed-loop control are also investigated. A predictive control scheme that addresses the problems caused by time-varying delays in practical WPSS closed-loop applications is proposed. The effectiveness of the proposed scheme is verified through simulation experiments of Guizhou Power Grid (GZPG) in Southwestern China using a real time digital simulator. Moreover, this novel scheme has the potential to be improved and used widely in many applications.

Introduction

The control theory of wide-area power system stabilizer based on wide-area measurement system (WAMS) has been studied extensively. Software simulations and real-time digital simulator (RTDS) based simulations have proved that WPSS can effectively damp the inter-area oscillations in large power systems [1–9]. However, the emergence of wide-area feedback signals has resulted in many communication problems, such as delays of remote signals and design of control parameters. Consequently, no WPSS closed-loop control system has been deployed in real systems, many practical problems still need to be solved. Examples of such problems include selecting the locations of the observation and controlled ends, the selection of wide-area feedback signals, the processing of time delays, the design of control system structure and control strategy, and the real-time synchronization of the system.

The identification of optimal sites for stabilizers is complicated. Yuan [1] and Hashman [2] proposed to place WPSS and select stabilizing signals based on the controllability and observability of linear systems using improved residue matrices. Yanase [3] introduced another method for the selection of generating units by small-signal Prony analysis. The selection of wide-area feedback signal includes rotor angle difference, power angle difference, frequency difference, real power difference, and their combinations [4,5]. The control system typically has a three-layer structure that consists of PMUs, a central controller, and actuators. The controller and actuators are spatially separated from each other. Research on the control strategy of WPSS (including parameter setting) mainly concentrates on the Prony method and its optimization algorithms based on online identification [6], such as $H\infty$ control [7], fuzzy logic control [8], and proportional–integral adjustment method.

In addition to the aforementioned aspects, time-varying delays are one of the key factors that influence the stability and damping performance of a power system and the effectiveness of control system damping [9–12]. Time-varying delays are generally affected by the transmission of remote signals and the transmission channel used. In [10], time delays can ranging from 0.02 s to 0.5 s that are affected by transmission channels were reported. In WPSS application of GZPG, time delays may even reach over 100 ms particularly [11]. In addition, the upper bound of time delay in power system wide-area damping controllers is discussed in [12]. Reference [13] indicates the occurrence of network-induced delays and delays caused by data packet dropout and data disordering in the communication of WAMS. However, the transmission delay jitter of PMUs and some delays caused by data section aligning, calculating, and processing were neglected in the study.

Time delay can weaken system performance or cause instability. Some methods for delay treatment in wide-area control systems, such as linear matrix inequality theory, Pade Smith approximation, fuzzy controllers and grey predictor have been

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proposed recently [14–18]. The simulation results show that these methods can achieve good control effect. However, these methods were verified only in a small-scale power system, and some of them may require large arithmetic complexity and considerable computation time. Consequently, if they are employed directly in real WPSS control systems, they may not be able to satisfy the real-time requirement of the control system.

To our best knowledge, currently, WPSS closed-loop control system has been rarely applied in engineering due to its complexity, so the time delays and their treatment in WPSS control engineering have been seldom studied. Motivated by our recent deployment of the WPSS system in GZPG, this paper investigates the causes of time delays in the practical applications of WPSS control system in GZPG. In comparison with previous works [13], we found that transmission delay jitter of PMUs is an important part of time delays and cannot be ignored, the jitter of three typical PMUs used in GZPG has been measured in this paper. In addition, some delays caused by data section aligning, calculating, and processing must be considered. Moreover, strategies to reduce these time delays and the data transmission jitter in engineering are also presented. Finally, a predictive control scheme that compensates the time-varying delays in practical WPSS applications is proposed. Differing from the previous works [14–18], the real-time characteristics of the proposed scheme is tested and its effectiveness is also verified in the large-scale RTDS simulation of GZPG.

The rest of the paper is organized as follows. Section 'WPSS closed-loop control model of a power system considering time-varying delays' introduces the model of a WPSS closed-loop control system with time delays based on a three-layer structure. Section 'Investigation of time delays in WPSS engineering' analyzes the source of delays of WPSS in practical application and proposes methods for reducing time delays. Section 'A predictive control scheme for WPSS control systems with time varying delays' presents the proposed time-delay adaptive WPSS control scheme. Section 'Experimental studies' discusses the experimental results of the transmission delay jitter, the accuracy and real-time performance of polynomial fitting, and the design of WPSS parameters. The results of the RTDS simulation in GZPG are also presented. The proposed method is found to be applicable to an actual interconnected grid. Finally, conclusions are drawn in Section 'Conclusions'.

WPSS closed-loop control model of a power system considering time-varying delays

A WPSS closed-loop control system based on WAMS generally has a three-layer structure that consists of PMUs, a central controller, and actuators (Shown in Fig. 1). Consequently, a WPSS closed-loop control system can be expressed as the set

$$\mathrm{WPSS} = \{P, S, C\} \tag{1}$$

where P is the set of optimal observation points, S is the set of central controllers, and C is the set of optimal control points.

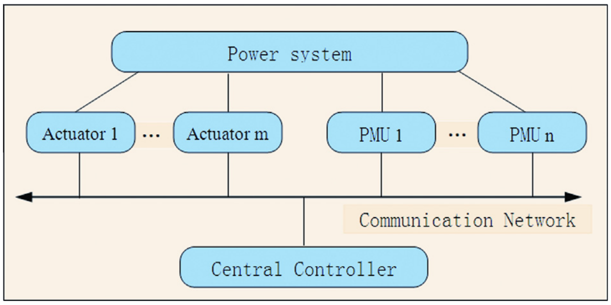

Fig. 1. Typical WPSS closed-loop control system.

A WPSS closed-loop control system is a control system with long delays, packet dropping, and data disordering. It has the following characteristics:

1. Network packet dropping occasionally occurs during node failures or message collisions.
2. Single-packet transmission where the data of PMUs or the controller are lumped together into one network packet and transmitted simultaneously.
3. PMUs are time driven with sending period h, whereas the controller and actuators are event driven.
4. In all data transmissions, each data packet is with time stamp.
5. The total time delays of a WPSS closed-loop control system are generally longer than the sending period h of PMUs.

As shown in Fig. 1, there can be several PMUs in both the observation end and the control end in a typical WPSS control system. For the sake of presentation, a simplified system is used here, which includes two PMUs, say PMU A in the control end, and PMU B in the observation end, one central controller (server), and one actuator. The PMUs send measurement data samples to the central controller at period h, and the central controller generates control data and transmits them to the actuator at period h. Generally, time delays have five types, as will be described in Section 'Investigation of time delays in WPSS engineering'. For a simple analysis, this study classifies these time delays into two categories, namely, PMU-to-controller delay τ_{down} and controller-to-actuator delay τ_{up}. Let

$$\tau = \max(\tau_{\mathrm{up\_A}}, \tau_{\mathrm{up\_B}}) + \tau_{\mathrm{down}} \tag{2}$$

be the total delay. The WPSS closed-loop control system can be considered as a special NCS [19,20] as shown in Fig. 2.

The model in Fig. 2 consists of a continuous part and a discrete part. The PMU collects continuous analog signals from the power system, digitizes and encapsulates them into a series of data packets, and sends them to the controller at certain intervals through the control network. After receiving the data packets from the PMU, the controller then processes them, generates control data based on the received data through a control strategy, and sends the control data to the actuator at certain intervals through the control network.

Investigation of time delays in WPSS engineering

In this section, the various delays in a WPSS control system will be analyzed. In practice, measurements and experience in the GZPG project will be used as an illustration, time delays in WPSS engineering can be generally represented by the following equation:

$$T_{\mathrm{Delay}} = \sum TP_i + \sum TU_j + \sum TS_k + \sum TD_l + \sum TC_m \tag{3}$$

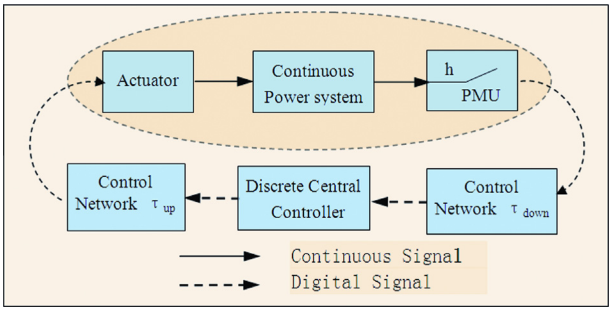

Fig. 2. Modeling of WPSS closed-loop control system with time delays.