Electric Power Systems Research 127 (2015) 22–31

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Design phasor data concentrator as adaptive delay buffer for wide-area damping control

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ARTICLE INFO

Article history:
Received 21 March 2015
Received in revised form 4 May 2015
Accepted 5 May 2015
Available online 6 June 2015

Keywords:
Phasor Measurement Unit
Phasor Data Concentrator
Communication delay
Delay buffer
Power system oscillation
Power system Stability
Wide-Area Monitoring and Control system

ABSTRACT

Phasor Data Concentrators (PDCs) are employed to aggregate data frames from multiple Phasor Measurement Units (PMUs) with the same time-stamp into data packets. This function is an essential step in the utilization of PMU data in Wide-Area Monitoring and Control (WAMC) system. This is facilitated by assigning a fixed and heuristically decided wait time to the PDC buffer. The processed PMU data packets are sent to WAMC applications or similarly PDCs at higher hierarchies in the WAMC system when either a PDC buffer is full or its wait time has passed. In this paper, two methods to configure adaptive PDC wait time based on recent PMU traffic delay patterns are proposed. The purpose is to reduce the frequency of performing delay compensations in wide-area damping control system. With the adaptive PDC delay buffer in place, the wide-area damping controller only switches its gain once every five seconds, given the studied PMU traffic delay scenarios, instead of the current practice which requires the control gain to be adapted on a per PMU data frame basis, e.g., 50 or 60 times every second. The proposed methods offer a perspective to efficiently utilize the supporting Information and Communication Technology infrastructure with the purpose to simplify the design and implementation of wide-area damping control system.

1. Introduction

The application of Phasor Measurement Unit (PMU) data to damp power system inter-area oscillations has been an emerging topic that attracts a great deal of attentions [1,2]. Research proposals on this subject are becoming reality [1,3,4], facilitated by investments on upgrade and expansion of the underlying Information and Communication Technology (ICT) infrastructure that carries PMU data. This is because, as data communication becomes essential in the utilization of PMU data, wide-area damping control system is in fact a networked control system [5], whose functionality is highly, though not exclusively, dependent on the performance of the supporting ICT system [6–8]. Among many ICT factors, the stringent delay requirement on input PMU data is considered as a major obstacle for the development of wide-area damping control system [9,10].

Many delay-robust control strategies have been applied to cater for PMU communication delays in wide-area damping control system. The application of Padé approximation to model communication delays has been at the heart of these solutions. Early proposals are mainly control schemes with fixed structures, e.g., unified Smith predictor-based damping controller proposed in [11]. However, the controller tuned against one specific nominal delay value inevitably leads to suboptimal control results in the full delay spectrum, as the communication delays are usually stochastic. To reduce conservativeness of the design, H_∞-based gain scheduling controller has been proposed in [12]. This control scheme is comprised of a collection of H_∞ controllers, each of which is tuned for one delay nominal value off-line. Based on PMU communication delays measured on the fly, the most appropriate controller is selected to perform the damping control function. However, this off-line approach lacks the flexibility to adapt to the network delays, and control functionality degradation may occur in case the network delay predictions are not accurate. Alternatively, delay compensations can also be performed by adapting control strategies on-line with respect to the encountered communication delays. Typical examples are damping

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http://dx.doi.org/10.1016/j.epsr.2015.05.002
0378-7796/

control schemes developed under the framework of generalized predictive control [13] and adaptive phase shift from rotating coordinates [14]. In addition, a method applying trajectory extrapolation to compensate communication delays has also been reported in [15].

Despite the fact that there are many algorithms available, the actual field tests of these PMU-driven control systems are still limited to the cases reported from the Nordic region [1] and China [3]. Apart from the challenges imposed by the scale and complexity of power system [16], implementing delay-robust wide-area damping control system that performs delay compensations on a per PMU data frame basis, can be challenging. This is because, for damping control purpose, the common practice is to use PMU data frames that are reported at the power system frequency, e.g., 50 Hz or 60 Hz. As the delay compensations are typical performed by solving nonlinear optimization problem or high-order matrix equations, implementation of damping controller, which adapts its control gains for the encountered PMU delays on-line at such high frequencies, requires significant computing power and complex design.

A more feasible alternative is to buffer the PMU data frames at a Phasor Data Concentrator (PDC) for a fixed duration of time prior to their playout. Data frames that arrive after the scheduled playout time, referred to as PDC wait time in the IEEE standard C37.244 [9], are considered late and discarded. In this work, the PDC wait time is designed to adapt to the recent PMU traffic delay patterns to counteract the randomness of the communication network delays (a.k.a, jitters). With the adaptive PDC in place, the wide-area damping controller can be configured against the adaptive PDC wait time and only switches its gain when the PDC wait time changes. As a result, the frequency of adapting delay compensation control strategies can be significantly reduced. The similar concept, named as playout delay buffer, has been widely employed to improve the quality of service for packet audio applications. In [17], the optimal buffer playout delay is estimated by minimizing a cost function formulated based on the patterns of the incoming traffic and intended packet loss rates. Alternatively, there are also solutions relying on modeling of communication delay distributions considering delay histograms. Typical examples are the Concord model, which emphasizes on the recent delay patterns, reported in [18], Pareto distribution suggested in [19], and composite autoregressive and moving average model proposed in [20].

In this paper, two methods to configure PDCs as adaptive delay buffers for wide-area damping control system are presented. The proposals offer an advantage to reduce the frequency of gain switching in wide-area damping control system without degrading the reliability of the control function. By doing this, the design and implementation of wide-area damping control systems can be simplified. To prove the concept, wide-area damping controllers with different configurations are simulated in a comparative study. With respect to the PMU delays in the studied communication network, the simulation study suggests that adapting delay compensation strategies every five seconds is sufficient to avoid control degradation.

The rest of the paper is structured as follows. Section 2 overviews the underlying ICT infrastructure for WAMC systems with a focus on the PDC function. The proposed PDC wait time configuration methods are presented in Section 3. A typical IP-based PMU communication network model is described together with the resulting communication delays in Section 4. Simulation scenarios including wide-area damping controllers with different PDC wait time configurations are presented in Section 5 and the comparative simulation results are analyzed and discussed in Section 6. Summary remarks are provided in Section 7 together with a brief outline of future works.

2. WAMC system and PDC

Generally, a WAMC system includes the following basic components: PMUs, PDCs, applications (which themselves are composed of different information technologies and underlying algorithms), and communication networks that link the above components together [21]. PMUs are sensors where phasors are computed and packed into data frames according to the IEEE standard C37.118 [22,23]. PDCs are the component where voluminous PMU data are aggregated, validated, and archived. Additionally, PDCs also provide functions such as conversion of PMU data format, protocol, and reporting rate, etc. [9]. This paper deals with the configuration of PDC wait time in the data aggregation with time alignment operation mode, while the other PDC operation modes, such as data transferring or aggregation without time alignment are outside the scope. The process of PDC data aggregation with time alignment is illustrated in Fig. 1.

The primary purpose of the PDC data aggregation with time alignment function is to discard PMU data with notable delays. The rationale behind this is twofold. First, as PMUs and PDCs commonly communicate over wide-area networks that cover large geographical territories. Thus, excessive delays due to communication network irregularities are inevitable. Second, WAMC systems are built to exploit the advantages of real-time information. Consequently, PMU data with excessive delays bring no value to the WAMC applications or even run the risk of degrading their functionality [9]. The data aggregation function is facilitated by assigning a wait time to the PDC processing buffer. This wait time represents the amount of time that the PDC processing buffer actively waits for PMU data with the intended time-stamp to arrive, any PMU data frame that is received after the PDC wait time will be discarded. When the buffer is full or the wait time has passed, the PDC forwards the processed data packets to WAMC applications or PDCs at higher hierarchies in the WAMC system. The wait time per se introduces a ceiling in terms of the maximum delay that is experienced at the PDC. This configuration ensures that the PDC can always forward the available PMU data within an expected time horizon by sacrificing data completeness.

3. Adaptive PDC wait time configuration

Though PDCs have been recognized as an essential part of the WAMC system by the standardization efforts [22,23,9], there is no established method available to configure its wait time. To the best of the authors' knowledge, the only published method is from [3], where the PDC wait times are heuristically set to integral multiples of the approximated PMU communication delays. As an initiative to develop quantitative methods to configure PDC wait time, two adaptive methods are proposed in this paper. With the proposed PDC delay buffer in place, not only PMU communication delays are aligned to the PDC wait time, but also packet loss percentiles can be regulated with reference to a scheduled value under various network traffic conditions. In this case, the wide-area damping controller can switch its gain at a more relaxed pace instead of on a per PMU data frame basis. Coupled with the adaptive PDC delay buffer, wide-area damping control system can be implemented without complex design that requires significant computing power. Though the proposed methods are intended for wide-area damping control system, they can also be applied to other PMU-driven applications that require compensations for input delays. The proposed methods can be summarized into the following steps

1 Continuously monitoring communication delays in the PMU traffic.