A US-Wide DETER-WAMS-ExoGENI Testbed for Wide-Area Monitoring and Control of Power Systems Using Distributed Synchrophasors

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Federating DETER, WAMS, and ExoGENI

In current state-of-art, using Synchrophasor data for research purposes is contingent on accessing the data from specific utility companies who own the Phasor Measurement Units (PMUs) at the locations of interest. Gaining access to such data may not always be easy due to the privacy and non-disclosure issues. More importantly, in many circumstances even if real PMU data are available they may not be sufficient for studying the detailed operation of the entire power system because of their limited coverage. To circumvent this problem, over the past two years Chakrabortty and his students at FREEDM Systems Center in NC State University have developed a hardware-in-loop (HIL) testbed where high-fidelity detailed models of large power systems can be simulated in Real-time Digital Simulators (RTDS), and the dynamic responses can be captured via real hardware Phasor Measurement Units from multiple vendors including Schweitzer Engineering Lab and ABB Inc. This PMU testbed has recently been federated with a state-funded, metro-scale, multi-layered dynamic 100gbps optical network testbed called Breakable Experimental Network (BEN), which is a part of the US-wide ExoGENI network, and also to the DETER cyber-security testbed at University of Southern California. The resulting testbed is referred to as the DETER-WAMS-ExoGENI testbed, partly shown in Fig. 1.

This testbed has been showcased in several recent federal demonstration events such as US Ignite 2013 and 2014 (winning the Best Energy Application award both times) , and SmartAmerica Challenge 2014 organized by the US White House. Three main research thrusts demonstrated at these events include:

1. How massive volumes of spatially distributed Synchrophasor data can be communicated in real-time through a wide-area communication network for oscillation monitoring and control.

2. How cloud computing and software defined networking (SDN) approaches can be exploited to integrate wide-area control loops with control algorithms in the underlying communication network to regulate delays and packet losses.

3. How to evaluate the impact of cyber-attacks (eg. Denial-of-Service, data corruption, jamming attacks) on closed-loop stability and performance of wide-area damping control.

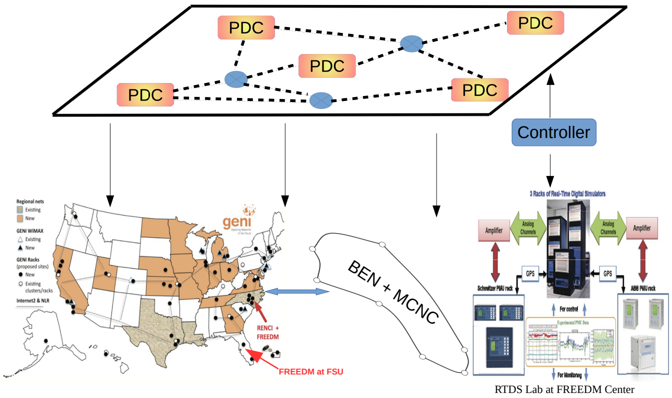


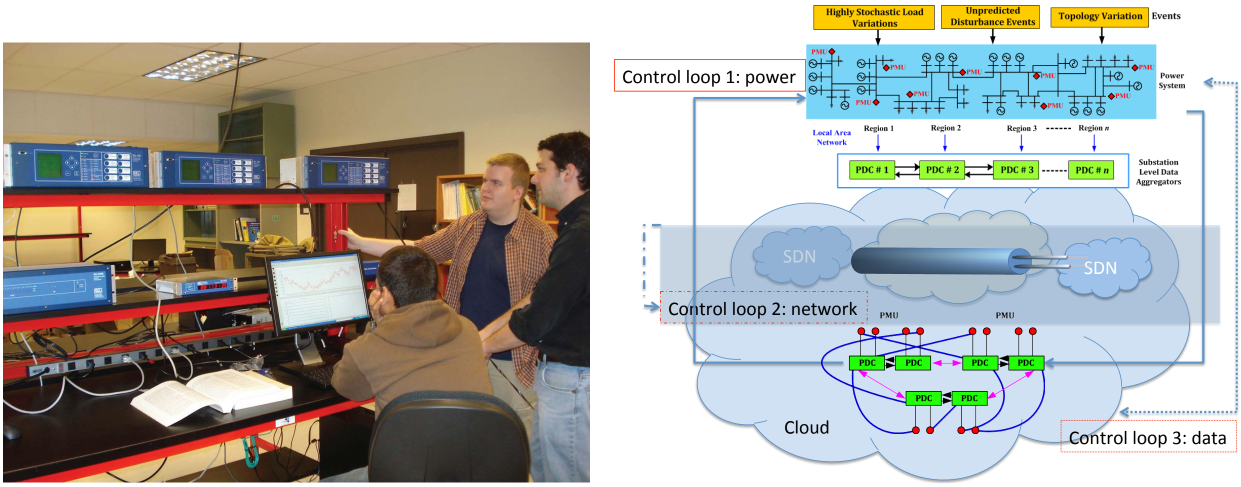
Figure 1: DETER-WAMS-ExoGENI testbed

Relevance to CPS

DETER-WAMS-ExoGENI is a perfect example of a cyber-physical system testbed; here, the physical layer consists of the hardware-in-loop RTDS and PMUs, while the cyber layer consists of GENI and DETER, where hundreds of virtual phasor data concentrators (*v-PDC*) can be created in the cloud on the fly. These v-PDCs receive real-time PMU data streaming in from the physical layer, run local monitoring and control algorithms, and communicate with each other to execute a system-wide control action in a completely distributed way. The two main benefits of this infrastructure are - (1) Explicitly shows how various performance bottlenecks of a wide-area communication network affect closed-loop stability of wide-area controllers while transporting gigabit volumes of PMU data, (2) Enables researchers to control the network configuration and delays to preserve stability and performance of the grid.

Virtualization Underneath Physical Controllers

The underlying computing infrastructure of DETER-WAMS-ExoGENI is partially based on a novel *Virtual Smart Grid* paradigm, recently developed by Chakrabortty and Xin by applying cloud computing concepts for wide-area monitoring via virtualization of the whole smart grid infrastructure including PMUs, network, computation and storage. The emerging SDN and NFV technology provides us with new tools to efficiently virtualize the network per application, and a programmable interface to control the network configurations adaptively.



(a) RTDS-PMU lab (b) Wide-area control loops

Figure 2: Wide-area control via RTDS and PMUs

Research Capabilities

The testbed consists of the following three multi-input multi-output control loops (Fig. 2):
(a) **Control loop # 1**: Physical controller - Run distributed optimal control algorithms for oscillation damping and voltage control using v-PDCs, and transmit the control signal to power system stabilizers (PSS) and FACTS devices installed in RSCAD/RTDS.
(b) **Control loop # 2**: SDN controller - Given the co-existence of the underlying legacy networks (PLC, IP, Ethernet) an application-level overlay SDN network is created and operated to serve different wide-area applications by controlling the stringent real-time and reliability constraints.
(c) **Control loop # 3**: Cloud based IaaS and security controller - Based on the PMU data exporting rate, processing requirements on the CPU and memory, and malicious data flows, this decision-making loop creates and reconfigures v-PDC clusters in the cloud to improve the latency, cyber-security and fault tolerance guarantees of Loop 2.

In addition to their own individual functions, complex information exchange exist between all of these three controllers. To make the implementation scalable and tractable we collocate the SDN controller, IaaS controller, and the central supervisory PDC at one server, but implement them in different threads (Fig. 3).

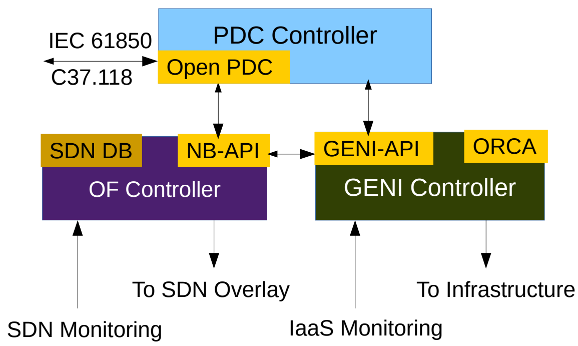


Figure 3: Testbed control software

Our ultimate goal is to make this testbed fully open-source to the power and IT community. The US power grid is regarded as the single most important infrastructural component in modern society as it is the backbone of many other infrastructures, especially in the very touted vision of a Smart City. Therefore, we strongly believe that this testbed would benefit not just the grid, but the entire CPS research community.

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