Validating a Real-Time PMU-Based Application for Monitoring of Sub-Synchronous Wind Farm Oscillations

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***Abstract*—This paper presents validation experiments performed on a Phasor Measurement Unit (PMU) based fast oscillation detection application. The monitoring application focuses on the detection of sub-synchronous oscillations, utilizing real-time measurements from PMUs. The application was first tested through Hardware-In-the-Loop (HIL) simulation. Validation experiments were carried out with a different set-up by utilizing a micro grid laboratory. This second experimental set-up as well as the results of the validation experiments are presented in this paper.**

***Index Terms*—Sub-synchronous oscillations; PMU; Hardware-In-the-Loop; Wind farm; Monitoring application; BableFish; Micro grid.**

I. Introduction

Electricity generation has evolved considerably during the last twenty years and renewable sources of energy have gained popularity. Among the different sources of renewable energy wind power will play a major role as most European countries have planned large installations in the coming years [1].

These intermittent sources of energy bring several new challenges for power systems. Taking the example of wind power, its impact on transient stability has been a concern subject to study [2]. Fast dynamic events remain, however, generally undetected by traditional monitoring tools provided by Supervisory Control And Data Acquisition (SCADA) systems due to low sampling frequencies and lack of time-synchronization in the sensing instruments used. Oscillatory events in the range of 13-15 Hz, involving interactions between wind farms, have been measured with PMUs on the power system of Oklahoma Gas & Electric (OG&E) [3]. These events were even observed at the consumer level in the form of flickering [4], motivating the work presented herein.

Figure 1 presents a comparison between SCADA and PMU measurements of this phenomenon. PMU-based tools for monitoring and control of this kind of phenomena are not common. These new tools can help providing operators with better information about unwanted system dynamics. Their development is however subjected to the access to relevant PMU data.

Considering that only a few European TSOs have a relatively small number of PMUs installed (as compared to the USA) and that some testing scenarios might endanger the operation of the transmission grid, the Hardware-In-the-Loop (HIL) simulation alternative offers numerous advantages for developing PMU applications, and enables fast prototyping of new algorithms and tools.

This paper presents the validation process performed on a PMU-based monitoring tool using both HIL simulation and hardware-based emulation. The HIL simulation environment is described in Section II and one example involving the oscillation detection application is presented in Section III. The micro grid and the set-up at IREC are described in Section IV. The experiments for validation of the HIL simulation approach, as well as the results obtained at IREC, are presented in Section V.

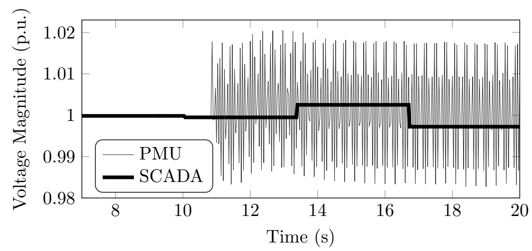


Figure 1. Comparison example between PMU and monitoring through SCADA during a fast dynamic event

II. Hardware-in-the-Loop simulation environment

Developing new tools for Wide Area Monitoring Systems (WAMS) implies the need of testing with real-time PMU measurements containing relevant information. Real-time PMU measurements need also to be accessible in a software development environment. The approach adopted at SmarTS Lab [5] is described below.

The set-up built in the lab makes use of HIL simulation, replacing the power system by models executed in real-time on a simulator equipped with analog reconfigurable inputs/outputs. The rest of the WAMS architecture is replicated, building a testing platform which is depicted in Fig. 2, with the following elements:

- The real-time simulation target from Opal-RT [6].
- A National Instruments compact RIO (cRIO) PMU connected to the analog outputs of the simulator.
- The connection cables of the PMU for acquiring voltage measurements, connected to the simulator.
- The network connection of the PMU to stream data to the Phasor Data Concentrator (PDC) server of the lab.
- The PDC server, running the SEL-5073 software from Schweitzer Engineering Laboratories, Inc (SEL).
- The application host workstation with the software development environment.

The usage of a real-time target thereby implies a broad flexibility in terms of the phenomena that can be simulated

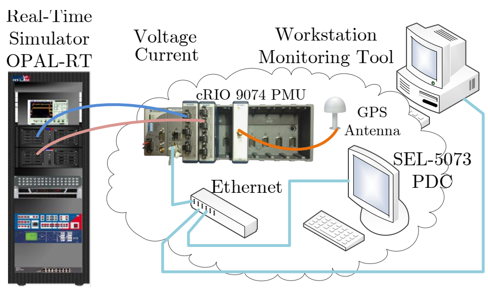


Figure 2. Diagram of the set-up at SmarTS Lab for WAMS applications development and testing

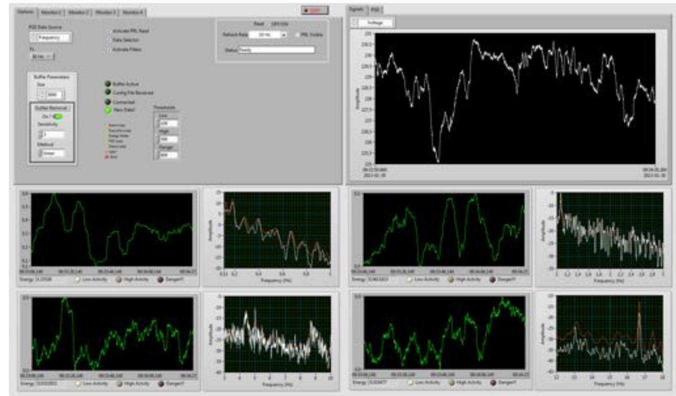


Figure 3. Screenshot of the interface of the *Monitoring Tool*

for different power systems. For a complete description of the HIL environment at SmarTS Lab refer to [5].

A. Real-Time Data Mediators (RTDM)

On the aforementioned application host workstation, LabView is chosen as the primary development environment. However, LabView does not provide libraries to handle the IEEE C37.118.2 standard [7] and therefore does not enable the direct use of PMU or PDC data streams. Consequently, a complementary software, namely BableFish [8], was developped to serve as mediator connecting the PMU/PDC and a LabView application.

The BableFish reads PMU measurements and lets its user choose the sets of data of interest. Moreover, it allows for transmitting chosen data over UDP to any remote or local location. Hence the final user will be able to receive the data of interest from the PDC/PMU while having the ability to choose the platform, language, OS, and geographical location that suits best the application.

The *Monitoring Tool* has also been successfully tested with Statnett's Synchrophasor SDK [9], which is another RTDM facilitating application development in LabView.

III. Monitoring Tool and HIL Simulation

The oscillatory event showed on Fig. 1 differs from the traditional and well studied inter-area or local oscillations, as mentioned in the Introduction, it remained undetected by traditional tools.

The tool combines two algorithm for performing oscillations detection at multiple frequency ranges up to 15-25 Hz (Nyquist limit of the PMU sampling rate). The first operates on a frequency range and computes the energy content of the oscillations. It extends the work in [10] inspired by signal envelope detection methods. The second algorithm computes the Power Spectrum Density (PSD) within the same frequency range with both a parametric method assuming an auto regressive model and a non-parametric method (Welch).

The Graphical User Interface (GUI) of the tool, depicted in Fig. 3 gathers several elements. The upper part is dedicated to the configuration of the tool (left) and a live display of the input signals (right). The lower part is reserved for the oscillation detection, it comprises four *Modules* set on different frequency ranges of interest (inter-area modes, local modes, faster oscillations events, etc.). Each *Module* presents one graph (left) showing the energy level computed in the frequency range for the time window within the buffer, LED indicating whether the energy level of the latest time stamp goes over user defined thresholds, and one graph (right) showing the PSD on the input signal within the same frequency range.

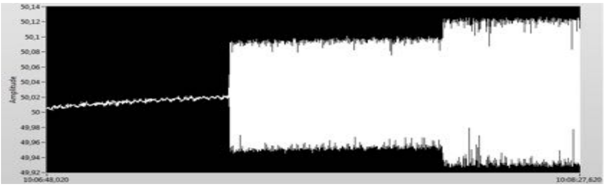
The tool's performance for detection of oscillations in various frequency ranges was tested with the set-up described in Section II and depicted on Fig. 2. It involved the development of a model capable of generating different events in a power system according to a certain testing scenario. Some results of the HIL simulation experiment will be shown in this paper for comparison purposes with the results obtained at IREC, presented in Section V. A more detailed presentation of the HIL environment and testing experiments can be found in [11].

The *Monitoring Tool* was primarily tested to assess its ability in detecting the phenomenon depicted in Fig. 1. The oscillation injected in the model had a frequency of 10.83 Hz[1]. Figure 4 presents the results obtained using the *Monitoring Tool*, when the oscillation injection starts at 0.05 p.u. and are then increased up to 0.07 p.u. (see Fig. 4b). As a result the amplitude of the oscillation increases when the injection's amplitude is increased (see Fig. 4a) on the *Module* identifying a clear frequency of 10.83 Hz (see Fig. 4b). It can be seen that the detection of the oscillation is fast, with a quick increase of the energy level computed in the range of [3 - 12 Hz], the activation of the *Danger!!!* indicator, and the correct frequency identified by the PSD. The tool successfully detected the oscillation cases it was designed to detect.

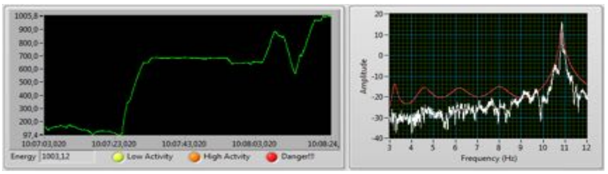
IV. Micro Grid of IREC - Emulators

The *Monitoring Tool* was validated in a micro grid laboratory at the IREC research centre in Barcelona, Spain. The lab is equipped with a small replica of a utility-connected micro grid. A full description of the micro grid can be found in [12]. This lab has five emulators available, which are power

[1] equivalent in a 50 Hz system to the original case of 13 Hz oscillation in a 60 Hz system (USA).



(a) Frequency



(b) *Module* [2 - 12 Hz]

Figure 4. Partial screenshot of the *Monitoring Tool* at the beginning of the oscillations injection and during a step increase in their amplitude

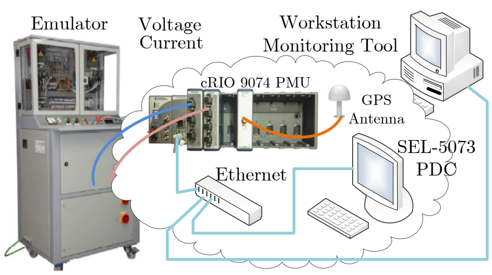


Figure 5. Diagram of the set-up at IREC.

electronic devices that can generate any variable AC power ($P_{max} = 4000\ W$).

Each emulator is composed by two identical three-phase voltage sources in back-to-back configuration, allowing bidirectional power flow. One converter is referred as Active Front End (AFE), and the other one is simply referred as Active Rectifier (AR). The AR controls the maximum power through the DC bus at all time. This power control is done by means of the DC bus voltage. On the other hand, the AFE receives of 3-phase active power and reactive power reference values (P* and Q* respectively), and attempts to generate them at the AC side using the energy at the DC bus.

A. Set-up for validation experiments

The existing set-up at KTH, presented in Section II, was replicated at IREC, substituting the real-time simulation target by the emulator described previously. The resulting set-up, presented in Fig. 5, does not rely on HIL simulation, but provides a scaled-down realistic environment for testing WAMS.

PMU measurements were obtained by measuring three line currents at the AC side of the AFE using 10/5A current transformers fed to a National Instruments cRIO PMU. In addition, three phase-neutral voltages were directly wired between PMUs and emulators at the AR side. The layout of the PMU installation can be seen in Fig. 6. PMU configuration parameters were adjusted according to the currents and voltages set-up using the PMU configuration and diagnostic web interface from National Instruments. PMU measurements were verified utilizing commercial power analyzers with the emulator generating constant real power.

Figure 6. PMU installation layout at IREC 24V power supply (left), cRIO PMU (center) and GPS splitter (right).

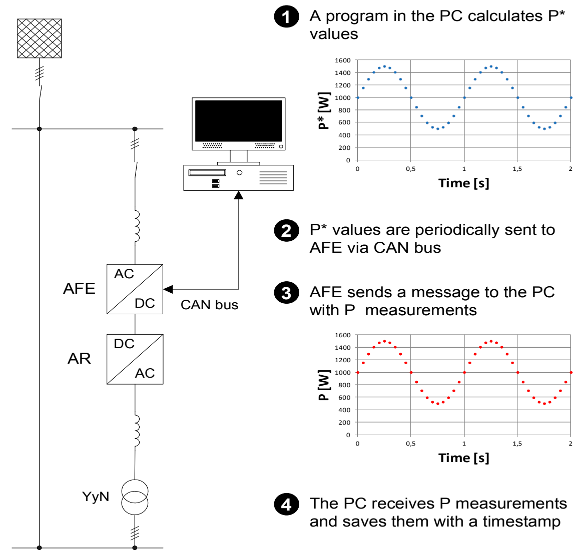


Figure 7. Set-up for power oscillations generation.

B. Generating oscillations

As shown in Fig. 7, P* values were periodically sent from a PC via CAN bus. In order to provide fixed-frequency power oscillations, it is critical to send P* at a constant rate. The computer used was a standard PC running Windows XP. This system does not guarantee precision timing in the order of tenths of milliseconds or milliseconds. For this reason, instead of using the timing functions in Windows XP, P* values were sent as shown in Fig. 8. The refresh rate was kept constant and equal to 16 milliseconds ($\Delta t = 16\ ms$). Figure 9 shows fixed-frequency power oscillations generated by the emulator. As depicted, it is possible to provide fairly precise power oscillations below 6 Hz.

V. Validation with the Micro Grid Lab

Prior to the validation experiment testing of the equipment at IREC was carried out to evaluate the performance of the control scheme of the inverters in the emulators. The

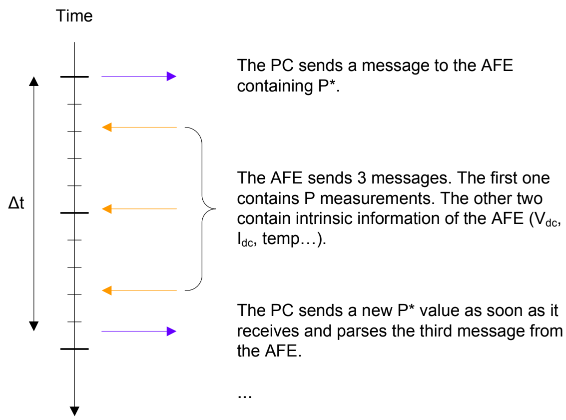


Figure 8. Messages exchanged between the PC and the AFE.

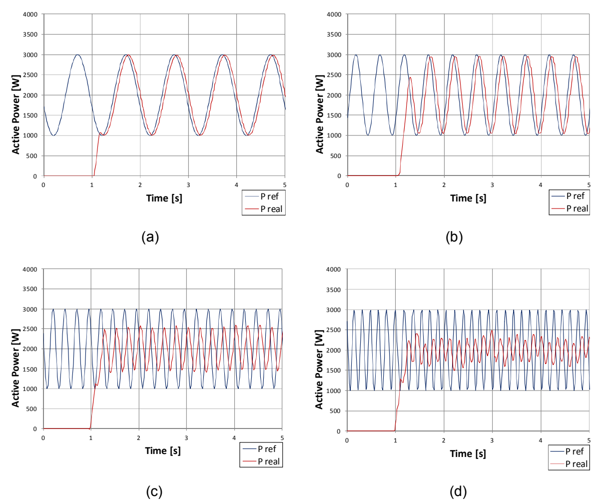


Figure 9. Power oscillations at different frequencies: (a) 1 Hz, (b) 2 Hz, (c) 4 Hz, (d) 6 Hz.

tests helped to identify limitations for the emulation of fast dynamic behaviours that led to an optimization of the internal emulator controls for increasing the equipment's capability to emulate faster dynamics events. The validation experiment has therefore been carried out in two steps. In the first step, several fixed frequency oscillation cases were tested to calibrate the *Monitoring Tool* taking into account local ratings. The second step used a recording of the simulation performed at KTH to be replayed in one emulator.

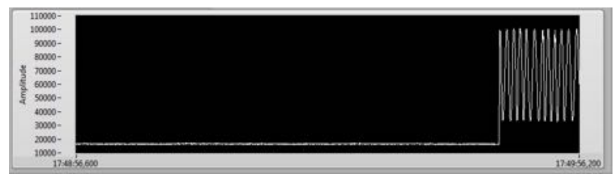
In the experiments carried out with the micro grid at IREC, voltage and frequency were both externally controlled at the connection point to the Spanish national grid. Thus, the *Monitoring Tool* was adapted to allow the oscillation detection algorithms to use current measurements. The results provided in this Section show the active power in the real-time display.

A. Fixed frequency power oscillations

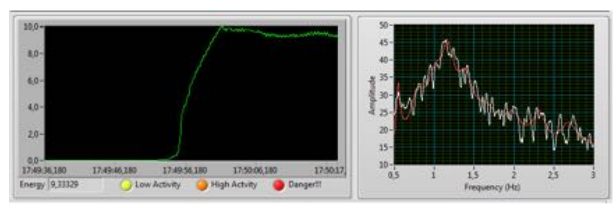
The first step of the validation experiment was designed taking into consideration the capability of the equipment. As mentioned in Section IV, the micro grid was conceived to emulate equipment having slow dynamics. Reproducing oscillatory phenomena around 1 Hz was therefore possible and the first power injection was done according to the following formula:

$$P(t) = 2000 + 1000 \sin 2\pi t$$

The detection was achieved in a few seconds, see Fig. 10, provided that the thresholds have been correctly calibrated, and the level of energy computed in the oscillations remains rather constant as the injection is sustained, see Fig. 10b. The frequency of the oscillations is detected around 1.1 Hz, see Fig. 10b, this difference between the reference frequency and the identified frequency is due to errors in the accurate reproduction of the reference signal by the emulator.



(a) Active power



(b) *Module* [0.5 - 3 Hz]

Figure 10. Partial screenshot of the *Monitoring Tool* at the beginning of the oscillation injection at 1 Hz

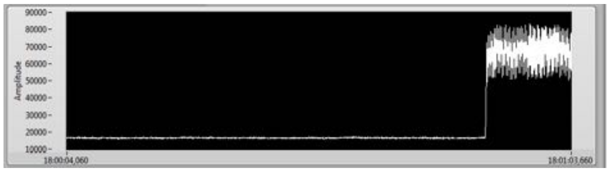
The second part of this first experiment tested the capability of the equipment to reproduce oscillations at a higher frequency of 6 Hz. The reference values were sent according to the following formula:

$$P(t) = 2000 + 1000 \sin 12\pi t$$

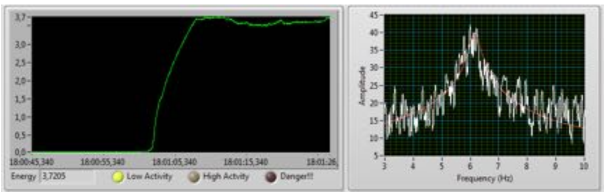
The measured values for the oscillations amplitude were however much lower, see Fig. 11a, highlighting the limits of the bandwidth of converter controls. The detection of the oscillations was nevertheless achieved, with a *Low Activity* flag, see Fig. 11b, while leaving the other frequency ranges without any activity flags. This experiment motivated an additional adaptation of the detection thresholds for the next experiment.

B. Replay experiment

Considering the limitations in the possibility to reproduce oscillatory events with a frequency higher than 6 Hz, the replay of the recorded simulation was adapted. The original experiment carried out at KTH contained oscillations at 10.83 Hz. The simulation was configured to inject therefore oscillations at half the original frequency (5.4 Hz). The trigger levels were set according to the results obtained in the previous



(a) Active power

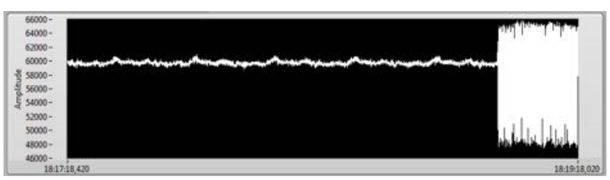


(b) *Module* [3 - 10 Hz]

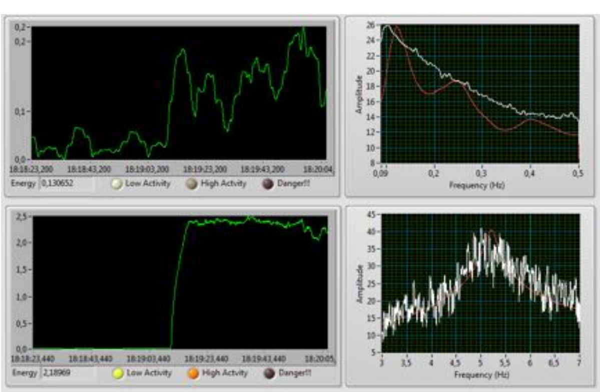
Figure 11. Partial screenshot of the *Monitoring Tool* at the beginning of the oscillation injection at 6 Hz

experiment. Compared to the original configuration of the tools the new detection levels were much lower due to the ratings of the micro grid and the use of a current measurements for detection.

Figure 12 presents partial screenshot of the *Monitoring Tool* at the beginning of the injection of the oscillations. The oscillations can be observed on Fig. 12a in the active power measured at the AFE. On Fig. 12b two modules are shown, the first one does not show any activity flag, whereas the second one, containing 5.4 Hz within its frequency range, shows a *High* activity level flag. This confirms the ability of the tool to detect oscillatory events and its selectivity even in the case when much lower thresholds need to be configured.



(a) Active power



(b) *Modules* [0.05 - 0.5 Hz] and [3 - 7 Hz]

Figure 12. Partial screenshot of the *Monitoring Tool* at the beginning of the replay of the oscillation injection

VI. Conclusion

The experiments carried out at IREC for validating the PMU software application revealed some challenges related to actual equipment. These limitations required several adaptations of the software, which explain certain differences between the results obtained in both cases. Experimental results showed that the capability of the tool to detect oscillations only suffered minor differences with respect to previous experiments, see [11].

The validation experiments highlighted also the flexibility allowed in the use of HIL simulation, where a broader range of phenomena can be simulated, with a smaller probability of breaching physical equipment limits, confirming the pertinence of such an approach for testing multiple types of grid operation scenarios.

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