# Architecture and laboratory implementation of a testing platform for Wide Area Monitoring Systems

Thuc Dinh Duong
Department of Energy System
SINTEF Energy Research
Trondheim, Norway
thuc.duong@sintef.no

Salvatore D'Arco
Department of Energy System
SINTEF Energy Research
Trondheim, Norway
salvatore.darco@sintef.no

John Olav Tande
Department of Energy System
SINTEF Energy Research
Trondheim, Norway
john.o.tande@sintef.no

***Abstract*—This paper presents a platform for testing wide area monitoring system (WAMS) applications in real time with a Hardware-in-the-Loop (HIL) approach. The power grid dynamics are emulated by performing real-time phasor simulations. Voltage and current phasors can be streamed to external systems based on the standard IEEE C37.118-2011, recreating synthetic synchrophasors. Moreover, phasors can be transformed into time-domain quasi-sinusoidal signals and transferred via a low-latency fiber optic connection to a 200 kW high-bandwidth grid emulator. The grid emulator can amplify the voltage and current signals, allowing Power Hardware-in-the-Loop (P-HIL) testing of physical hardware components. A graphical user interface has been developed to facilitate the interactions with the real time simulation and for better visualizing the power system dynamics. Two WAMS applications for assessing voltage stability margins and for detection of power oscillation are implemented and tested as examples. These examples demonstrate that the framework is a suitable platform to test WAMS applications in power systems**

***Keywords— PMU, Power oscillation, Real-time simulation, Voltage stability, WAMS***

## I. INTRODUCTION

Power system operation experiences new challenges associated to the increasing share of renewable energy sources and power electronic interfaced generation. Indeed, future power systems are expected to be more vulnerable and more prone to instability phenomena linked to more variable generation and lower physical rotating inertia. As the operating condition can change faster than before, there is a growing demand for implementing online monitoring tools in the transmission system operators (TSOs) control rooms. These tools could early detect situations when the grid is operated close to stability limits and warn the system operators to promptly actuate appropriate preventive and corrective measures.

Phasor measurement units (PMU) are devices that can measure the phase angle of sinusoidal signals using time synchronization obtained from the GPS system. Unlike conventional measurement devices, PMUs can measure phase angle of voltages and currents in power systems with high resolution (up to 50 measurements per second in a 50 Hz grid [1]). Moreover, all the PMU measurements are synchronized and can be easily sent to remote devices or applications (e.g. phasor data concentrator (PDC) or real-time applications) via TCP/IP or UDP. This is a unique possibility to obtain a true snapshot of the state of power systems, and it is considered as a prerequisite for WAMS applications [2], [3]. A large number of WAMS applications based on PMU measurements have been developed and some have been utilized by the TSOs to monitor their grids [4]. For example, several algorithms have been developed and tested for online voltage stability [5]-[7] and power oscillation monitoring [8]-[10]. Additional application areas are online line rating, estimation of inertia and detection of islanding events. Beside WAMS applications, there are efforts to close the loop in power system operation with wide area monitoring, protection and control (WAMPAC) applications, where PMU measurements are further utilized in special system protection scheme and wide area control [11], [12].

WAMS applications can be implemented and tested with different methodologies. A common practice is using offline phasor simulations of power systems and implement WAMS in the simulation software. However, with offline simulations, it is difficult to realistically account for practical challenges related to the PMU measurements like the latency of the communication and computing time requirements. As an alternative approach, WAMS applications can be tested on platforms where PMU data is streamed from a power system emulated in real time. Such a testing platform would more closely replicate the real-life operation conditions where the WAMS application are deployed in power systems.

This paper presents the architecture for a platform for testing wide area monitoring system (WAMS) applications in real time according to Power-Hardware-in-the-Loop (P-HIL) and Control-Hardware-in-the-Loop (C-HIL) approaches. This platform structure integrates a real-time phasor simulation of a power system. Phasors can be transformed into time-domain quasi-sinusoidal signals and transferred via a low-latency fiber optic connection to a 200 kW high-bandwidth grid emulator. The grid emulator can amplify the voltage and current signals, allowing P-HIL testing of physical hardware components. Moreover, the platform can function as a training tool and a graphical user interface has been developed to facilitate the interactions with the real-time simulation and for better visualizing the power system dynamics. Thus, the operators can interact with the simulated grid in real time by creating several critical operating conditions and testing different remedial actions to maintain stability in the grid.

This article is structured as follows. Section II describes issues related to real-time simulation of power systems, followed by Section III that briefly describes the real-time platform which is demonstrated in Section IV. In section V, two WAMS

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applications for assessing voltage stability margins and detection of power oscillation are briefly introduced. Section VI continues with the results from the demonstrated platform, and finally Section VII ends with some concluding remarks.

## II. Real-time Simulation of Power Systems

### A. Phasor simulation of power system dynamics

Phasor simulation of power system dynamics is a vital tool to analyze behaviors of the power grid during the transient periods triggered by disturbances. Power system dynamics simulation allows larger time steps than electromagnetic transient (EMT) simulations (i.e. in the range of 1-10 ms [13]), since the main interest is to replicate electromechanical transients in the system. Although several different methods for simulating power system dynamics have been proposed, they can be generalized by Fig. 1, which adopts the current-balance form of the simulation [14]. In this figure, there are two key elements:

- Grid: this is a network of impedances, consisting of line impedances, series and shunt impedances, e.g. load impedance, capacitors, inductors. In this grid, voltages and currents are assumed sinusoidal and represented by phasors, which can be expressed by complex numbers. Assume that $\bar{\boldsymbol{I}}$ is a column vector representing all the current sources connected to the grid and $\bar{\boldsymbol{V}}$ is a column vector of voltages of all nodes in the system. The following relation holds true:

$$\bar{\boldsymbol{I}} = \boldsymbol{Y}\bar{\boldsymbol{V}} \text{ or } \bar{\boldsymbol{V}} = \boldsymbol{Z}\bar{\boldsymbol{I}}$$

  where $\boldsymbol{Y}$ is the admittance matrix and $\boldsymbol{Z}$ is the impedance matrix of the grid. It is noted that these are algebraic equations.

- Current injector: these are electrical components that inject or draw current from the grid in a controlled manner, e.g. generators, FACTS devices, etc. Depending on the setpoint and the actual measurements, these components change their behavior to achieve the predefined objective. Normally, the current injector is a complex system, which can be described by a set of algebraic and differential equations. Since the current injector is connected to the grid, its internal variables are linked to the voltage of the connection point by a set of algebraic equations.

Seen from the grid, a current injector can be represented by the Norton equivalent circuit, which comprises a current source in parallel with an impedance. To simulate power system dynamics, the simulation must be first initialized. This means that power flow needs to be solved to determine power injection and voltages in the grid. Based on this condition, internal state variables of all the current injectors are computed; the principle is that all the derivatives must be initially equal to zero. Therefore, if there is no disturbance, all the variables in the simulation must remain unchanged. When a disturbance occurs, e.g. tripping of a line, voltages of all the nodes will change since the grid topology is different from the initial condition. As a result, variables of current injectors in the grid are affected, which leads to a change of the current source. This in turn will change voltages in the grid. The process continues until the entire system establishes a new equilibrium operating point. If not, the system becomes unstable.

### B. Real-time simulation of power system dynamics

Simulation of power systems is a mature technology applied in industry for many years with several tools for offline simulation commercially available. To simulate dynamics of the power grid in real time, the computing time must be smaller than the time step of the simulation, which is typically in a range of a few milliseconds [13]. Since power systems are generally very large in size, this could become challenging in terms of computing demand. However, in recent years, real-time simulation of power systems is becoming more affordable and popular [16].

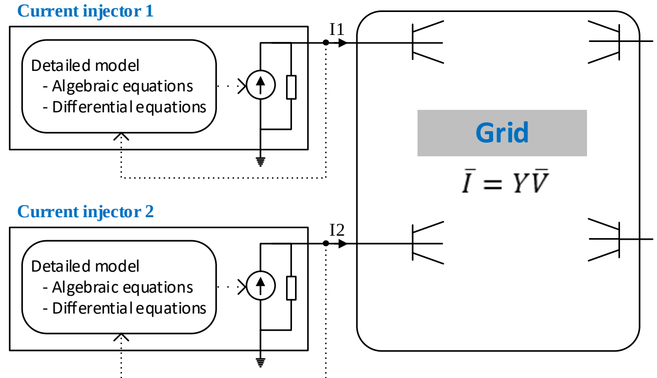


Figure 1. Illustration of power system dynamics simulation.

## III. Description of the Testing Platform

### A. Overview

Figure 2 shows an overview of the testing platform, where it is possible to use both phasor and EMT approaches to simulate power systems. Some of the results from the simulation can be sent to the grid emulator to create physical voltages and currents. Outputs of the grid emulator are connected to a physical grid with real line impedances and power hardware components. In this scheme, both synthetic PMUs and physical PMUs can send their measurements to the Phasor Data Concentrator (PDC). This tool collects and streams PMU measurements to WAMS applications. The WAMS applications can be implemented directly in the same real-time simulator or alternatively in another environment (e.g. Labview). The simulator can also receive measurements from physical PMUs via the PDC. It is noted that GPS time synchronization is also included in the platform.

### B. Power-hardware-in-the-loop (P-HIL) testing in real-time power system simulation

The results of the real-time phasor simulation, e.g. voltages and currents, are just digital values. To connect power hardware devices to the real-time simulation, digital voltages and currents need to be converted into physical quantities that normally have sinusoidal waveforms as illustrated in Fig. 3. It is noted that to have a smooth waveform, the time step ($Ts$) of the block that converts phasor to waveform must be much higher than that ($Tsp$) of the phasor simulation, e.g. $Ts$ = 100 µs and $Tsp$ = 10 ms.

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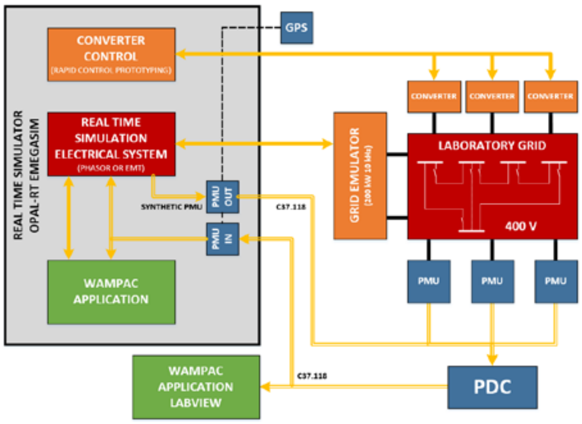


Figure 2. Overview of the testing platform.

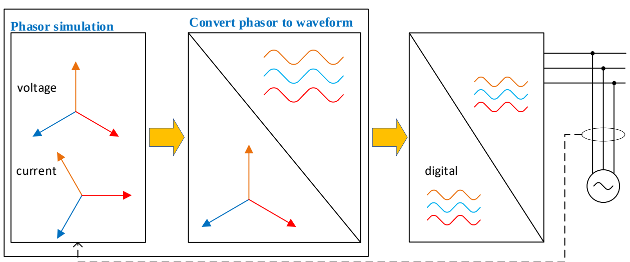


Figure 3. Conversion of phasors to waveforms to enable PHIL testing.

To convert a phasor to a sinusoidal waveform, the scheme shown in Fig. 4 can be implemented. First, both magnitude and phase angle of the phasor are filtered by a low-pass filter to smoothen the input signals. These filtered signals are then converted to the real and imaginary parts and considered as d-q signal components in the synchronous rotating coordinate. Finally, an inverse Park transformation is performed to obtain three-phase waveforms.

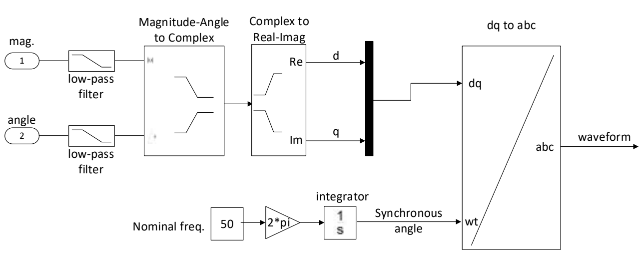


Figure 4. Implementation of phasor-to-waveform conversion.

## C. *Synthetic phasor measurement unit (PMU)*

WAMS applications can be implemented within the real time simulator or in an external environment. In the second case, the WAMS will require phasors of voltages and currents from the power system simulated by the simulator. Therefore, these phasors can be streamed to the external applications in the PMU measurement format. According to the standard IEEE C37.118-2011, the time error of the PMU clock should be less than 1 µs. If the time error is larger, the error of the phase angle will become larger, and the PMU might not meet the requirement for the maximum total vector error (1%). Additionally, each measurement must be time tagged based on the clock that is synchronized with the GPS system clock. If the external application requires only phasor measurements from the simulator, time synchronization is not needed since all the measurements are generated by the simulator at the same time, and the timestamp is obtained from the CPU clock of the simulator. However, if there are both simulated PMUs and physical PMUs in the set-up, both types of PMUs need to be synchronized with the GPS system.

# IV. Demonstration of the Platform

The testing platform architecture described in the previous section has been implemented in the Norwegian National Smart Grid laboratory located in Trondheim. The laboratory is suitable for studying different grid configurations, hybrid ac/dc networks, offshore grids and grid connection issues regarding small hydro power plants and wind generation. Figure 5 shows an overview of the implementation. A simplified representation of the Nordic power grid in Europe referred as Nordic 44 is simulated, and phasors of voltages and currents are streamed to an external computer where WAMS applications are implemented and tested.

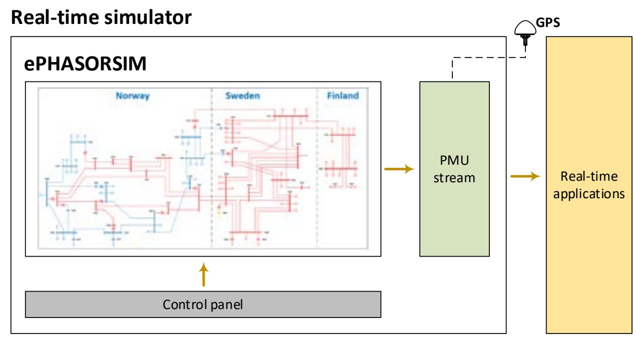


Figure 5. Overview of the set-up.

## A. *The Nordic 44 bus system*

The Nordic 44 model, as the name indicates, consists of 44 nodes at three voltage levels (420, 300 and 130 kV). This model captures the main characteristics of the synchronous Nordic power system, which comprises the transmission grids in Norway, Sweden, Finland and the western part of Denmark. The Nordic 44 model has been designed and developed so that it is possible to reproduce operating conditions with poorly damped modes, and with voltage instabilities. This is a suitable condition to demonstrate online applications for wide area monitoring, protection and control. Additionally, power flow between areas in the real system, which can be imported from the power market Nord Pool, can be mapped into the model; this results in various operating conditions which are close to the real operation conditions in the actual Nordic power system. Details of the model and its use cases are presented in several work [15].

## B. *Grid simulation with ePHASORSIM*

In this implementation, the real-time simulator is based on an Opal-RT OP5600 hardware, and phasor simulation is conducted by the ePHASORSIM software [16]. The grid topology and all controller models (governor, AVR, PSS, etc.) can be specified with a few input options as either an Excel file, PSS/E files, PowerFactory or CYME. PSS/E files are been preferred for the applied Nordic 44 model. It is worth mentioning that

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ePHASORSIM has a relatively limited number of built-in models for generator, governor AVR and PSS, which is in many cases not sufficient for power system simulation. However, it is possible to build new models in OpenModelica and link these models to ePHASORSIM. Moreover, Opal RT has defined a syntax for how to develop these user-defined models. Basically, there are two types of model: current injection and non-current injection. Current injection model is a model which injects current into the grid; models belonging to this type are typically generator, HVDC, FACTS devices. On the other hand, non-current injection models do not have direct connection to the grid; they are typically controllers, such as governor, AVR, PSS, etc.

### C. *PMU stream and time synchronization*

In the Opal RT simulator, there is a driver supporting the standard IEEE C37.118-2011 that allows transferring PMU data to external systems (e.g. phasor data concentrator or real-time applications). Outputs of ePHASORSIM include already voltages and currents in phasor format. Thus, the phasors should be only selected and mapped to the PMU stream with no further processing. As mentioned in the previous section, the time clock that is used to timestamp PMU measurements is needed in case the WAMS applications combine both simulated PMUs and physical PMUs. In this case, integrating the GPS time into the real-time simulator is needed. As shown in Fig. 6, a GPS antenna is connected to a GPS master clock, which is the SEL-2407 in the set-up. This clock distributes synchronization signal using the IRIG-B protocol, which is a popular standard used to synchronize different devices. In the real-time simulator, a synchronization board Oregano syn1588 PCIe NIC is installed. This board synchronizes its internal clock with the GPS system based on the IRIG-B signal sent from the clock SEL-2407.

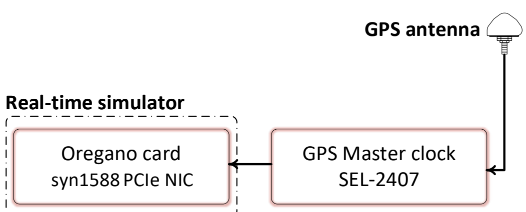


Figure 6. Synchronization of the real-time simulator with Oregano syn1588 PCIe NIC board and GPS master clock SEL-2407.

## V. Demonstrated WAMS Applications Examples

Since the first commercial PMU was introduced to power systems in 1991 [2], there have been several research activities to develop WAMS applications. In this paper, two of the proposed algorithms, namely online voltage stability monitoring and real-time detection of power oscillations, are demonstrated.

### 1) *Online voltage stability monitoing*

Voltage stability remains one of the main concerns in power systems. This phenomenon might happen when the demand is larger than the power transfer capacity of the grid. The power drawn from the load results in the grid voltage amplitude progressively decreasing until the system collapses. Thanks to PMU measurements, a large amount of research activities on online voltage stability monitoring has been conducted; several algorithms have been proposed to monitor voltage stability in real time. Among others, the method proposed in [5] is selected for this platform since this algorithm has been tested both in simulation, in the lab environment and in the Norwegian transmission system. The main feature of this algorithm is that it can properly estimate the maximum power transfer at a load bus. By comparing this value with the load power, the power margin at the monitored bus can be detected. Additionally, a new indicator called S-Z sensitivity is introduced, which can properly detect whether the load has crossed the maximum loadability. Details of the method are presented in [5].

### 2) *Online detection of power oscillation*

In power system operation, power oscillations are another concern, and they need to be detected as soon as possible. Poorly damped or unstable power oscillations may cause severe damage for equipment or lead to cascading tripping of lines and generators. To early detect power oscillations as they are arising, a method has been proposed in [8]. When a power oscillation (whether it is a ringdown or sinusoid) occurs and its magnitude is larger than a predefined threshold, the oscillation is automatically captured and analyzed by the Prony analysis. Then information about the oscillation will be displayed to help system operators be aware of the ongoing oscillation in the grid. This is a useful tool to detect disturbances in the power systems, especially the ones occurring in external systems, where there is no observability. Moreover, the algorithm provides actual modes in the system obtained from large disturbances, which gives a true picture of the dynamics in the grid.

## VI. Results from the Demonstrated Platform

### 1) *Cross-validation between ePHASORSIM and PSS/E*

ePHASORSIM is a rather new simulation tool, and to the best of the authors' knowledge, cross-validation between this tool and other software has not been published. Therefore, it is necessary to compare the performance of this software with other widely used tools in power systems, such as PSS/E or PowerFactory. In this section, the Nordic 44 is simulated by both PSS/E and ePHASORSIM; both simulation tools use the same PSS/E files. It is noted that some combinations of generator, governor, AVR and power system stabilizer (gensal_scrx_stab1_hygov, genrou_ieeet1_stab1_ieesgo, etc.) are developed in OpenModelica and linked to ePHASORSIM since this software has a limited number of built-in models. The simulated scenario is tripping of a line between node 7 and 32 at *t* = 10 s. Figure 7 shows the voltage at bus 7 during the event. As can be seen, both simulations show a very similar performance, and the difference between them is negligible.

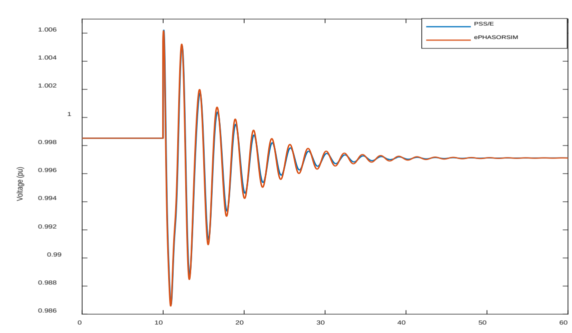


Figure 7. Voltage at bus 7 obtained from PSS/E and ePHASORSIM simulations when a line between bus 7 and 32 is tripped.

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*2) Real-time demonstration*

The demonstration is a real-time application developed in Labview and its main interface is shown in Fig. 8. The application continuously receives a PMU stream from the real-time simulator; then it processes the data and visualizes all the signals in the PMU stream. In parallel, the two online monitoring tools mentioned in the above section are also running. Fig. 9 shows a snapshot of the application for online detection of power oscillations. As can be seen, the oscillation (a ringdown) is properly captured and analyzed. In this case, the magnitude of the oscillation is 50.8 MW, and the frequency and damping ratio are 0.48 Hz and 4.2% respectively. These parameters, especially the frequency, are quite close to actual oscillation frequency in the Nordic power system at this corridor.

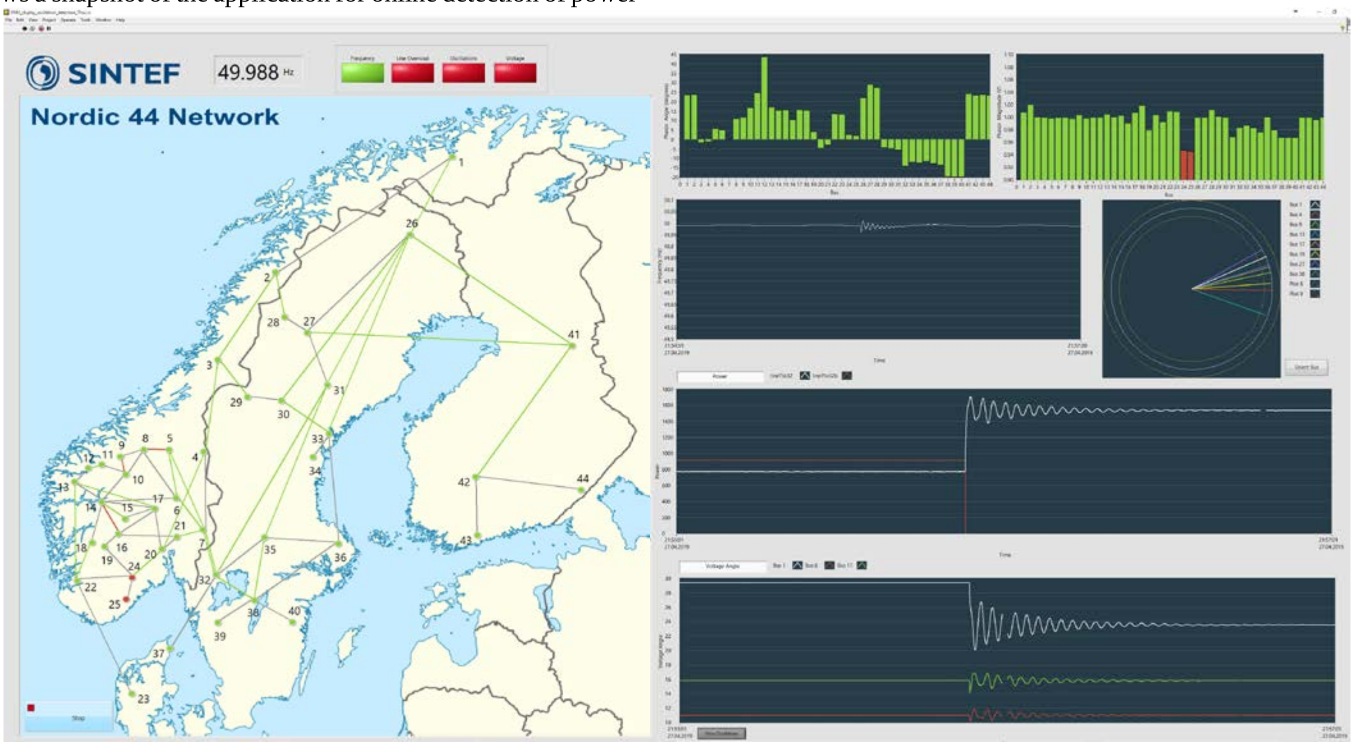


Figure 8. The main window of the demonstrated platform, where the user can freely visualize measurements from the real-time simulation.

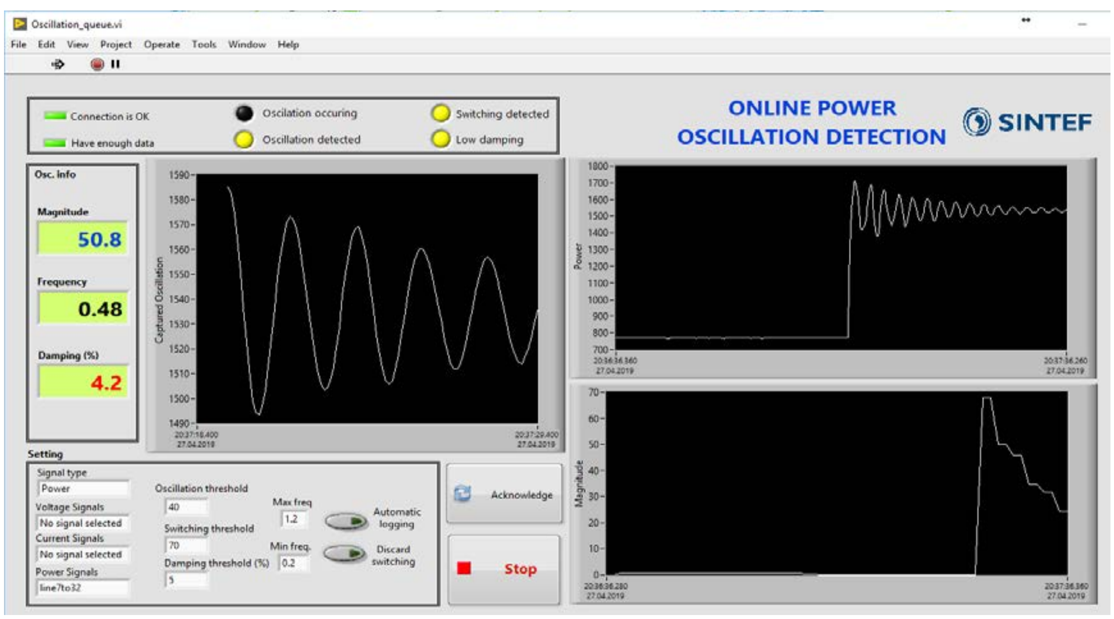


Figure 9. An oscillation captured by the online monitoring tool.

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The application for voltage stability also successfully detects an alert situation when load is close to voltage stability limit as shown in Fig. 10. In this application, the Thevenin impedance (in red) of the grid seen at the monitored bus is estimated and compared with the load impedance (in white). Meanwhile, the estimated maximum loadability (in red) and the load power (in white) are shown together in another graph. As can be seen, the maximum power transfer is reduced significantly after the last disturbance in the grid; the load is now very close to the maximum limit. Additionally, the red dot is the currently measured S-Z sensitivity. This value is negative, meaning that the load is still within the voltage stability limit, and actually it is. If the load crosses the maximum loadability, this sensitivity will become positive.

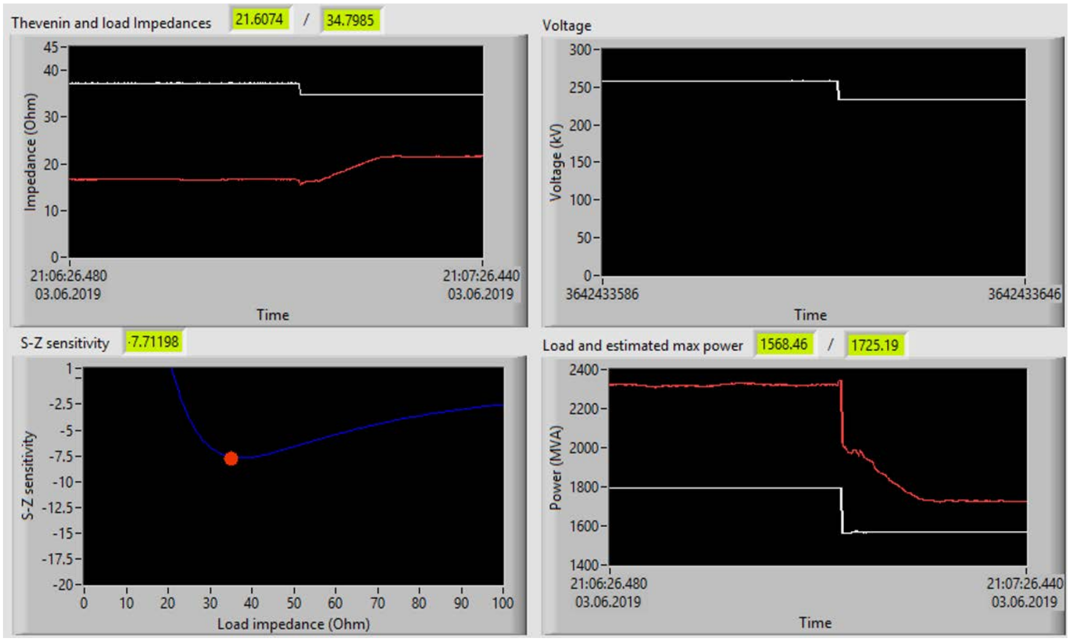


Figure 10. The online voltage stability monitoring application detects that the load at node 25 is close to voltage stability limit.

## VII. Conclusion

The paper has presented a platform where real-time simulation of bulk power system is integrated with PMU measurements, which lays the groundwork for testing WAMS applications. As demonstrated, the Nordic 44 model is simulated in real time, and phasors from the simulation are streamed to the external application, where phasors of voltages and currents in the grid are visualized giving insight into the dynamics of power systems. In addition, the two online monitoring tools for voltage stability and detection of power oscillations have been implemented and tested. The fact that these monitoring tools work properly with the data from the simulated grid shows that the proposed scheme is an effective platform for testing WAMS applications.

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