Available online at www.sciencedirect.com

ScienceDirect

IFAC Papers Online
CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 50-1 (2017) 79–84

Delay-Aware Control Designs of Wide-Area Power Networks [★]

Seyed Mehran Dibaji [*] **Yildiray Yildiz** [**]
Anuradha Annaswamy [*] **Aranya Chakrabortty** [***]
Damoon Soudbakhsh [****]

[*] *Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA, {dibaji,aannu}@mit.edu.*
[**] *Department of Mechanical Engineering, Bilkent University, Ankara, Turkey, yyildiz@bilkent.edu.tr*
[***] *Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695 USA, achakra2@ncsu.edu*
[****] *Department of Mechanical Engineering, George Mason University, Fairfax, VA 22030 USA, dsoudbak@gmu.edu*

Abstract: A co-design of the implementation platform and control strategies for wide-area power networks is addressed. Limited and shared resources among control and non-control applications introduce delays in transmitted messages. The design is based on a delay-aware architecture and cloud computing has been proposed for damping wide-area oscillations. We accommodate possibly large delays in the network and take into account their values in the designs. Moreover, we design output feedbacks for the cases that some state variables are not accessible. The designs are verified through a simulation on 50-bus Australian model.

Keywords: Power systems stability, Wide-area measurement systems, Optimal operation and control of power systems, Cyber-physical Systems, Systems with time-delays

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, 2012; Chakrabortty and Khargonekar, 2013; Phadke et al., 1983). 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. For example, according to UCAlug Open Smart Grid (OpenSG) ope, every PMU requires 600 to 1500 kbps bandwidth, 20 ms to 200 ms latency, almost 100% reliability, and a 24-hour backup. With several thousands of networked PMUs being scheduled to be installed in the United States by 2020, WAMS will require a significant Gigabit per second bandwidth. The challenge is even more aggravated by the gradual transition of the computational architecture of wide-area monitoring and control from centralized to distributed for facilitating the speed of data processing (Nabavi et al., 2015)

One of the greatest challenges for implementing wide-area control is the issue of communication delay. If a US-wide communication network capable of transporting gigabit volumes of PMU data indeed needs to be implemented then power system operators must have a clear sense of how the various forms of delays that are bound to arise in such networks, affect the stability of these control loops. One important question is - how can wide-area controllers be co-designed in sync with these communication delays in order to make the closed-loop system resilient and *delay-aware*, rather than just *delay-tolerant*? Since utilities are unlikely to establish highly expensive, dedicated communication links for these types of system-wide controls, the communication infrastructure must be implemented on top of their existing subnetworks. As a result, PMU data used for 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. Currently, there is very little insight on how the different protocols for PMU data transport may lead to a variety of such delay patterns, and how controlling these delays can potentially help wide-area control designs The existing PMU standards, IEEE C37.118 and IEC 61850, only specify the sensory data format and communication requirements. They do not indicate any *dynamic* performance standard of the closed-loop system. In recent literature, several researchers have looked into delay mitigation in wide-area control loops (Chaudhuri et al., 2004; Wu et al., 2002; Zhang and Vittal, 2013). Especially relevant is the recent work in Zhang and Vittal (2013) where $\mathcal{H}_\infty$ controllers were designed for redundancy and delay insensitivity. All of these designs are, however, based on worst-case delays,

---

[★] This work was supported in part by NSF grant ECS 1054394.

10.1016/j.ifacol.2017.08.014

which make the controller unnecessarily restrictive, and may degrade closed-loop performance.

Motivated by these concerns in our recent papers (Soudbakhsh et al., 2017), we presented a cyber-physical architecture for wide-area control using Arbitrated Network Control Systems (ANCS) for mitigating the destabilizing effects of network delays on small-signal models of power systems. The ANCS framework facilitates one in co-designing the wide-area controllers in sync with the knowledge about the delays arising from shared resources among control and non-control applications. The design in Soudbakhsh et al. (2017) investigates the case when all the delays are smaller than the sampling period h of the Synchrophaors, and also assumes full state availability. In reality, however, both of these assumptions may not hold. Therefore, in this paper we expand our results to a more practical case when (1) some delays in the network are larger than h, and (ii) the controller is implemented via output feedback instead of state feedback. We illustrate the effectiveness of proposed designs on a 50-bus Australian power system network consisting of 14 generators across four coherent areas.

The rest of the paper is organized as follows. In Section 2, the problem statement is described. Section 3 devotes to the extension of the ANCS design for accommodating delays larger than the sampling period, while Section 4 derives the output feedback control. Simulation results are shown in Section 5. Finally, Section 6 concludes the paper. Due to space limitations, the proofs are left out of this version, but are available in Dibaji et al. (2017).

2. PROBLEM STATEMENT

2.1 Problem Description

We consider a power system with a total of n generators distributed among p areas, with a_j generators each, $j = 1, \dots, p$. Each area j has its own virtual machine (VM) which is responsible for computing the control inputs of the a_j generators (see Fig. 1). Assuming that each generator i has n_i states, $i = 1, \dots, n$, which include rotor phase angle and frequency, excitation voltage, d-axis sub-transient flux, exciter states, power system stabilizer states, turbine/governor states, active-and reactive load modulation states, and states of Static Var Compensators, and FACTS devices, and has a scalar input which corresponds to the field excitation voltage, stacking all n_i states together, the network model can be compactly written as

$$\dot{x}(t) = A_c x(t) + B_c u(t), \tag{1}$$

where $B_c = [B_c^1, \dots, B_c^n] \in \mathbb{R}^{N \times n}$, $\sum_{i=1}^{n} n_i = N$, and $A_c \in \mathbb{R}^{N \times N}$. The wide-area damping control problem is to design a global state-feedback controller $u(t)$ in (1), using discrete measurements sampled every h secon+++ds, such that the overall closed-loop is asymptotically stable with the closed-loop poles placed at desired locations which correspond to the requisite damping. The main challenge is that even though these N states are measured at area j, the measured information arrives at other areas $i \neq j$ with a delay, as they go through a network of VMs. In this paper, we assume that these delays are $\tau_s, \tau_m, \tau_\ell$, which correspond to the local-delay, intra-area delay, and inter-area delay, respectively, with $0 < \tau_s < \tau_m < \tau_\ell$. We assume in this paper that $\tau_m < h$, while τ_ℓ is significantly large, and such that $4h < \tau_\ell < 5h$, and that all three delays are constants. Such assumptions are based on the typical values of these delays that can be expected to be encountered in a wide area network.

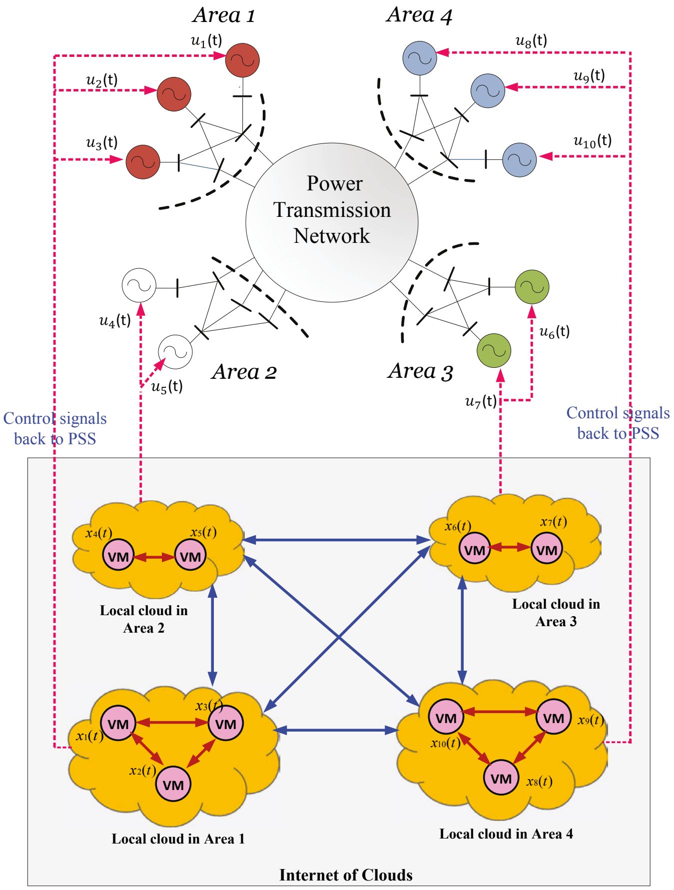

Fig. 1. Control of WAMS via Internet of Clouds

To have a better understanding of the problem, we provide an example:

Example 1. Assume that generators 1, 2, and 3 are in area 1 and generator 4 is in area 2 ($p = 2$). The control input of generator 1, for example, is obtained in the interval $[kh+\tau_m, kh+\tau_\ell)$ using $x_1[k]$, $x_2[k]$, $x_3[k]$ and $\hat{x}_4[k]$, where $x_i[k] \in \mathbb{R}^{n_i}$ is the vector of all state variables of generator i and $\hat{x}_i[k] \in \mathbb{R}^{n_i}$ is an estimation of the state measurements of generator i. The control inputs $u_{1j}[k]$, $j = 1, 2, 3$, are applied after each time new measurements arrive at the VM of area 1. Fig. 2 exhibits the architecture of designs for generator 1, where $\tau_\ell > 4h$.

2.2 A Sampled-Data Plant Model with Delayed Inputs

Given that the goal is the control of (1) using input at discrete instants, we convert (1) into a zero-order sampled-data model as follows.

$$x[k+1] = Ax[k] + Bu[k], \tag{2}$$

where

$$A = e^{A_c h} \quad \text{and} \quad B = \int_0^h e^{A_c s} B_c ds. \tag{3}$$

With the assumptions on the three delays $\tau_s, \tau_m, \tau_\ell$, we address the problem for three different cases : (i) $\tau_m < \tau_\ell -$