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A delay-aware cyber-physical architecture for wide-area control of power systems

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ABSTRACT

In this paper we address the problem of wide-area control of power systems using Synchrophasor measurements in the presence of network delays. We propose a novel cyber-physical architecture that uses an arbitrated network control systems approach for mitigating the destabilizing effects of delays in power systems. The approach consists of: (1) utilization of Synchrophasor measurements from distributed measurements across different buses in the power network, (2) estimation of delays that control messages experience, (3) a delay-aware control design that explicitly accommodates the delays and judiciously utilizes estimated system states when needed, and (4) a switching control strategy that aborts the computation of control signals when delays exceed a certain threshold to improve resource utilization. While the control gains are determined using a centralized power system model and state feedback, it is shown that the delay-aware aspects of the proposed architecture allow both distributed measurements and distributed implementation of the control law. The results are illustrated using a 50-bus, 14-generator, 4-area power system model. The results clearly demonstrate that the proposed controller recovers the ideal system performance (such as deviations in frequency<3 mHz) even in the presence of large intra-area and inter-area delays with a small amount of additional control effort. Using the proposed overrun strategy, the results also confirm that about 30% drops can be accommodated with the proposed arbitrated network control systems approach.

1. Introduction

The wide-area measurement systems (WAMS) technology using Phasor Measurement Units (PMUs) has been regarded as the key to guaranteeing stability, reliability, state estimation, control, and protection of next-generation power systems (Chakrabortty & Khargonekar, 2013; Chakrabortty, 2012; Phadke & Thorp, 2008). Wide-area control of power grids helps in suppression of undesired oscillations in power flows, but requires real-time feedback of large volumes of PMU data from one operating region of the grid to controllers located at other regions. Over the past few years several researchers have started investigating such control designs using robust control methods (Zhang & Vittal, 2013), adaptive control (Chakrabortty, 2012; Zima, Larsson, Korba, Rehtanz, & Andersson, 2005), and LQR-based optimal control (Dorfler, Jovanovic, Chertkov, & Bullo, 2013). One of the foremost requirements for wide- area control is the need for a highly robust communication system that works in sync with the control functionalities. The envisioned architecture of wide-area communication for the US grid, often referred to as the North American Synchrophasor Initiative Network or NASPInet (Myrda, Taft, & Donner, 2012) involves PMUs inside the operating boundary of utility companies to send real-time data to local controllers via a local-area communication network, and to remote controllers over a secure wide-area communication network. However, with the exponentially increasing number of PMUs deployed in the North American grid, and the resulting explosion in data volume, the design and deployment of an efficient wide-area communication and computing infrastructure is evolving as one of the greatest challenges to the power system and IT communities. One primary reason behind this challenge is the gradual transition of the computational architecture of WAMS from centralized to distributed for facilitating the speed of data processing (Nabavi, Zhang, & Chakrabortty, 2015). The existing local-area network (LAN) or Internet based communication, as well as the centralized computing infrastructures will no longer be sustainable under the PMU databurst, especially with strict real-time requirements. Moreover, since utilities are unlikely to establish highly expensive, dedicated communication links, the communication infrastructure must be implemented on top of their existing subnetworks. As a result, PMU data used for

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control will have to be transported over a *shared* resource, sharing bandwidth with other ongoing applications, giving rise to not only transport delays, but also significant delays due to queuing and routing.

Motivated by this need to address the stability and performance of wide-area control in the presence of large delays, in this paper we propose a novel cyber-physical WAMS architecture that builds on the approach of Arbitrated Network Control Systems (ANCS) (Annaswamy, Chakraborty, Soudbakhsh, Goswami, & Voit, 2012, 2013; Kauer, Soudbakhsh, Goswami, Chakraborty, & Annaswamy, 2014; Soudbakhsh, Phan, Sokolsky, Lee, & Annaswamy, 2013; Voit, Schneider, Goswami, Annaswamy, & Chakraborty, 2010). The architecture allows for the following three hierarchies: (i) it enables generators distributed over different parts of the grid to exchange PMU measurements of their states with each other for the computation of control signals; (ii) it results in control signals that are delay-aware instead of delay-tolerant, i.e., the control design accommodates the knowledge of the various delays that the PMU measurements are subjected to while being transmitted from one point to another through a wide-area network due to shared computational resources, network traffic, queuing and routing; (iii) it enables the designed controller to be implemented in a completely distributed way.

Figs. 1(a) and (b) illustrate the key aspects of our proposed cyber-physical architecture that accomplish wide-area control using cloud-in-the-loop. The figure depicts a power system divided into multiple areas, each operated by a different utility company. PMU measurements from generators are first aggregated at a local control center, denoted as local Phasor Data Concentrator (PDC), and, thereafter, communicated to an underlying shared computational platform such as a cloud network, where every company is allowed to create its own virtual machine (VM) in a local private cloud. PMU measurements from the local PDC of any utility are first transmitted to its local or private cloud, where these measurements are assigned to their corresponding sets of VMs. For convenience, here we assume that the measurements from any PMU are assigned to one unique VM. We also assume that every generator is equipped with a PMU, which then essentially means that every generator is paired with a unique VM that stores its state measurements (see Fig. 1(a)). The VMs then communicate with each other securely inside the cloud through a high-speed wide-area communication network such as Internet2, and the control input of the i^{th} generator is computed locally at its corresponding VM (see Fig. 1(b)). In the process of communicating measurements among the VMs, control node block of the i^{th} generator receives measurements from other VMs with delays that vary in size depending on the measurement location. Such delays can have a destabilizing effect on the computed input of generators.

The specific wide-area control application that we address in this paper is the damping control of small-signal oscillations in the tie-line power flows following a disturbance in the power system. We assume that all states are measurable at all generators. An ANCS approach will be used to estimate an upper bound for the delays experienced by the control signals before they are actuated. As can be seen from Figs. 1(a) and (b), these delays are due to communication between VMs which may be located in disparate locations, communication between PMUs to PDC, PDC to VM, and VM to generators. Using a network calculus approach that estimates these delays (Annaswamy et al., 2013; Chakraborty et al., 2003), we restate the underlying problem of control of a system with distributed measurements, as the control of a system with centralized measurements with delays. That is, we explicitly accommodate the fact that the state measurements are available at the VMS only after a certain delay (see Section 2 for more details).

The ANCS approach that is used builds on the earlier work in Annaswamy et al. (2012), Voit et al. (2010), Annaswamy et al. (2013), Soudbakhsh et al. (2013), Kauer et al. (2014), Soudbakhsh, Phan, Sokolsky, and Annaswamy (2015), which uses the estimation of the worst case delay in the nominal control design and a standard LQR approach to compute the control gains. Hence, again, as stated before, unlike the traditional robust control designs, our design is delay-aware, not delay-tolerant. In addition to this delay-aware component, we also allow for the delay to vary in relation to a pre-determined threshold, and employ a switching controller that switches between the nominal

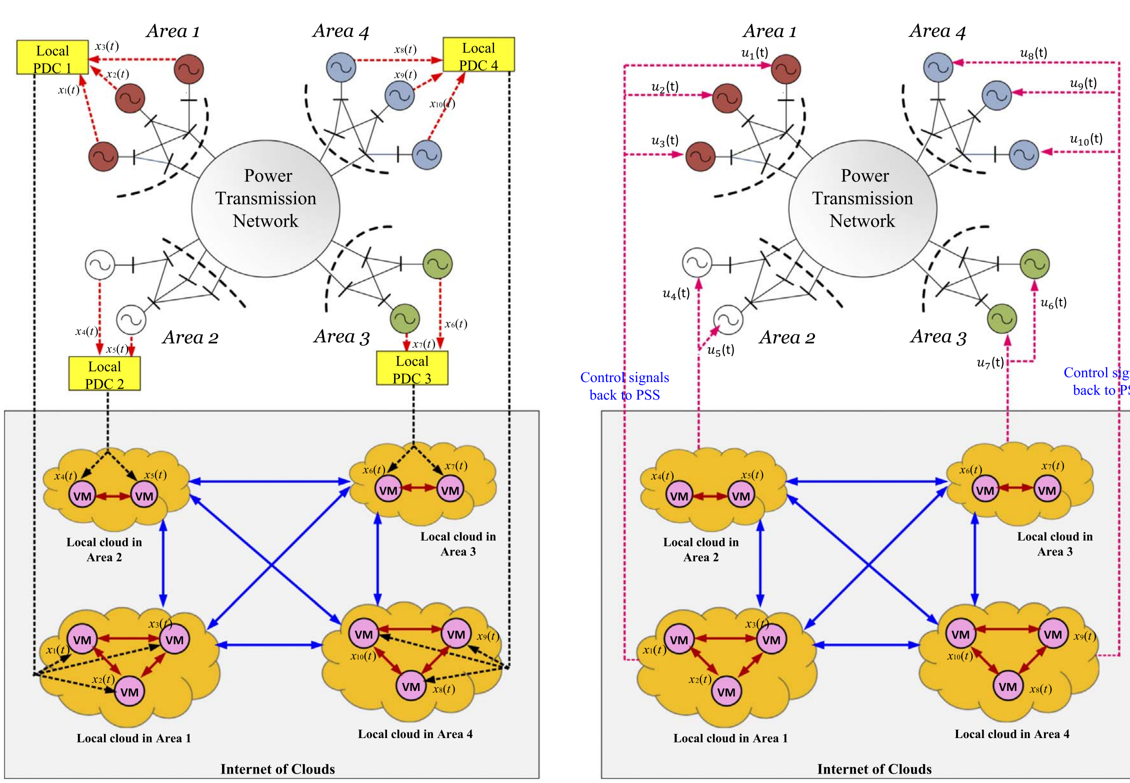

Fig. 1. Cyber-Physical architecture of wide-area control using cloud-in-the-loop, (a) Downlink communication of PMU data to cloud followed by VM-to-VM communication, (b) Uplink communication of control signals from cloud to generation sites.