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Conference Paper · January 2013

DOI: 10.1109/PESMG.2013.6672308

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Test Platform for Synchrophasor based Wide-Area Monitoring and Control Applications

Kun Zhu, Samarth Deo, Ahmad T Al-Hammouri, Nicholas Honeth, Moustafa Chenine, Davood Babazadeh, and Lars Nordström

***Abstract*—Synchrophasor technology has been viewed as one of the enablers for the "Smart Grid" at the transmission level. Many synchrophasor driven applications have been proposed by the academic literatures, however, their deployment in reality is still relatively limited. This could be traced back to the lack of platforms specialized to test and validate these application proposals. In this paper, an on-going research effort to develop a real-time co-simulation platform serving for this purpose is reported. The platform is composed of a virtual Phasor Measurement Unit (PMU), a real-time simulator for power system, a real-time simulator for communication network, and an implementation of an open-source Phasor Data Concentrator (PDC). Specifically, this paper focuses on the implementation and validation of the virtual PMU, as well as on the extension of its function to support communication over UDP.**

I. Introduction

PHasor measurement units (PMU)s are digital measurement instruments that are capable to provide globally synchronized positive-sequence voltage and current phasors at high sampling rates [1], [2]. The deployment of this technology provides many opportunities to operate the power system at a more responsive and responsible manner [3]. Promising results have been reported by the academic literaturea, e.g [3], [4]. However, despite some preliminary field tests reported by [5], the majority of the proposals are still in simulation, engineering or advanced laboratory test stages. A well recognized obstacle to deploy such system is the capability of the supporting ICT infrastructure [4]. This is evidenced by a recent NASPI report stating that 71% of the networked PMUs in the US power grid on the east coast failed to deliver valid data due to communication problems [6]. The tight coupling between the functionality of the synchrophasor application and the capability of the supporting ICT system decides that the latter system needs to be viewed and designed as an integrated part of the Wide-Area Monitoring and Control (WAMC) system enabled by the synchrophasor technology [7], [8].

There are different ways to develop new applications using synchrophasors. According to [9], harvesting data from PMUs deployed in the grid through *ad hoc* WAMC systems can be limited by several technical, economical and organizational constraints. A more practical alternative to develop synchrophasor application is to perform tests within a simulation environment [10], [11]. There are several research attempts to design co-simulation platforms to test and validate the synchrophasor applications. A pioneering work in this context is the EPOCHS platform [12]. Three off-the-shelf simulators are federated in this integrated platform: PSCAD/EMTDC for power system transients, PSLF for power system modeling, and Network Simulator 2 (`ns-2`) for communication network modelling. A recent update of this platform, which was instead referred to as GECO, was presented in [13]. The accuracy of the synchronization between the local clocks of the involved simulators was improved in the GECO platform. Moreover, the new platform also allows to adjust the resolution of the simulation according to the time-scale of the scenario in question. Other than this platform, another test system built with a similar concept was reported by [9], where `ns-2` is interfaced with Modelica to allow power system and communication network co-simulation. These early attempts do provide means to study the inter-dependency between the power system and supporting ICT infrastructure in a cost-efficient manner. However, their suitability to test the synchrophasor applications still needs to be further justified. First of all, in the aforementioned works, synchronization of the reference time of the involved simulators is in general cumbersome and prone to error. Second, the above platforms do not provide interface to the real-life devices, therefore, they do not support hardware-in-the-loop tests.

An appealing approach is to use real-time power system simulators that are capable to perform fine-grained simulations, e.g., at a resolution of a millisecond, and also provide interface to support hardware-in-the-loop tests. The real-time power system simulator can be cascaded with a communication network emulator. In this case, all of the involved simulations are performed in real-time, therefore, the complicated and proprietary solutions to synchronize the time reference of the involved simulators can be avoided. Instead, precise time synchronization, e.g., to fractions of a millisecond, can be achieved by implementing off-the-shelf technologies, e.g., the IEEE 1588 time synchronization protocol [14]. Additionally, to ensure the fidelity of the simulation, these real-time simulators should provide indications when their simulations are off the real-time simulation course.

To test the synchrophasor application with global information, e.g., synchrophasor based state estimation, it is necessary to have a synchrophasor data stream from a multitude of PMUs placed at different locations in the grid [15]. However,

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this is not practical in reality, since the study can be limited by the number of physical adaptors interfacing the real-life devices and the number of physical devices in possession. To meet this scalability requirement, the "virtualization" [16], i.e., the development of an entirely software-based synchrophasor measurement unit, was proposed as a cost-efficient complement to the real-time co-simulator described above. This virtual PMU is designed to deliver real-time synchrophasors by harvesting the three-phase voltage and current waveforms from a real-time power system simulator. This virtual device can send out PMU data frames on both physical and emulated communication networks.

A. Purpose

This paper reports an on-going research effort to develop a real-time co-simulation platform to test synchrophasor applications. The initial results of this project was reported by [17]. Specifically, the revised architecture of this co-simulation platform, with new components, is presented by this paper. Also, the implementation and validation of a robust synchrophasor algorithm in the *soft*PMU are reported. Finally, the extension of the *soft*PMU communication function to provide data frames over UDP is described.

B. Outline

The remainder of this paper is structured as follows: Section II overviews the architecture of the proposed real-time co-simulation platform. Next, the implementations of the robust synchrophasor algorithm and communication function using UDP are described in Section III. In Section IV, the performance of *soft*PMU are validated against the IEEE standard C37.118.1 [18] and compared with a commercial PMU. Finally, the paper is concluded by Section V.

II. Architecture of the Co-Simulation Platform

The architecture of the real-time co-simulation platform is illustrated in Fig. 1, it is composed of four components:

1) eMEGAsim Real-Time Digital Simulator [19]. The eMEGAsim is a highly accurate commercial power system simulator. Being a computationally powerful platform, it can simulate large-scale power systems in real-time. This platform supports hardware-in-the-loop simulations by providing interfaces to real-life devices, and the simulation models are constructed with SimPowerSystems Toolbox in Simulink [19].
2) *Soft*PMU. A virtual block where the synchrophasors are computed and provided as data frames according to the IEEE standard C37.118 [18], [20]. The *soft*PMU serves as an interface between the real-time simulator of power system and the emulator of communication network. By introducing this component to the co-simulation, the complication to synchronize the time references of the event-based communication network simulation and time-continuous power system simulation can be avoided. Furthermore, it provides a cost-efficient solution to overcome the scalability challenge described above.
3) OPNET [21]. OPNET is a communication network emulator that is capable to perform fine-grained simulations of communication network with various scales. A major motivation to choose OPNET is because the OPNET simulation model can import data frames from the real-life devices through the System-In-The-Loop (SITL) module that functions in real-time [21]. Therefore, by integrating the OPNET simulations to the other components of the platform, the impact of communication network impairments on the functionality of the synchrophasor application can be studied in a realistic environment.
4) KTH-PowerIT. This is an application-level platform that collects real-time synchrophasor data frames from the PMUs. Moreover, this platform also supports off-line analysis of the aggregated PMU data. Additionally, it serves as a user front-end by arranging and presenting synchrophasor data in a user-friendly manner. A complete report of the KTH-PowerIT platform can be found in [22].

The architecture of this real-time co-simulation platform is presented in Fig. 1. The physical PMU is an actual PMU device or a substation instrumentation device, e.g., digital fault recorder or an intelligent electronic device, that is capable to provide synchrophasor data frames. They collect synchrophasors from the simulated power system, and then send them out as data frames on the communication network. To those entities connected to the PMU at the downstream side, the synchrophasor measurements appear as if they were coming from an actual power system.

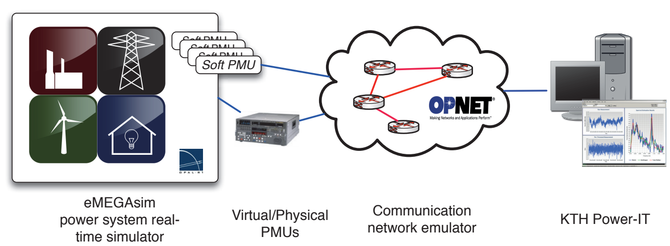

Fig. 1. The architecture of the real-time co-simulation platform.

The proposed platform maintains one of the most important advantages of the eMEGAsim real-time simulator: it provides interfaces to the real-life devices and power system components to facilitate hardware-in-the-loop tests. Also, the inclusion of *soft*PMU overcomes the scalability challenge by facilitating simulations of synchrophasor application with input from a multitude of PMUs deployed at different locations in the grid. Additionally, the complicated and proprietary solution to synchronize the power system simulation with the communication network simulation can be replaced by off-the-shelf technologies. In Section III, the implementation of the new *soft*PMU functions are presented.

III. The enhanced *Soft*PMU

The high-level architecture of the *soft*PMU is depicted in Fig. 2. The *soft*PMU is composed of two functional blocks:

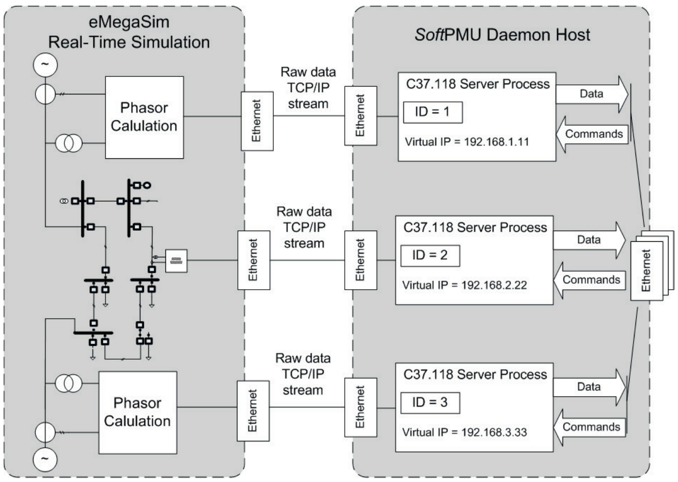

Fig. 2. The *soft*PMU architecture.

phasor calculation block and *PMU Daemon*, an interface for communication purposes. First, the computation of the synchrophasor is performed in the Simulink environment. This allows the virtual PMU component to be run on the eMEGAsim real-time simulator. The input to the phasor calculation block is the three-phase voltage and current, and the output is the positive sequence voltage and current phasors in both polar and Cartesian formats, power system frequency, and the rate of frequency change. The *PMU Daemon* is implemented to receive the calculated phasors from the phasor calculation block, and then craft the received raw data into payloads according to the IEEE standard C37.118.2 [20]. The output of the *PMU Daemon* are the PMU data frames sent out to a connected entity, e.g., a PDC or an application software that consumes the synchrophasor data frame. The *PMU Daemon* is implemented in the Linux environment on a separate machine. To craft synchrophasor payload in the intended data format, a portal library of C37.118 protocol [20] is develop using the C++ programming language [17].

The information exchange between the two blocks is carried out over TCP/IP. At the phasor calculation end, the socket-communication models that are compliant with the eMEGAsim simulator are used. At the *PMU Daemon* end, custom code is developed to retrieve and interpret the data sent from the other end. The data reporting and receiving intervals are configurable for both blocks. Clearly, it is necessary to have a consistent setting at the both ends to achieve valid results. Up to this point, the features that were first reported in [17] were reviewed. The new function of the *soft*PMU is presented in the coming section.

A. Implementation of a robust synchrophasor algorithm

A pioneering attempt to compute synchrophasor in a computationally efficient manner was reported by [23]. The proposed

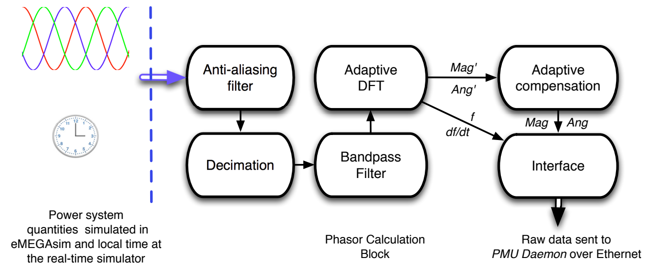

Fig. 3. The robust synchrophasor algorithm implemented in the *soft*PMU

solution was based on a recursive Discrete Fourier Transformation (DFT). More recent works has been focusing on proposing robust algorithms to compute synchrophasor, e.g., [24], [25], particularly in presence of input with off-nominal frequency, harmonic distortions, and low frequency oscillations.

An adaptive DFT method presented by [26] is implemented with minor modifications in the *soft*PMU. A block diagram illustrating the computation process is presented in Fig. 3. This component corresponds to the phasor calculation block presented on the left of Fig. 2. The synchrophasor is computed in the Simulink enviroment which runs on the eMEGAsim real-time simulator. Three-phase voltage and current from the simulated power system are sampled and time-stamped in the phasor calculation block. The sampling is performed by cascaded decimation filters whose sampling rate can be adjusted. To avoid aliasing effects, a low-pass Finite Impulse Response (FIR) filter is also included in the sampling process. Moreover, the measurements from the power systems typically contains harmonic distortions. To limit their impacts, a FIR band-pass filter is also deployed. This choice is motivated by the desirable linear phase shift characteristic of the FIR filter [27]. Next, an adaptive DFT is applied to compute the phasors and frequency. Due to the space constraint, the details of the adaptive DFT is not provided in this paper, and the a complete description of this algorithm can be found in [26]. The algorithm uses two windows of data to calculate the frequency deviation, and based on the obtained frequency error, the phase angle and the amplitude of the synchrophasor are estimated. The estimated phase angle, *Ang'*, and magnitude, *Mag'*, are further adjusted to improve the accuracy in a frequency dependent compensation stage. Finally, the compensated synchrophasor in polar, i.e., magnitude, *Mag* and phase angle, *Ang*, and Cartesian formate, power system frequency, and the rate of frequency change are sent to the *PMU Daemon* as raw data.

B. PMU Daemon *Communication over UDP*

PMU Daemon is a software bundle in charge of communication of the *soft*PMU. It receives the raw data from the phasor calculation block, crafts them into C37.118 payloads, and send the data frames out through Ethernet, see Fig. 2. An elaborated description of the *PMU Daemon* together with its flow chart is presented in the previous paper [17]. In the updated *PMU Daemon*, the communication function is extended to support

UDP. The main concept of the implementation remains the same as that for the TCP. A major difference is that UDP is a connectionless protocol, therefore, the process of building connections by exchanging data frames between the sending entity, *PMU Daemon*, and the receiving entity, a PDC or a software that consumes the synchrophasor data, is removed. Due to the space constraint, the revised flow chart for UDP communication is not included.

IV. Results of PMU conformance tests

To validate the performance of the *soft*PMU and its conformance to the IEEE standard C37.118, several tests are performed under the guidance of [28].

A. PMU protocol conformance test

The purpose of this test is to validate the compliance of the *soft*PMU with respect to the frame definition specified by the IEEE standard C37.118.2 [20]. The PMU Connection Tester [29], a part of the OpenPDC project [30], is connected to the *soft*PMU daemon to perform the protocol conformance test. The test results (suppressed here for space constraints) suggest that the PMU Connection Tester can successfully receive and decipher the data frames sent by the *soft*PMU including data frames, header frames, and configuration frames.

B. PMU frame rate conformance test

The purpose of this test is to validate the capability of the *soft*PMU to report at the frame rate as it is configured. Three configurations with frame rates of, 10 Hz, 25 Hz, and 50 Hz are validated in this test. The *soft*PMU is connected to the PMU Connection Tester, and it is configured to provide synchrophasor data frames at a specific frame rate for one hour. The traffic is captured by Wireshark [31], an open source tool to analyze network traffic. The PMU frame rate is validated by examining the traffic damp. The results (also suppressed here for space constraints) show that the *soft*PMU indeed transmits frames at the rate as it is configured in all of the tested scenarios.

C. PMU performance conformance Test

The IEEE standard C37.118.1 [18] specifies the performance of the synchrophasor by introducing Total Error Vector (TVE) for two performance levels. Specifically, the TVE of the synchrophasor measurement computed from a input signal whose frequency deviates from the nominal frequency by ± 5 Hz, and contains 10% Total Harmonic Distortion (THD) and 10% out-of-band signal distortion should be smaller than 1%. However, the TVE only reflects the performance of the PMU measurement in power system steady state, PMU performance in other occasions also needs to be considered in design of PMUs. A more elaborated framework to evaluate the performance of the PMUs was proposed by [28].

In this paper, the performance of the *soft*PMU is validated by following the test procedure proposed by [28]. Due to the space constraint, only the PMU responses to step changes, and the TVE of *soft*PMU measurements with input containing off-nominal frequencies and harmonic distortions are reported. The input signal to the *soft*PMU is generated by a symmetrical three-phase voltage source. The nominal voltage magnitude is 120 V and the nominal frequency is 50 Hz. The harmonic components of the input signal is of 10% THD.

1) Test A: The frequency and phase angle of the input are maintained as constant at their nominal values. Whereas, the input magnitude is subjected to step changes with magnitudes of $\pm 10\%$ of the nominal values. The system response to the positive and negative magnitude step changes are presented in Fig. 4.

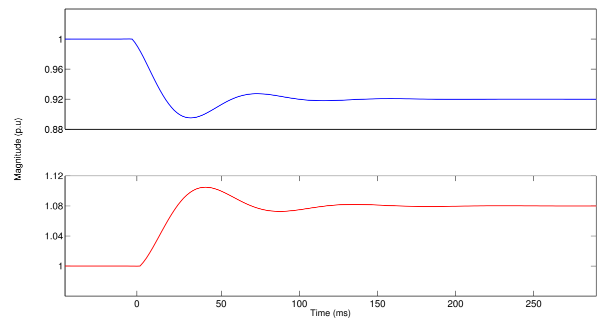

Fig. 4. The *soft*PMU magnitude step response.

2) Test B: The magnitude and frequency of the input are maintained as constant at their nominal values. Whereas, the phase angle is subjected to step changes from 0° to 15° and from 0° to -15°. The system response with respect to the positive and negative phase angle steps are presented in Fig. 5.

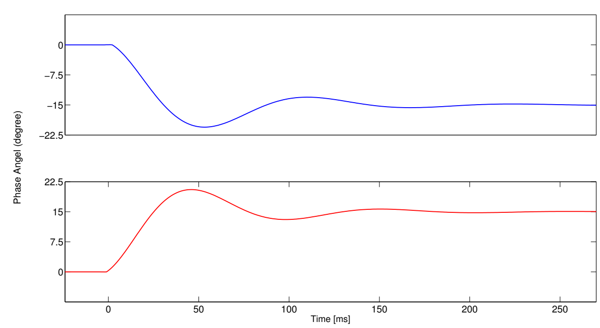

Fig. 5. The *soft*PMU phase angle step response.

3) Test C: The magnitude and phase angle of the input are maintained as constant at their nominal values. Whereas, the input frequency is subjected to step changes of magnitudes of ± 1 Hz. The system response to the positive and negative frequency steps are presented in Fig. 6.

The results from Fig. 4, 5, and 6 show that the *soft*PMU has very similar step response compared to the commercial PMU whose performance were tested by [32]. Also, the resulted TVE from all of the tested the steady state cases are below 1%, see Table I. The results suggest that the performance of the *soft*PMU is acceptable in all of the tested power system scenarios.

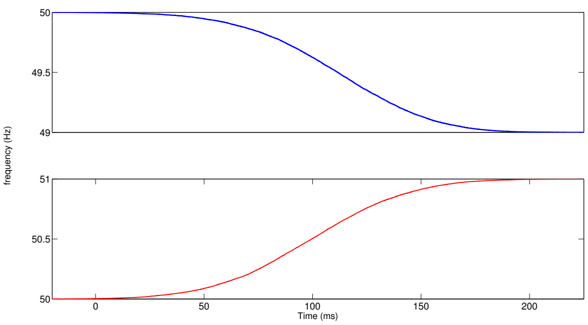

Fig. 6. The *soft*PMU frequency step response.

TABLE I
TVE (%) FOR THE STEADY STATE TEST CASES WITH THD OF 10%

Frequency (Hz)	5th harmonic	7th harmonic	11th harmonic
45	0.87	0.79	0.87
55	0.83	0.80	0.86
49.5	0.62	0.54	0.55
50.5	0.51	0.68	0.62

V. CONCLUSION AND FUTURE WORKS

This paper reports recent improvements made to the *soft*PMU. Specifically, the implementation of a robust synchrophasor algorithm in the *soft*PMU and the extension of its communication function of to incorporate UDP are presented. Additionally, updates of the framework supporting real-time co-simulation of power system and communication network are also described in this paper.

As suggested by the promising test results, the implemented synchrophasor algorithm is robust to input signal with off-nominal frequency and harmonic distortions. However, the tests do not include the power system low frequency oscillation, which could as well impact the performance of the synchrophasor algorithm [33]. Validation of the *soft*PMU under such a situation is left to future works.

REFERENCES

[1] A. G. Phadke, J. S. Thorp, and M. G. Adamiak, "A New Measurement Techniques for Tracking Voltage Phasors, Local System Frequency, and Rate of Change Frequency," *IEEE Transactions on Power Apparatus and Systems*, vol. 102, no. 5, pp. 1025–1038, May 1983.

[2] A. Phadke and J. Thorp, *Synchronized Phasor Measurements and Their Applications*. New York: Springer, 2008.

[3] A. Bose, "Smart transmission grid applications and their supporting infrastructure," *Smart Grid, IEEE Transaction*, vol. 1, no. 1, pp. 11–19, Jun 2010.

[4] N. Chaudhuri, S. Ray, R. Majumder, and B. Chaudhuri, "A New Approach to Continuous Latency Compensation With Adaptive Phasor Power Oscillation Damping Controller (POD)," *Power Systems, IEEE Transactions on*, vol. 25, no. 2, pp. 939–946, May 2010.

[5] L. Chao, X. Wu, J. Wu, P. Li, Y. Han, and L. Li, "Implementations and Experiences of Wide-area HVDC Damping Control in China Southern Power Grid," in *IEEE PES General Meeting*, San Diego, Jul 2012.

[6] A. Silverstein, "NASPI Update and Technology Roadmap," Dec 2011. [Online]. Available: https://www.naspi.org/File.aspx?fileID=745

[7] K. Zhu, M. Chenine, and L. Nordström, "ICT Architecture Impact on Wide Area Monitoring and Control Systems' Reliability," *Power Delivery, IEEE Transaction*, vol. 26, no. 4, Oct 2011.

[8] P. Kansal and A. Bose, "Bandwidth and latency reuirements for smart transmission grid applications," *Smart Grid, IEEE Transaction*, vol. 3, no. 3, Sep 2012.

[9] A. T. Al-Hammouri, "A comprehensive co-simulation platform for cyber-physical systems," *Computer Communications*, vol. 36, no. 1, pp. 8–19, 2012.

[10] T. Rauhala and P. Järventausta, "Testing the Quality of PMU Output Data Based Subsynchronous Damping Analysis in Real-Time Simulation Environment," in *International Conference on Power Systems Transients (IPST '07)*, Jun 2007, pp. 1–8.

[11] H. Kang, B. Cvorovic, C. Mycock, D. Tholomier, and R. Mai, "PMU simulation and application for power system stability monitoring," in *IEEE/PES Power Systems Conference and Exposition, 2009 (PSCE '09)*, Mar 2009, pp. 1–7.

[12] K. Hopkinson, X. Wang, R. Giovanini, J. Thorp, K. Birman, and D. Coury, "EPOCHS: a platform for agent-based electric power and communication simulation built from commercial off-the-shelf components," *Power Systems, IEEE Transactions on*, vol. 21, no. 2, pp. 548–558, May 2006.

[13] H. Lin, S. Veda, S. Shukla, L. Mili, and J. Thorp, "GECO: Global Event-Driven Co-Simulation Framework for Interconnected Power System and Communication Network," *Smart Grid, IEEE Transactions on*, vol. 3, no. 3, pp. 1444–1456, Sep 2012.

[14] "IEEE Draft Standard Profile for Use of IEEE Std. 1588 Precision Time Protocol in Power System Applications," *IEEE PC37.238/D5.7, April 2011*, pp. 1–72, 2011.

[15] R. Nuqui and A. Phadke, "Phasor measurement unit placement techniques for complete and incomplete observability," *Power Delivery, IEEE Transactions on*, vol. 20, no. 4, pp. 2381–2388, Oct 2005.

[16] J. Stamp, V. Urias, and B. Richardson, "Cyber security analysis for the power grid using the virtual control systems environment," in *IEEE Power and Energy Society General Meeting,*, Jul 2011, pp. 1–4.

[17] A. Al-Hammouri, L. Nordstrom, M. Chenine, L. Vanfretti, N. Honeth, and R. Leelaruji, "Virtualization of synchronized phasor measurement units within real-time simulators for smart grid applications," in *Power and Energy Society General Meeting, 2012 IEEE*, july 2012, pp. 1 –7.

[18] "IEEE Standard for Synchrophasor Measurements for Power Systems," *IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005)*, pp. 1–61, 2011.

[19] eMEGAsim PowerGrid Real-Time Digital Hardware in the Loop Simulator — Opal RT, [Online]. Available: http://www.opal-rt.com/.

[20] "IEEE Standard for Synchrophasor Data Transfer for Power Systems," *IEEE Std C37.118.2-2011 (Revision of IEEE Std C37.118-2005)*, pp. 1–53, 2011.

[21] "OPNET System-In-The-Loop (SITL) Module," OPNET, Tech. Rep. [Online]. Available: http://www.opnet.com/solutions/network_rd/system_in_the_loop.html

[22] M. Chenine, L. Vanfretti, S. Bengtsson, and L. Nordström, "Implementation of an experimental wide-area monitoring platform for development of synchronized phasor measurement applications," in *Power and Energy Society General Meeting, 2011 IEEE*, Jul 2011, pp. 1–8.

[23] A. Phadke, J. Thorp, and M. Adamiak, "A new measurement technique for tracking voltage phasors, local system frequency, and rate of change of frequency," *Power Apparatus and Systems, IEEE Transactions on*, vol. PAS-102, no. 5, pp. 1025–1038, May 1983.

[24] J.-Z. Yang and C.-W. Liu, "A precise calculation of power system frequency and phasor," *Power Delivery, IEEE Transactions on*, vol. 15, no. 2, pp. 494–499, Apr 2000.

[25] P. Banerjee and S. Srivastava, "A subspace-based dynamic phasor estimator for synchrophasor application," *Instrumentation and Measurement, IEEE Transactions on*, vol. 61, no. 9, pp. 2436 –2445, sept. 2012.

[26] M. Wang and Y. Sun, "A practical, precise method for frequency tracking and phasor estimation," *Power Delivery, IEEE Transactions on*, vol. 19, no. 4, pp. 1547–1552, Oct 2004.

[27] J. Tate and T. Overbye, "Extracting steady state values from phasor measurement unit data using fir and median filters," in *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, Mar 2009, pp. 1–8.

[28] "PMU System Testing and Calibration Guide," NAPSIPerformance & Standards Task Team, Tech. Rep., Dec 2007. [Online]. Available: https://www.naspi.org/File.aspx?fileID=555

[29] PMU Connection Tester, [Online]. Available: http://pmuconnectiontester.codeplex.com/.

[30] "*open*PDC: The Open Source Phasor Data Concentrator," available online: http://openpdc.codeplex.com/.

[31] Wireshark, [Online]. Available: `http://www.wireshark.org/`.

[32] Z. Huang, T. Faris, K. Martin, J. Hauer, C. Bonebrake, and J. Shaw, "Laboratory performance evaluation report of SEL 421 Phasor Measurement Unit," Pacific Northwest National Laboratory, Tech. Rep., 2007. [Online]. Available: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-16852.pdf

[33] Y. Zhang, P. Markham, T. Xia, L. Chen, Y. Ye, Z. Wu, Z. Yuan, L. Wang, J. Bank, J. Burgett, R. Conners, and Y. Liu, "Wide-Area Frequency Monitoring Network (FNET) Architecture and Applications," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 159–167, Sep 2010.