WIDE-AREA CONTROL OF POWER SYSTEMS USING CLOUD-IN-THE-LOOP FEEDBACK

Matthew Weiss[*†]   *Jianhua Zhang*[*]   *Aranya Chakrabortty*[†]

[*†]North Carolina State University
Department of Electrical and Computer Engineering
Raleigh, North Carolina 27695-7911

ABSTRACT

We propose the use of cloud-computing platforms and virtual network laboratories such as GENI (Global Environment for Network Innovations), together with high-speed software defined networks such as Internet2 to combat various cyberphysical implementation challenges for wide-area control of large power systems using Synchrophasors. Experimental results from a cloud-in-the-loop testbed environment are reported to support our proposed architecture.

Fig. 1. Electrical topology of WECC's 500kV network

1. INTRODUCTION

The Wide-area Measurement Systems (WAMS) technology using GPS-synchronized Synchrophasor measurements is an ideal way to control instabilities in large power systems [1, 2, 3]. The challenge, however, is the bottleneck in data communication and computation, which cannot be handled by today's Internet [4, 5, 6, 7]. In this paper we propose the use of cloud-computing platforms such as GENI [9] together with high-speed software defined networks such as Internet2 to combat this challenge. We consider a five-area reduced-order model of the Western Electricity Coordinating Council (WECC), i.e. transmission grid of the US west coast as our test system. This system is first implemented in Realtime Digital Simulators (RTDS), and integrated with hardware Phasor Measurement Units (PMU), which are further connected to the ExoGENI cloud. PMUs are assigned to the terminal bus of every area of the WECC model. The states measured by the PMUs are then communicated to unique sets of virtual controllers constructed in the cloud. The virtual machines (VMs) share the state information between each other in the cloud over Internet2, and cooperatively compute a state-feedback LQR control algorithm for small-signal oscillation damping of the five-area model. The control signals from each VM are thereafter communicated back to the excitation system of every generator in the RTDS for actuation. A cloud-in-the-loop control system is thereby created. In the following sections we describe different parts of this closed-loop system in more details.
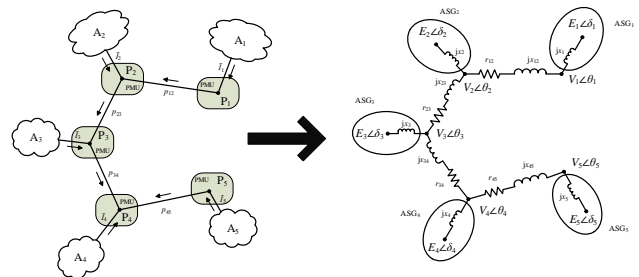
2. FIVE-AREA MODEL OF THE WECC SYSTEM

Recently, a reduced-order five-machine dynamic equivalent model of the WECC has been developed by the authors to represent its interarea oscillation patterns [8]. The WECC system is divided into five separate areas which are connected in a linear topology through long 500 kV transmission lines. These five areas were represented by five aggregated synchronous generators (ASG) with the interconnecting 500 kV lines between any two areas can be reduced to a single equivalent transmission line between those two areas. This reduction is shown in figure 1. All parameters, including intra and inter-area impedance, machine inertia, machine damping, and power flow were computed in [8] and then an RSCAD model was created using these parameters to simulate WECC. Although the equivalent transmission lines are reduced versions of real-world transmission lines, they connect five real-world sub-stations, namely, Area 1: Colstrip in Montana, Area 2: Grand Coulee in Washington, Area 3: Malin in Northern California, Area 4: Vincent in Southern California, and Area 5: Palo Verde nuclear plant near Phoenix, Arizona. These substations are referred to as pilot buses.

In face of both small-signal and large-signal disturbances, these five areas oscillate with respect of each other thereby giving rise to inter-area oscillation modes. For the reduced-order system, these modes will be reflected in the inter-machine oscillations as every area now is represented by a unique generator. To damp these oscillations, we next design a linear quadratic regulator (LQR) state feedback controller
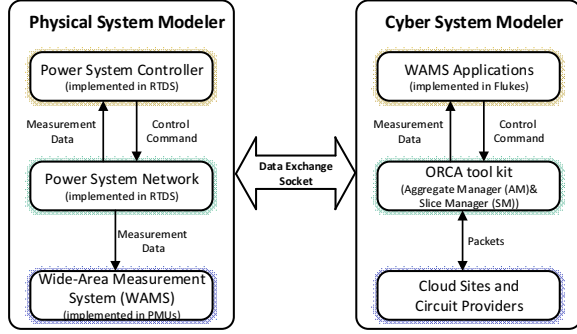
Fig. 2. Architecture of the ExoGENI-WAMS Testbed

$u(t) = K\,x(t)$ using excitation voltage as the control signal. A third-order state-space model consisting of swing and excitation states is considered for each generator. The model is linearized at a chosen operating point and the gain matrix K is computed offline. PMUs are installed at every pilot bus, and the measured values of the bus angle, frequency, current and voltage are used for estimating the machine states. The estimated states of each machine are then passed to a dedicated VM in the cloud, whereafter the states are exchanged between the VMs over a shared yet secure network to compute $u(t)$ in a distributed fashion. The control signals are then communicated back to the respective exciters to actuate the damping action.

3. CLOUD-IN-LOOP TESTBED ARCHITECTURE

The architecture of the hardware-in-loop power system testbed with the cloud platform in the feedback, also referred to as the ExoGENI-WAMS cyber-physical testbed, for testing our wide-area LQR control is shown in Figure 2. The data exchange between cyber and physical layers is time-critical, and needs be done in real-time at every sampling instant. The various blocks in Figure 2 are described as follows:

1) **Physical System Modeler**: The Physical System Modeler consists of the WECC power system model, its associated controllers, and hardware PMUs with phasor data concentrators (PDC) and GPS clocks. The power system model implemented in RTDS includes all the modeling components that represent a physical power system, such as generators, transformers, lines, loads and wind turbines. The controller (e.g. exciter, governor) collects the measurement data from the power system model and sends back control commands. The GTNET card, GTAO card, and PMUs enable the RTDS to communicate with the cloud through ethernet or analogue/digital I/O ports.

2) **Cyber System Modeler**: The Cyber system modeler refers to the ExoGENI networked cloud computing platform, which interacts with the physical system modeler by emulating the reconfigurable virtual communication and computation network. The ExoGENI platform consists of 5
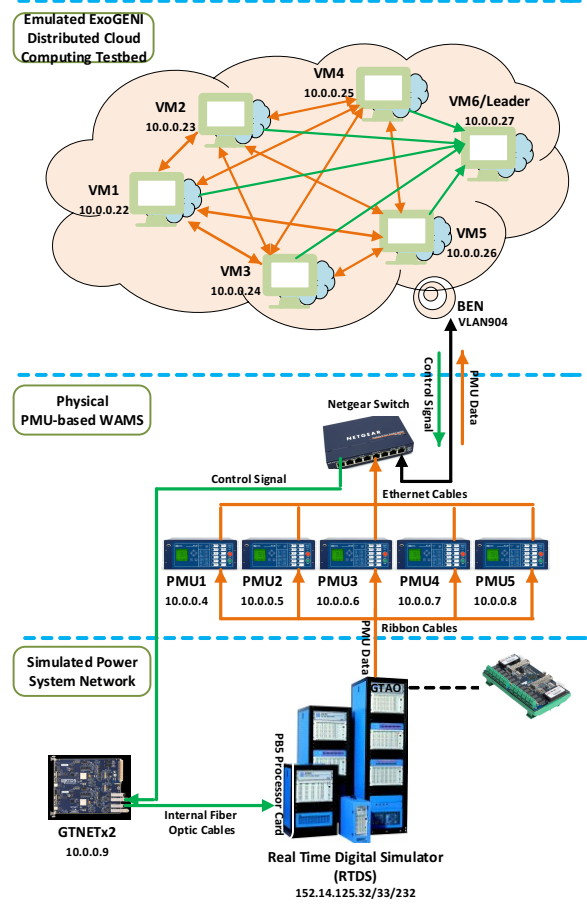

Fig. 3. Setup of the ExoGENI-WAMS Testbed

circuit providers and 14 cloud sites at the physical layer, and the corresponding Open Resource Control Architecture (ORCA) control software including Aggregate Manager (AM) and Slice Manager (SM) at the software layer. The ORCA AM configured at each site, i.e., either cloud site or circuit provider, comprises of a cloud handler plug-in to invoke the cloud service and an image proxy server to obtain VM's images through the URL address. A slice refers to an experiment or application run in ExoGENI. The ORCA SM is used to create, maintain, and delete an experiment or slice. The ExoGENI sites and control software enable the software-defined networking using OpenFlow. ExoGENI thus offers a powerful unified hosting platform for deeply networked, data-intensive cloud computing applications such as distributed WAMS applications. Flukes, a web-start GUI application, is used to run these WAMS applications on ExoGENI.

3) **Data Exchange Socket** Data exchange socket enables PMU data to be exchanged between the cyber system modeler and the physical system modeler. The analogue and the digital signals generated by the GTAO card are converted into packets that are streamed by the hardware PMUs, and fur-

ther transferred into the cyber system modeler. Packets from the cyber system modeler are formatted and converted to analogue or digital signals through the GTNET card of RTDS before using by the physical system modeler. The data exchange socket runs in real-time, thereby introducing minimum communication delays.

3.1. ExoGENI-WAMS Testbed for Wide-Area Control

The setup of ExoGENI-WAMS testbed for the wide-area control loop is described in Figure 3. At the physical power grid layer, one PC is used for hosting RTDS and the RSCAD for modeling the 5-machine reduced-order model of the WECC system described in the previous section. RTDS can run at a time-step of 50 micro-seconds while showing the required system response on the host PC. At the information layer, the WAMS consists of five PMUs connected to the Gigabit Transceiver Analog Output (GTAO) card of RTDS connected through ribbon cables. With the GTAO card, RTDS sends out the generated voltage and current waveforms from the model to the PMUs. The PMUs record the phasor values of voltages, frequencies, and phase angles from these voltage and current waveforms, time-stamp them using the GPS clock, and output the data at a rate of 30-60 samples per second.

The RTDS is integrated to ExoGENI through an intermediate physical fiber network called Breakable Experimental Network (BEN) using VLAN technology. All PMUs and GT-NETx2 cards that are used to receive control commands are configured into the VLAN 904. All cloud sites at ExoGENI are configured into VLAN 11. Then a network rule is manually created to translate traffic between VLAN 11 of Exo-GENI and VLAN 904 of the RTDS connected to BEN.

At the WAMS application layer, the data packets generated by PMUs are captured and pushed through a virtual communication and computation network developed in Exo-GENI. The packet capture capability is enabled by the software of the IEEE C37.118 *message reader* using C++ over a Linux image. The designed LQR wide-area state-feedback controller is emulated in ExoGENI by creating a 6-VM slice. The network topology between the VMs, as shown in Figure 3, in this case is a full connected topology since K, in general, is a dense matrix. VM1 to VM5, the so-called *regular VMs*, execute the following functions at every sampling instant: 1) receive streaming PMU data from their corresponding PMUs using C37.118 protocol in real-time; 2) exchange PMU measurements with other VMs; 3) calculates the inter-area damping control signal for the controller; 4) sends the control command to the leader VM. The VM6 serves as a leader VM, and is used to collect control commands from all five regular VMs, convert them into one message in IEEE 754 format, and finally send this packet back to the GTNETx2 card which is connected to PB5 processor card of RTDS through internal fiber optic cables, as shown in Figure 3. The flow chart of implementing the wide-area controller is shown in Figure
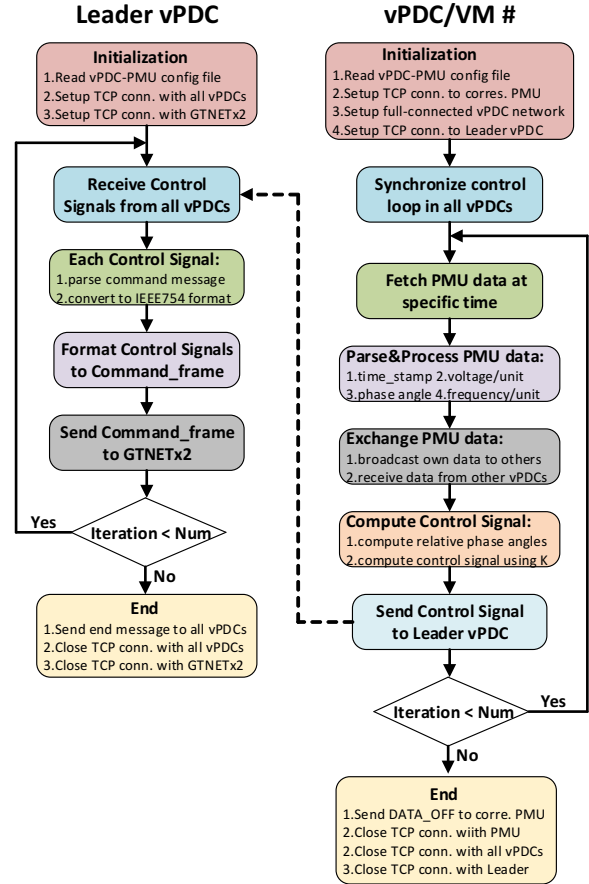

Fig. 4. Flowchart of Wide-Area Controller

4. It is worthy to note that the data packets, whether they be measurement data or control commands, will go through the virtual network and experience a network delay that is determined by both different VM topologies and their physical locations, as well as the network traffic.

4. EXPERIMENTAL RESULTS

4.1. Unstable System without Wide-Area Control

Table 1. Alteration of Load Reference Sliders, in per-unit

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
Before	0.4926	0.8646	0.4687	0.4722	0.5856
After	0.4926	0.8646	0.3687	0.4722	0.6856

First, the steady-state condition of the model is altered by adjusting the load reference sliders on the aggregate machines, thus altering power flow throughout the system. The new load reference values are shown in Table 1. These refer-

ences were found through a series of simulations in RSCAD, and adjusting the sliders accordingly until the system went unstable. The new steady-state operating point was observed by running RSCAD without the LQR controller, and K was recomputed and reentered accordingly.

4.2. Controller Comparison Tests

A comparison of the transient response of WECC was conducted with both the LQR feedback controller on and off. Note that the controller is implemented directly in RSCAD for this test, not in ExoGENI. A three phase fault of duration four cycles was applied to Area 3, and the resulting phase angle differences between each aggregate machine are recorded. First, only local frequency feedback using power system stabilizers (PSS) is actuated for every machine, without the wide-area controller being ON. The plots of the phase angle differences between the pilot buses are shown in Figure 5. It can be seen that local PSS feedback does guarantee the closed-loop system to be stable, but the dynamic performances are still notably degraded.
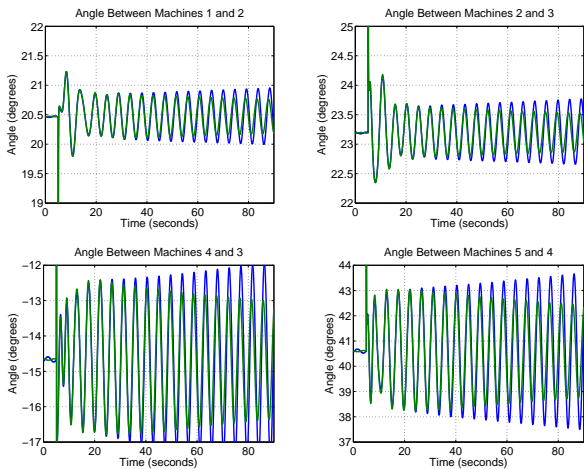

Fig. 5. WECC Transient Response, Local Frequency Feedback with no WAC

Next, the wide-area controller is switched on together with the PSSs. The resulting transient responses of the angle differences are shown in Figure 6. The system performance improves drastically in this case.

4.3. ExoGENI Implementation

Finally, we implement the LQR control law in ExoGENI using the VM concept described in Section 3 instead of RSCAD. Figure 7 displays a comparison of transient responses for the four inter-area angles when the WECC is faulted with the same three phase line-to-ground fault at bus 3 for four cycles. The closed-loop responses are almost same as the ideal responses when the control was implemented
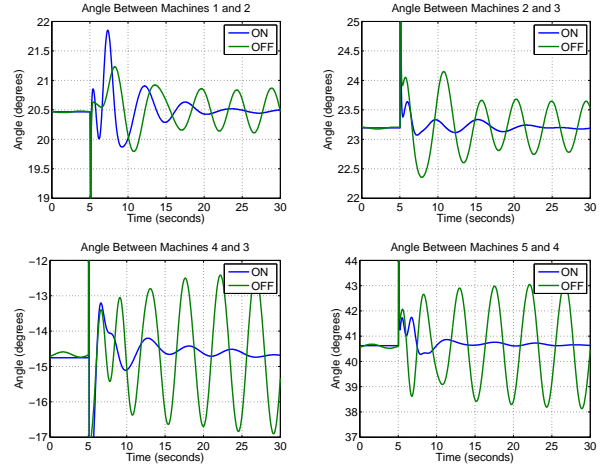

Fig. 6. WECC Transient Response With and Without WAC

in RSCAD. However, a slight degradation in performance is noted due to network delays and use of hardware-in-loop compared to the purely software implementation. Such degradations can be avoided by designing more robust network-layer controllers using SDN principles [10], which is part of our ongoing work.
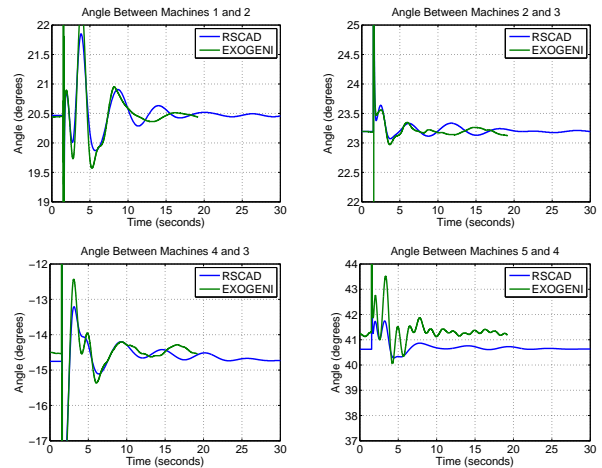

Fig. 7. WECC Transient Response, RSCAD vs ExoGENI Controller Implementation

5. CONCLUSION

In this paper we described an experimental set-up for implementing wide-area control of power systems using cloud computing as a computational resource for the feedback path. Our experiments show that the controller performs close to ideal when implemented in the cloud under nominal network traffic conditions. The proposed architecture provides a feasible way to control any cyber-physical system using distributed state or output feedback control.

6. REFERENCES

[1] A. G. Phadke and J. S. Thorp *Synchronized Phasor Measurements and Their Applications,* Springer, 2008.

[2] A. Chakrabortty and P. Khargonekar, "Introduction to Wide-Area Control of Power Systems," *American Control Conference*, Washington DC, 2013.

[3] North American Synchrophasor Initiative (NASPI) - *www.naspi.org*

[4] S. Nabavi, J. Zhang, and A. Chakrabortty, "Distributed Optimization Algorithms for Wide-Area Oscillation Monitoring in Power Systems Using an Inter-Regional PMU-PDC Architecture," *IEEE Transactions on Smart Grid*, vol. 6(5), pp. 2551-2559, Sep. 2015.

[5] P. Myrda and K. Koellner, "NASPI-net: The Internet for Synchrophasors," *Hawaii International Conference on System Sciences*, (HICCS), 2010.

[6] D. Bakken, A. Bose, C. Hauser, D.Whitehead, and G. Zweigle, "Smart Generation and Transmission with Coherent, Real-Time Data," *Proceedings of the IEEE*, 99(6), June 2011.

[7] K. Zhu, M. Chenine, and L. Nordstrom, "Design Requirements of Wide-Area Damping Systems-Using Empirical Data From a Utility IP Network," *IEEE Transactions on Smart Grid,* vol. 5(2), 2014.

[8] G. Chavan, M. Weiss, A. Chakrabortty, S. Bhattacharya, A. Salazar, and F. Ashrafi, "Identification and Predictive Analysis of a Multi-Area WECC Power System Model Using Synchrophasors," *to appear in IEEE Transactions on Smart Grid*, 2016.

[9] Global Environment Network Innovations (GENI): *wwww.geni.net*

[10] F. Hu, Q. Hao, and K. Bao, " A Survey on Software-Defined Network and OpenFlow: From Concept to Implementation, *IEEE Communication Surveys and Tutorials,* vol. 16(4), 2014.