Testing and validation of a fast real-time oscillation detection PMU-based application for wind-farm monitoring

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Testing and Validation of a Fast Real-Time Oscillation Detection PMU-Based Application for Wind-Farm Monitoring

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***Abstract*—This article provides an overview of a monitoring application, its testing and validation process. The application was developed for the detection of sub-synchronous oscillations in power systems, utilizing real-time measurements from phasor measurement units (PMUs). It uses two algorithms simultaneously to both detect the frequency at which the oscillatory event occurs and the level of energy in the oscillations. The application has been developed and tested in the framework of SmarTS Lab, an environment capable of hardware-in-the-loop (HIL) simulation. The necessary components of the real-time chain of data acquisition are presented in this paper, as well as testing and validation results, to demonstrate the accuracy of the monitoring tool and the feasibility of fast prototyping for real-time PMU measurements based applications using the SmarTS Lab environment.**

***Index Terms*—Power system oscillations; monitoring application; BableFish; PMU; Wide Area Monitoring Systems.**

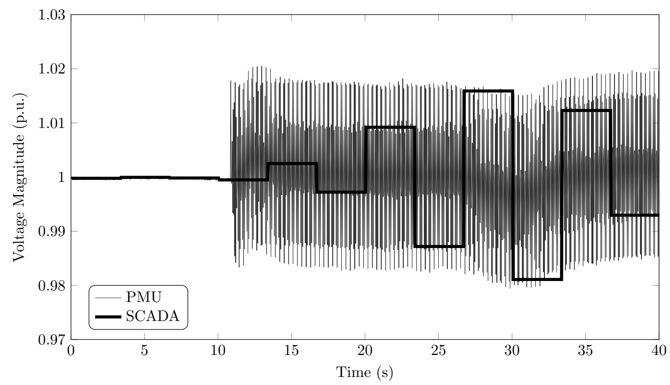


Fig. 1. Comparison example between PMU and traditional equipment measurements(SCADA) during a fast dynamic event

I. Introduction

The environmental impact of electricity generation has raised concerns in western countries, engaging a shift to renewable energies among which wind power has become the fastest growing energy technology since the 1990s [1]. This expansion will continue, especially in Europe, where several countries have fixed high goals for the coming years [2].

The increasing amount of wind power, which is one kind among different intermittent generation sources, involves numerous new challenges for its integration in existing power systems. As such transient, stability issues have already been studied [3]. However, it is only recently that some Transmission System Operators (TSOs) have measured, with PMUs [4], sub-synchronous oscillatory events resulting from interactions between wind farms at frequencies around 13-15 Hz. The oscillations were even observed at the consumer level in the form of flickering [5].

Fast dynamics at such frequencies remain unobservable by most of the standard monitoring tools (SCADA), due to too low sampling frequencies and lack of time synchronisation, leaving this kind of phenomenon unstudied.

Figure 1 presents a comparison between SCADA and PMU measurements of this phenomenon. The usage of PMUs enables observability for phenomena occurring at frequencies up to 15-25 Hz, opening new wide perspectives for monitoring and control applications based on synchrophasors. These new tools will help acquiring a better knowledge on the challenges brought by the increase of intermittent energy sources.

This paper presents a hardware-in-the-loop (HIL) validation process for a PMU-based monitoring application aiming at the detection of the phenomenon aforementioned. The developed application is briefly introduced in Section II and the HIL-simulation environment is described in Section III. The validation experiment as well as the results obtained are presented in Section IV.

II. Monitoring Application

The oscillatory event presented in Fig 1 differs from the traditional and well studied inter-area or local oscillations. It also remained undetected by traditional monitoring tools present in the control room of the TSO. An application dedicated to the detection of such phenomena was developed using LabView at SmarTS Lab. This tool will be introduced in this Section, however, a more detailed presentation of the algorithms behind the oscillation detection will be the subject of a future publication; the focus here will be put on the tool's testing and validation process.

This monitoring tool has been developed as a real-time application that exploiting PMU measurements. The detection of oscillations is performed by two separate algorithms, the first one is an adaptation of an algorithm for fast detection of low frequency oscillations from the work by Hauer in [6]. It computes the energy content of oscillations within a frequency range by signal envelope detection. The second algorithm computes the Power Spectrum Density (PSD) within the same frequency range with a parametric method assuming an auto regressive model and a non-parametric method (Welch). The application also implements several pre-processing steps to accommodate for the PMU measurements, which can contain measurement errors. The pre-processing algorithm was inspired by previous work used for off-line analysis [7], and adapted for real-time application.

As mentioned previously, the tool is fed by real-time PMU measurements coming directly from a PDC output stream,

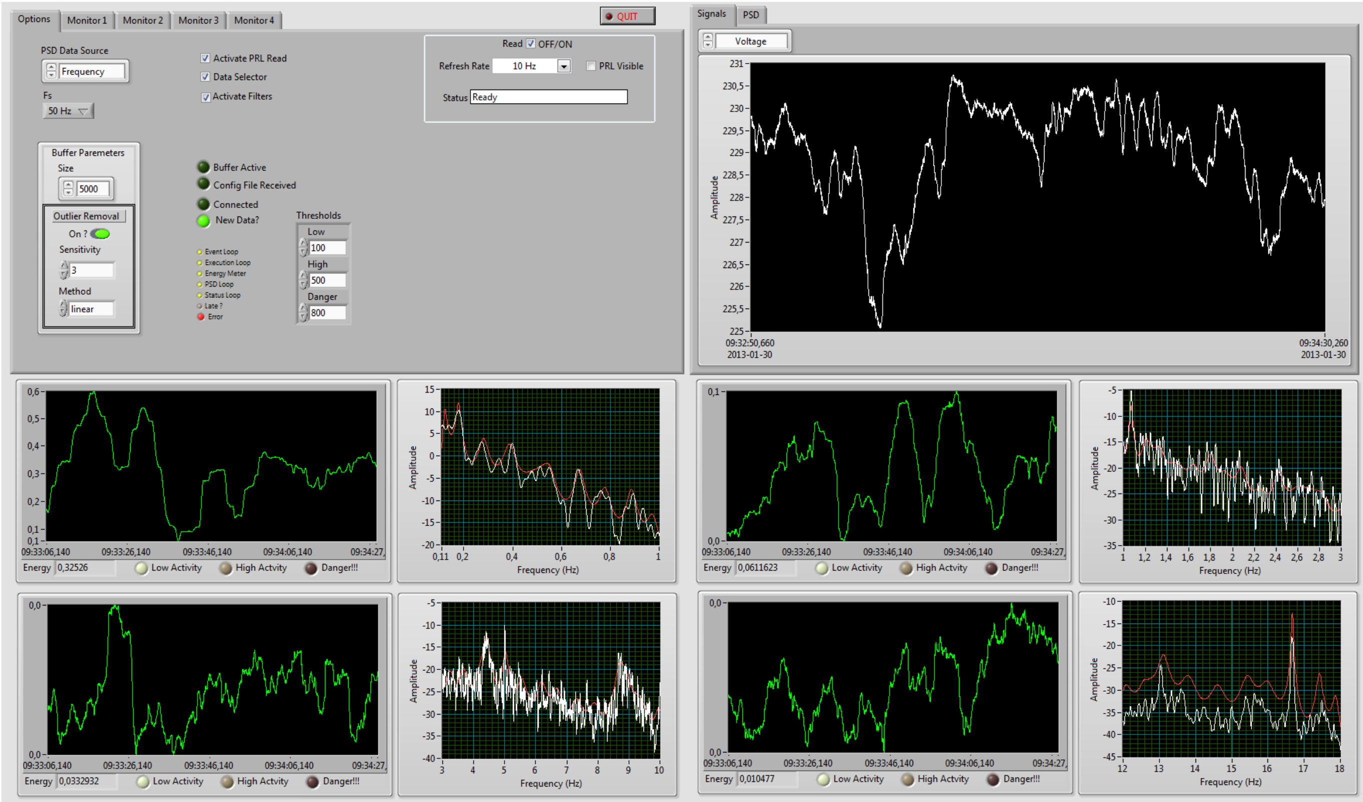


Fig. 2. Screen shot of the interface of the *Monitoring Tool*

explained further in Section III. It updates the results of the detection algorithms in real-time, although subject to small delays from the filters implemented in the algorithms. The graphs present the results of a buffer of data, which length is set by the user.

Figure 2 depicts the main Graphical User Interface of the *Monitoring Tool*,which is divided in several parts. The top-left part is the configuration interface, the top-right part contains an input signal visualization graph and the bottom part is dedicated to the oscillation detection interface. The monitoring interface is comprised by four *Modules*, see Fig. 3, containing two graphs and LED indicators. Each *Module* is configured to monitor a separate frequency range, targeting several ranges of interest (inter-area modes, local modes, faster oscillations events, etc.) The graph on the left part of a *Module* depicts the level of energy computed in the frequency range for the time window of the buffer. The LED indicators define three thresholds of energy, set by the user, they light up according to the energy computed at the latest time stamp. The graph on the right shows the Power Spectrum Density (PSD) of the frequency range, completing the information on any occurring oscillation.

III. Chain of Real-time Data Acquisition

Development of new monitoring applications utilizing synchronized PMU measurements requires a testing platform which can provide real-time data. This is accomplished with a chain of real-time data acquisition as described below.

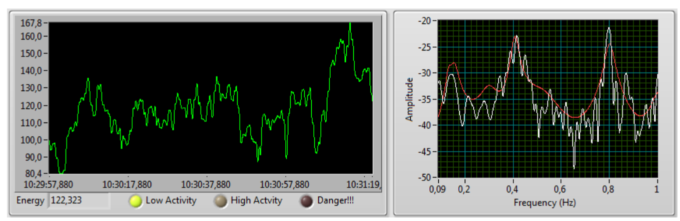


Fig. 3. Screen shot of one *Module* of the *Monitoring Tool*

A. Wide Area Monitoring Systems

Monitoring systems based on PMU measurements are commonly referred to as Wide Area Monitoring Systems (WAMS). The main components of WAMS are:

- Phasor Measurement Units (PMUs)
- Phasor Data Concentrators (PDCs)
- Communication Networks

The PMUs are the measuring equipment, which sample the voltage and current data at a frequency of typically 30 to 50 Hz with a time stamp derived from a GPS clock reference. The PDCs are servers responsible for gathering PMU measurements, aligning them in time and forwarding them as clustered output streams (with possible format conversion), they can also serve as archiving systems. A PMU can usually support the forwarding of PMU measurements to one or several PDC servers[1]. PDCs offer more flexibility, but also have certain

[1]This varies in different commercially available PMUs, with some only allowing one connection, and others up to four.

limitations. They can be used to share PMU measurements with several other PDC servers. The traditional layout of such monitoring system is depicted in Fig 4. This layout represents several local PDC servers, which can by owned by different entities (private owner, electricity generation company, etc.) The PDCs are then concentrated in a super PDC owned by the TSO, from which all monitoring tools are fed. All synchronised phasor data is transported via a communication network using the IEEE C37.118.2 protocol [8].

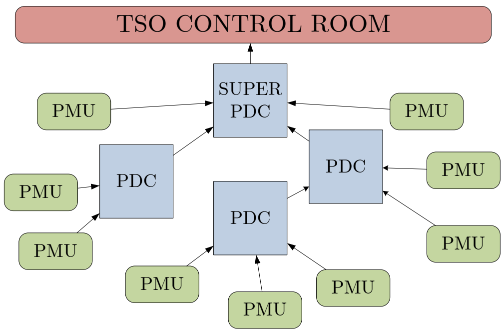


Fig. 4. Layout of the communication and computer architecture of wide-area monitoring systems

This kind of set-up is replicated at SmarTS Lab, with some simplifications due to the impracticality of building an entire power system in the lab. 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 described above is replicated, building a testing platform which is depicted in Fig. 5, with the following elements:

1) The real-time simulation target from Opal-RT.
2) An oscilloscope connected to an analog output of the target, showing the three-phase signal produced by the model (only for lab. set-up purposes).
3) A National Instruments cRIO PMU connected to the analog output aforementioned.
4) The connection cables of the PMU for acquiring voltage measurements, connected to the back of the simulator.
5) The network connection of the PMU to stream the data to the PDC server of the lab.
6) The PDC server of the lab receiving the PMU data and broadcasting an output stream to itself for this photo.

In the PMU configuration a scale-up factor is added for the measurements so that the simulated values are well transcribed in the phasor calculation, despite the low ratings of the analog output of the simulator.

B. Real-time data mediators

The monitoring application development has been carried out in the LabView language, which doesn't provide libraries for the IEEE C37.118.2 standard to connect to either PMUs or PDC servers. An additional software has therefore been

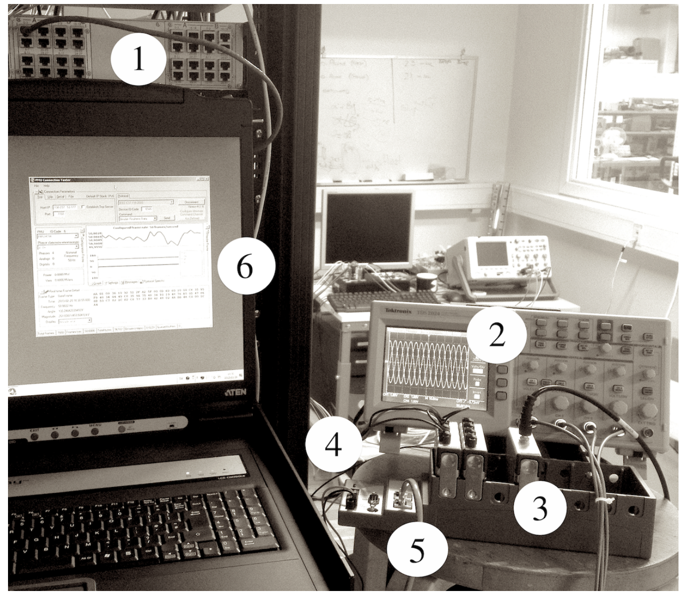


Fig. 5. Photo of the set-up of the experiment at SmarTS Lab

developed (BableFish) that handles the communication with a PDC server and delivers the PMU measurements to the LabView environment after decoding the standard protocol.

BableFish is comprised by several modules with different functions. The core of the application consists of Visual C++ libraries that handle the communication with the PDC server to establish the connection and perform real-time acquisition of new measurements. Interactions with the core application are possible using the ActiveX technology that interfaces the Visual C++ libraries with a LabView VI, depicted in Fig 6. It allows for the configuration of the connection to the PDC, selection of the measurements to be delivered and saving of the configuration. The measurements are then forwarded to a LabView sub-VI, which can be integrated in an external application (such as the monitoring tool presented in this article) for delivering the decoded measurements to processing algorithms.

The monitoring application has also been adapted to Statnett's PMU Recorder Light (PRL), which provide similar functions for real-time data mediation within LabView. More information about the PRL are available in [9].

IV. Testing and Validation

The development of the application was carried out with a test output stream containing the PMU measurements from a PMU connected to the distribution network. This set-up was primarily used to develop the integration of the chain of real-time data acquisition in the application and did not provide any behaviour of interest apart from a local harmonic at 16.7 Hz created by the feeding system of a railway nearby the lab. This frequency component was used to develop and configure the spectrum analysis algorithm. Figure 2 depicts the monitoring tool running in this set-up and the local harmonic is well detected on the bottom right Module.

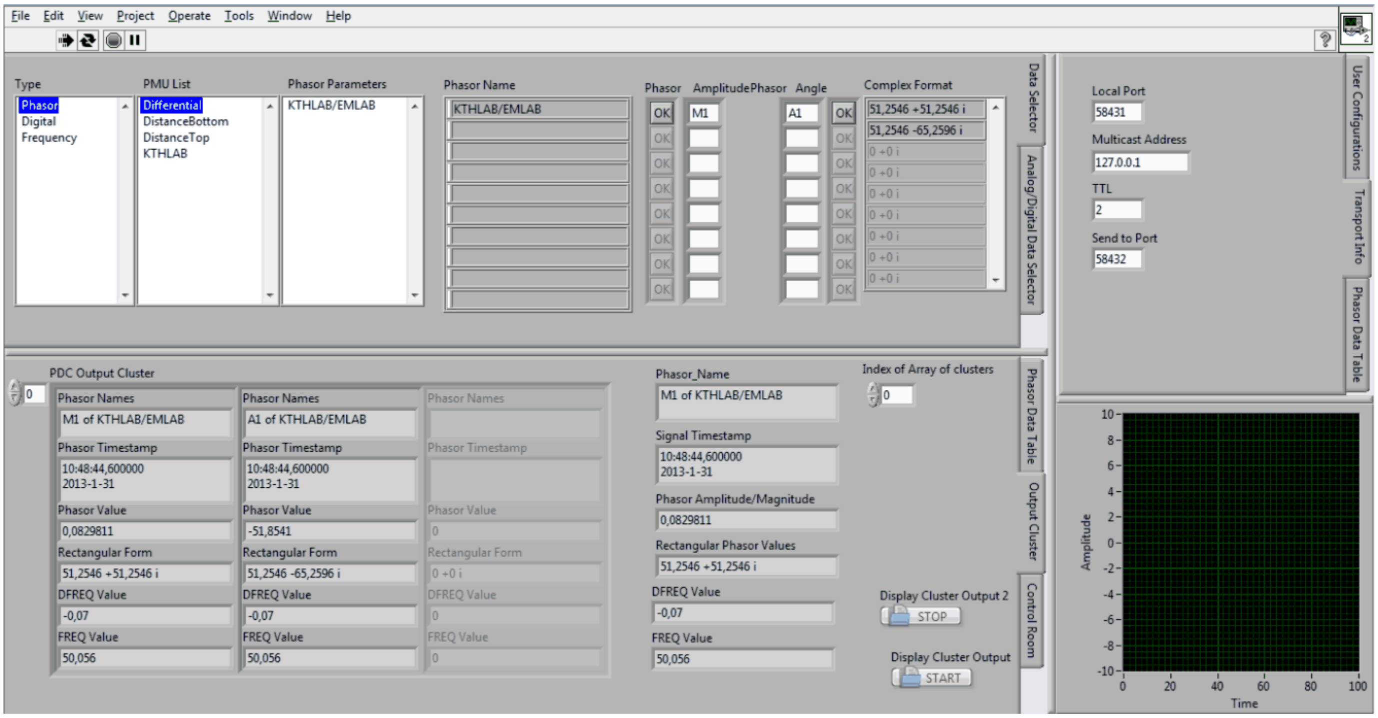


Fig. 6. Screen Shot of the main interface of BableFish

TABLE I. Time-line of the experiment

Start	Oscillation Injection	Additional Perturbations	Major Fault	End
Random load variation	Set perturbation at 10.83 Hz	Generating minor faults	Three phase Fault and line opening	End of the oscillation injection

For validating the monitoring tool, HIL simulation was used with the development of a power system model capable of recreating the event described in Section I and additional perturbations [10]. The power system model is equipped with two variable loads introducing random variation and sinusoidal variation that will excite lower dynamics oscillations in the power system. The model performs the simulation of wind farms interaction by injecting oscillations at 10.83 Hz, which was chosen as the equivalent of the 13 Hz oscillations in a 50 Hz system (the original case occurred in the USA, where the nominal frequency is 60 Hz). Finally, the model also includes the generation of faults in the system, with perturbation of the mechanical input of one of the generators and a three phase fault followed by line tripping on an heavily loaded line.

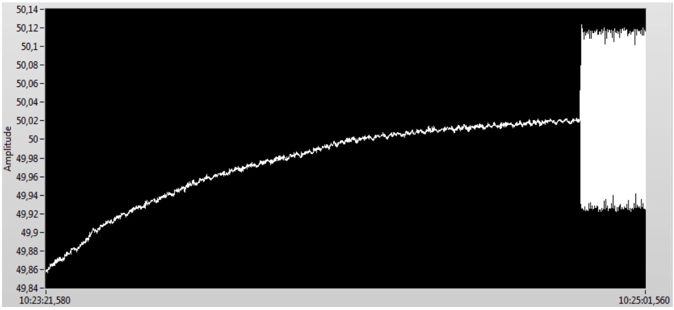
The validation of the algorithms is performed with a scenario including all of the events aforementioned according to the time-line summarized in Table I, enabling the testing of the tool's performance in different situations. The validation experiment has been performed several times to ensure a satisfying configuration of the numerous parameters of the processing algorithms.

The simulation of the power system model is started with both wind farms receiving an average wind speed 12 m/s with 10 % turbulence. The loads are also configured to have a sinusoidal profile at different frequencies, according to the following parameters:

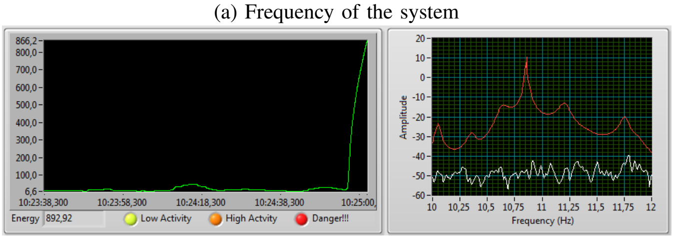
- Load in Area 1:
  - Active power 1 MW random load variation and 2 MW of sinusoidal load at 0.4 Hz.
  - Reactive power 1 MW random load variation and 2 MW of sinusoidal load at 0.8 Hz.
- Load in Area 2:
  - Active power 1 MW random load variation and 2 MW of sinusoidal load at 1 Hz.
  - Reactive power 1 MW random load variation and 150 MW constant load.

The processing algorithms of the *Monitoring Tool* detect the slow dynamic activity resulting from both load variations and wind turbulences, see Fig. 3, where the spectral estimator highlights both frequency components at 0.4 Hz and 0.8 Hz.

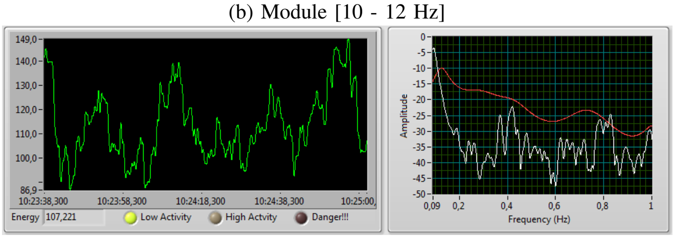
Forced oscillations are then injected at first with 0.05 p.u. amplitude at the point of common coupling of the first wind farm. They can be observed in the frequency graph of the tool, see Fig. 7(a). It can be noticed that the frequency range containing 10.83 Hz is active with the flag *Danger!!!*, see Fig. 7(b), while the other frequency ranges remain inactive or with a low activity, see Fig 7(c). This shows the fast reaction of the tool, its selectivity and its ability to estimate in real-time the level of energy in these oscillations. The frequency estimation algorithm does not update as quickly as the energy detection algorithm, the frequency of the injected oscillations is thus not detected as quickly. However, it can be noticed that the parametric method starts to show distinctively a peak at the right frequency, see Fig. 7(b).



(a) Frequency of the system



(b) Module [10 - 12 Hz]



(c) Module [0.09 - 1 Hz]

Fig. 7. Partial screen shot of the *Monitoring Tool* during the oscillation injection at 10.83 Hz

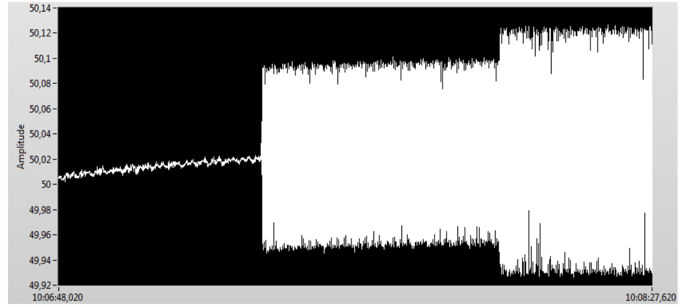
After the beginning of the injection with 0.05 p.u. amplitude the injection is increased up to 0.07 p.u. amplitude. The resulting oscillations have a larger amplitude, as shown in Fig. 8(a), and the energy detection algorithm identifies an increase in the energy level in the oscillations. The frequency estimation algorithm also detects very precisely the frequency at which the oscillations are occurring as shown in Fig. 8(b).

The injection of oscillations is maintained and the power system model stabilizes with these high frequency power oscillations still active. Additional (minor) perturbations performed on the system are implemented:

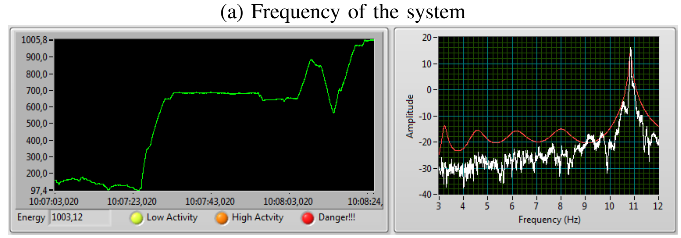
- A step increase in the mechanical power input of one of the synchronous generators (0.05 p.u.).
- A three-phase fault at the bus of one of the sub-system of the first wind-farm (Three wind turbines affected).

The perturbations are performed sequentially, see Fig. 9. The first perturbation is performed at an instant approximately at the middle of the figure and the second at the end of the figure.

The first perturbation induces a small ripple in the frequency of the system, leading to the detection of activity in almost every frequency range. While the most affected are the lower frequency ranges, which was expected. The detections mostly result in discontinuities in the voltage measurements. The phenomenon is amplified in the case of the second perturbation, which induces a greater discontinuity in the voltage measurements and therefore triggers the *Danger!!!* flag in almost all frequency ranges, see Fig. 9.



(a) Frequency of the system



(b) Module [3 - 12 Hz]

Fig. 8. Partial screen shot of the *Monitoring Tool* during the increase of oscillation injection at 10.83 Hz

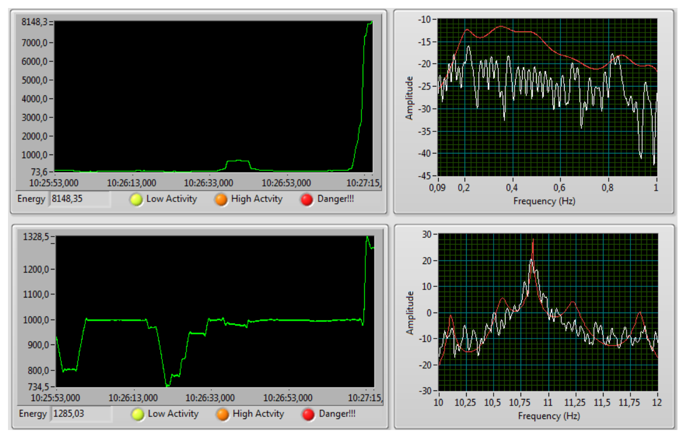


Fig. 9. Partial screen shot of the *Monitoring Tool* during the oscillation injection at 10.83 Hz and minor faults

The major fault performed is a three phase fault on one of the lines between the two sectors of the power system model. After the fault is applied, the line is opened and re-closed after clearing the fault, eleven seconds after the application of the fault. The effect on the power system model is strong, but stability is maintained after re-closing the line.

The *Monitoring Tool* is affected by discontinuities in the voltage measurements, triggering temporarily a *Danger!!!* flag in all frequency ranges, see Fig. 10 for two *Modules*. This behaviour should be eradicated and the tool should be less sensitive to such behaviours. The only reliable information that can be retrieved from the tool during such events is estimated modes of oscillation at lower frequencies that are the most affected by such perturbation. This is noticed by the trigger flag being displayed for a longer time in this frequency range. The frequency estimation algorithm is also vastly affected by the discontinuities in the measurements, making it very difficult to make interpretations during such events.

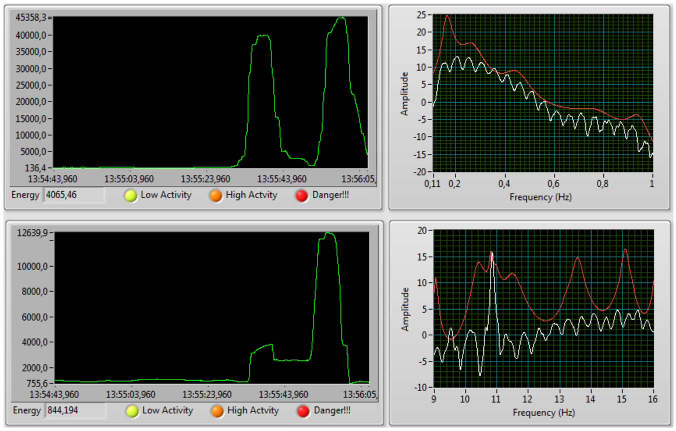


Fig. 10. Partial screen shot of the *Monitoring tool* during a fault

V. Conclusion

Developing new algorithms or new applications for monitoring the power grid is a complex task that faces several challenges such as the access to real-time measurements from a real power system. On the one hand, actual data from a TSO would not follow an established testing scenario such as the ones presented in Table I without significant planning efforts and implementation costs, leaving some cases untested. Moreover it is important to emphasize that some scenarios may endanger the stability of the power system, they could therefore not be envisaged for the purpose of testing algorithms. On the other hand, the traditional approach of working with off-line simulations and recorded data offers a some flexibility in the calibration of the oscillation detection algorithms. However, it neglects all off the real-time aspects such as computing time, rolling data window length and the quality of the data (no missing data, no bad measurements, etc.). HIL simulation offers in this case a good compromise between the experiment feasibility in a lab and closeness to an actual WAMS architecture implementation.

In Section IV the validation experiment of the tool covers a wide variety of cases that such a tool could encounter in a real power system. The first and primary conclusion is that the tool was successful in the detection of both underlying activity and strong oscillatory events in the higher frequency range, performing according to its design. The underlying activity was detected in the low frequency range (below 1 Hz), resulting from the cyclic load variation and higher frequency range with the detection of the sub-harmonic generated by the nearby railway system. The injected oscillations at 10.83 Hz, modelling wind farms interactions were successfully detected. The detection speed was fast, with negligible delay. However, the validation process unveiled the sensitivity of the algorithms to strong discontinuities in the measurements, such as the ones created by large faults in the power system. The improvements necessary for handling such situations will be the object of future work.

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