A PMU-Based Fast Real-Time Sub-synchronous Oscillation Detection Application

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***Abstract*—The share of wind power has strongly increased in electricity production, raising several issues concerning its integration to power grids. Unexpected dynamic phenomena, such as oscillatory events around 13 Hz have been recorded in the US by Oklahoma Gas & Electric (OG&E). Such interactions differ from traditional and well studied inter-area oscillations, and the ability to detect them is beyond the measurement capabilities of most of the existing measurement equipment and monitoring tools in Energy Management Systems (EMS) systems.**

This paper presents the development and implementation of algorithms for PMU-based real-time fast sub-synchronous oscillation detection, focusing on the aforementioned case.

The paper focuses on the tool itself and its algorithms, briefly presents an approach carried out for testing and validating it. Experience from the use of the tool at OG&E is also described.

***Index Terms*—Power system oscillations; monitoring application; PMU; wind farm; sub-synchronous oscillations.**

I. Introduction

Recent concerns about the environmental impact of traditional electricity generation in the western world has led to a strong increase in renewable sources of energy. Since the 1990s, wind power has been the fastest growing power generation technology [1], a trend expected to continue as several countries have politically engaged themselves into large investments in wind power [2], [3].

Wind power is one kind among different intermittent generation sources, that brings several challenges to power system dynamics. For example, its integration in existing power systems can involve transient stability issues [4]. Unexpected dynamic behavior is now appearing in the form of sub-synchronous oscillations. Oklahoma Gas & Electric (OG&E) has recently measured with PMUs [5] sub-synchronous oscillatory events resulting from interactions between wind farms at frequencies around 3-15 Hz. These oscillations were also observed at the consumer level in the form of flicker [6].

Traditional monitoring tools build on Supervisory Control And Data Acquisition (SCADA) systems cannot detect these fast dynamics, due to the low data rate of conventional metering and the lack of time synchronization among all metering devices. Figure 1 presents a comparison between SCADA and PMU measurements for this phenomenon. The utilization of PMUs enables observability for phenomena occurring at frequencies up to 15-25 Hz across wide geographical regions, opening new wide perspectives for monitoring and control applications based on synchrophasors. These new tools will help in acquiring a better knowledge on the challenges brought by the increase of intermittent energy sources.

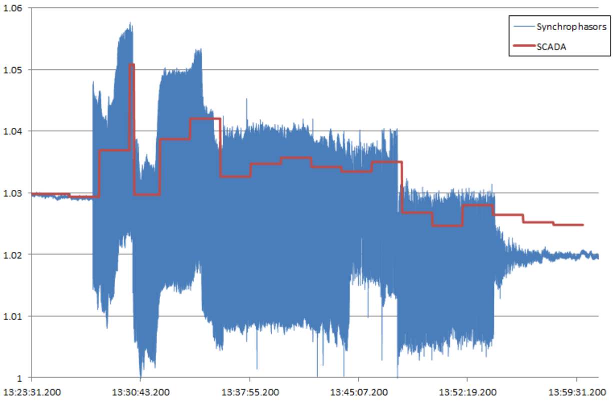


Figure 1. Comparison example between PMU and monitoring through SCADA during a fast dynamic event

This paper presents a PMU based monitoring tool developed for detecting the phenomenon depicted on Fig. 1, as well as a testing method used during the development. The algorithms used in the tool are presented in Section II, the developed application is introduced in Section III. Testing of the application via replay of archived data is described in Section IV, where comparisons are made with another tool developed at OG&E.

II. Algorithms for Fast Oscillation Detection

The effects of high frequency oscillations presented in the Introduction are undesirable [5], monitoring algorithms should therefore enable fast oscillation detection from PMU measurements. Traditional monitoring tools for inter-area oscillations estimate the frequency and damping for each oscillatory mode with two separate algorithms. A similar strategy is adopted in this case, with one algorithm dedicated to the estimation of the amount of energy in the oscillations and the other dedicated to frequency estimation. The three algorithms used by the proposed PMU application are described next.

A. Fast Oscillation Detection

The proposed oscillation detection algorithm in this paper builds from work in [7]. As highlighted in [8], it is desirable for a fast oscillation detection tool to provide information about oscillatory behavior at different bands of the spectrum. The spectrum of frequency of interest with potential oscillatory activity starts from 0.1 Hz and up to the maximum frequency according to the Nyquist-Shannon criterion considering the sampling frequency of the PMUs (up to 50 or 60 Hz reporting rate). To cover such a broad span of frequencies, multiple instances of the algorithm can be executed in parallel. Each instance can be configured independently and thus monitor different frequency ranges. The following ranges can be used for configuration:

- 0.10 Hz - 1 Hz: Inter-area modes, e.g. system-wide electromechanical swings.
- 1 Hz - 3 Hz: Local-area modes.
- 3 Hz - 15 Hz: High frequency oscillations, e.g. wind farms controller interactions.
- 15 Hz - 25 Hz: Other sub-synchronous oscillations, e.g. sub-synchronous resonance.

As shown in Fig. 2, after pre-processing the real-time measurements, each frequency range previously mentioned, can be separated by four different band-pass filters set to the boundary frequencies of each range.

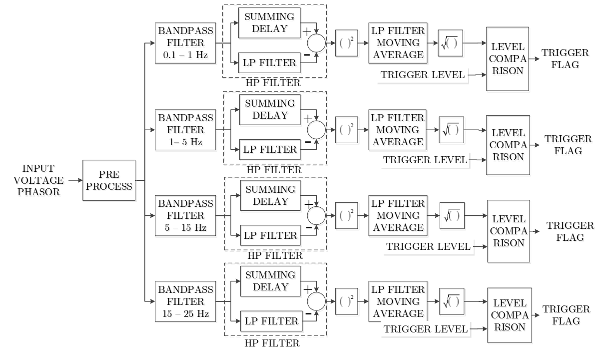


Figure 2. Diagram of the adaptation of the algorithm for fast real-time oscillation detection

The output of the high-pass filter provides a measure of the "oscillatory activity" at the selected frequency range. The Root Mean Square (RMS) value of this output is used for energy computation, implying that the following computations are performed sequentially: squaring, averaging and finally computing the square-root of the signal. A low-pass moving average filter is used to extract the main trend of the squared signal. This is necessary so that a persistent and stable signal is provided to the forthcoming trigger level comparison. Finally, a trigger level comparison indicates if the computed energy exceeds a pre-set level.

B. *Frequency Estimation*

The frequency estimation algorithm, depicted in Fig. 3, is comprised by two different algorithms running in parallel, leaving to the user the choice to activate one of them or both simultaneously. A non-parametric method can be used when the frequency of the oscillations within a certain range is unknown, whereas a parametric method is appropriate when the knowledge about the number of possible oscillations within a range is known.

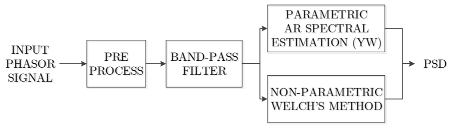


Figure 3. Diagram of the algorithm for Spectral Estimation

1) Non-Parametric Welch's Method: Welch's power spectrum estimation is a method based on the standard Periodogram. The method attempts to increase the readability of the Power Spectrum Density (PSD) by reducing the noise, however it decreases the PSD's frequency resolution.

The method has the following procedure: (1) The input signal is split into overlapping segments of length M (the overlapping rate is set by the user). (2) Each segment is windowed (the window is chosen by the user). (3) The Fast Fourier Transform (FFT) is computed for each windowed segment. (4) The PSD is obtained by averaging all the resulting spectra, thereby reducing the final variance. For a complete description of the method, refer to Peter Welch's original article [9].

Because this method is based on FFT computations, it will highlight all the content of the power frequency spectrum, which is an intrinsic property of non-parametric estimation. This property is especially useful for signals, which actual frequency content is unknown.

2) Parametric Auto-Regressive Methods: These methods use an auto-regressive mathematical model of the input signal for estimating power spectral density. In this way, they integrate available knowledge about the input signal to improve spectral estimation.

Auto-regressive models have been applied for estimating power system frequency content, as described in [10], [11]. For this specific reason, this model is chosen in the *Monitoring Tool*. The specific method utilized is, however, left to the choice of the user. All of the implemented methods work on the principle of model fitting. They differ on the method used to optimize the fitting process. For further details on parametric methods refer to [12] and for further details on their application to power systems, refer to [11]. It is worth mentioning that during experimentations, the *Burg Lattice* method has been particularly efficient.

The order of the model is a very important parameter. Its value cannot be fixed in advance because it is mainly dependent on the number of oscillations to be identified, and thus, the frequency content itself. In the case of the *Monitoring Tool* where the frequency spectrum of interest is divided into four frequency ranges, the order can be different in each of the frequency bands. It is worth mentioning that too small orders will lead to a smooth spectrum and some modes might be left unidentified. On the other hand, too large orders might lead to the identification of artificial modes and their appearance on the estimated spectrum.

C. *Data Pre-Processing:*
Outlier Removal and Down Sampling

The algorithms for estimating the energy and frequency of oscillations described previously involve filtering, averaging and spectral estimation processes. These processes require reliable data. In the case of PMUs, measurements are reported at a high rate (30, 50 or 60 samples per second) and transmitted over IP networks, and might contain erroneous or missing measurements. The pre-processing of input data thus appears necessary to satisfy the requirements imposed by the methods used in the detection tool.

The pre-processing implementation was inspired from the prior work on PMU data pre-processing available in [13], which were executed off-line on archived data. The *Monitoring*

Tool processes the measurements in real-time, and thus, the following algorithm was developed.

In general, the variation of frequency in a power system is the result of the interaction between varying loads and the generation that follows the same variations with an inertial delay. It should thus be a rather smooth process that implies that any value is expected to be within a confidence interval, as shown in Fig. 4, which can be determined from neighboring values and intrinsic system properties. The performance of the outlier removal algorithm is determined by the level of confidence of the interval used.

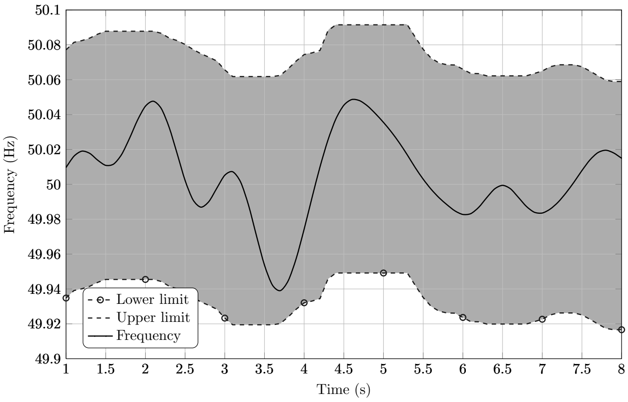


Figure 4. Example of a confidence interval for the frequency

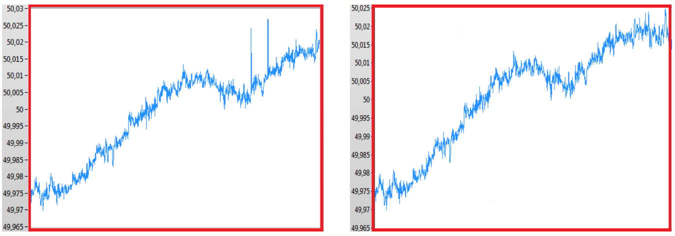
The confidence interval suggested here is built according to the following steps:

1) The input signal: (f).
2) Create one copy (A) of the input signal delayed by 10 samples: $A_i = f_{i+10}$, where i is the time index.
3) Filter one copy (M) of the input signal with a moving average filter of order equal to 20: $M_i = \frac{\sum_{0<t<20} f_{i-t}}{20}$.
4) Subtract (M) from (A). The combination of a delayed copy (A) and (M) is equivalent to a having a moving average filter, where the average is computed on the 10 preceding samples and 9 following samples. Compute the standard deviation σ of the resulting signal.
5) Create the upper (U) and lower (L) limits of the confidence interval by adding/subtracting $k\sigma$ to (M), k the sensitivity factor, is set by the user.

Each element of (A) is then compared to (U) and (L). If $U_i > A_i > L_i$ the element is preserved, else it is dropped and will be replaced by an interpolated value. The interpolation is performed by taking as inputs the elements of the signal, the indexes of theses elements and all the indexes at which an element will be returned. Each returned element is either an input element if its index is on both lists or an interpolated value if its index is only on the second list. The chosen method for interpolation is linear interpolation, as it gave the best results during testing. Testing results showed that it has no divergence risks compared to methods involving higher order polynomials.

An example of the outlier removal algorithm applied to real-time PMU data is shown in Fig. 5. The data points removed are single points far from the neighbouring values, likely corresponding to measurement errors. The outlier removal effectively performs the tasks described above.

After removing outliers, the signal is processed further to feed the frequency estimation algorithms by mean removal and high-pass filtering. This aids to attenuate frequency components related to the action of generator governors and loads, which are close to 0 Hz and lower than electro-mechanical modes.



(a) Outlier removal inactive

(b) Outlier removal active

Figure 5. Screen shots of the frequency signal with and without outlier removal

Furthermore, according to Shannon's theorem, all the frequency content below frequency f_1 can be restored if the sampling frequency is at least $2 \times f_1$. The typical reporting frequencies of PMUs are 30, 50 or 60 Hz, which correspond to a highest observable frequencies 15, 25 or 30 Hz. The observed frequency in the tool can be much lower, thus, a step of down-sampling is added to remove redundant data[1]. This step is preceded by a low-pass filter acting as an anti-aliasing filter.

The implementation was carried out with a band-pass filter for each frequency range configured. The down-sampling factor is calculated from the cut-off frequency of the band-pass filter, considering Shannon's criterion. An upper limit equal to 10 was added to the down-sampling factor, motivated by the limited size of the rolling window of buffered data.

III. MONITORING APPLICATION

The *Monitoring Tool* has been implemented as a real-time graphical analysis tool, which could be used by system operators or wind farm owners. LabVIEW was chosen as the software development environment due to the availability of two different real-time mediators, namely Statnett's Synchrophasor SDK [14] and BableFish [15]. These data mediators are compliant with the IEEE C37.118.2 standard [16] for PMU data exchange and deliver the PMU measurements in the LabVIEW development environment. In addition, LabVIEW also allows designing a graphical user interface in a straightforward manner.

The tool is provided with real-time PMU measurements, allowing monitoring of oscillatory events at a frequency up to the Nyquist limit. This broad frequency spectrum contains different categories of phenomena, mentioned in Section II. The tool has been implemented for monitoring four frequency ranges simultaneously. The elements in four instances are named *Modules*. The resulting Graphical User Interface (GUI) is depicted in Fig. 6 (for concision purposes, only the interface of the *Replay Tool* introduced in Section IV is shown in this paper).

The interface includes a data display that is a simple representation of the buffered input signals received. The signals are displayed one at a time, letting the user choose from the list box on top of the graph in Fig. 6 (the frequency is

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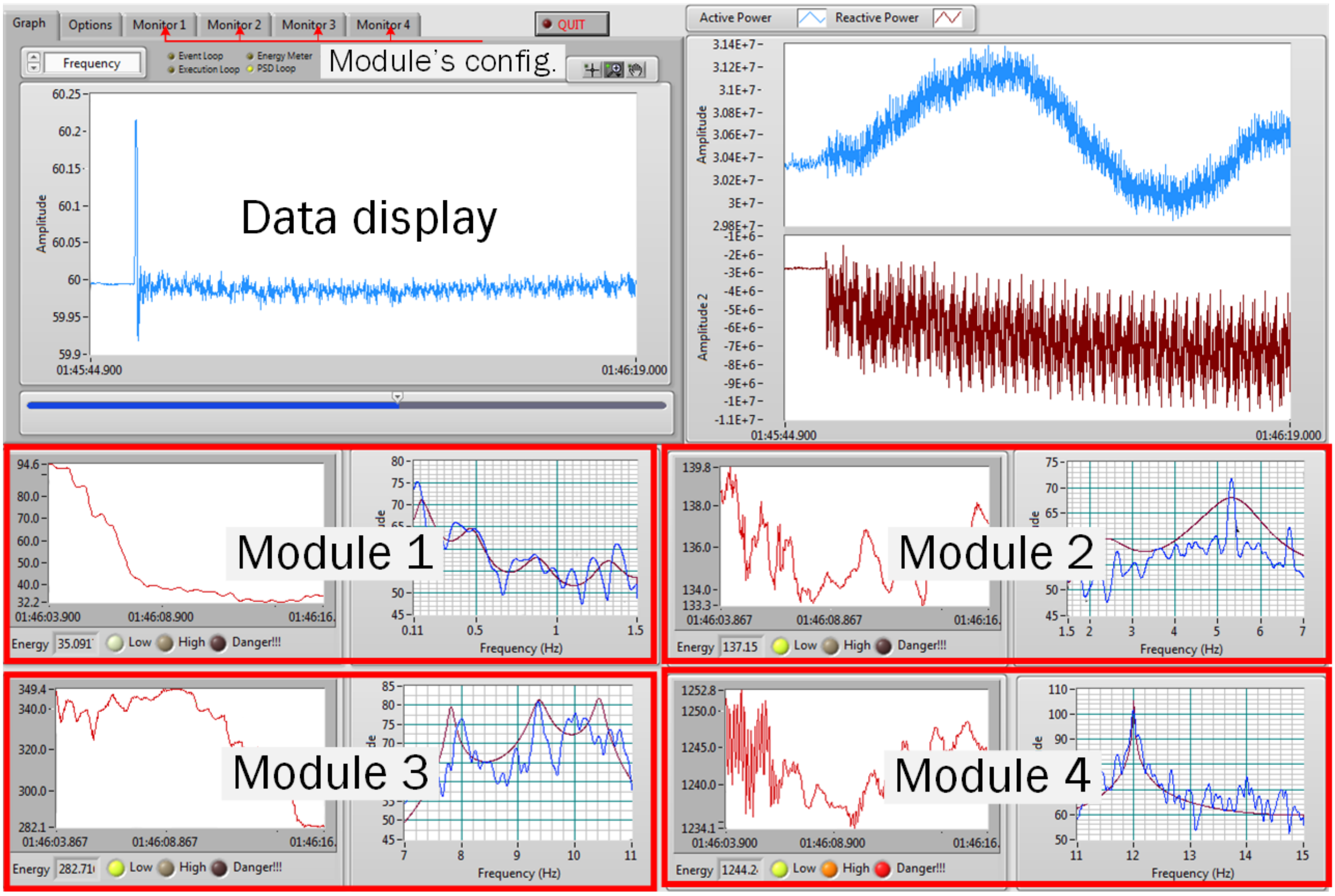
[1] Down-sampling is applied for frequency estimation and not performed in the oscillation detection algorithm in order to avoid lowering the reaction times of the algorithm.



Energy 35.091

Energy 137.15

Energy 282.71

Energy 1244.2

Figure 6. Screenshot of the tool reading the file of the oscillation case at OG&E, shown in Fig. 8

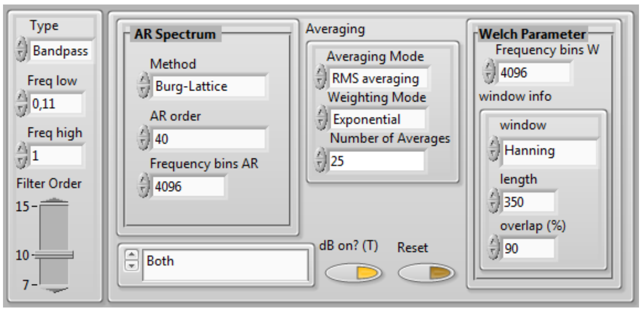
displayed in this case). This graph is also useful for calibrating of the outlier removal algorithm.

The top left part of the GUI is used to configure the tool and divided in five tabs. The tab “*Options*” gathers the general configuration of the tool related to the data acquisition as well as state LEDs. The remaining tabs “*Module 1 to 4*” are four identical tabs used for the configuration of the estimation and detection modules, see Fig. 7. The configuration should be done after launching and initializing the tool.

Figure 7 presents an interface with two separate blocks. The block on the left is used to configure the band-pass filter, the parameters are common for both the *Oscillation Detection* and the *Frequency Estimation* algorithms. The block on the right is dedicated to the *Frequency Estimation* algorithm and contains the parameters for each of the methods mentioned in Section II. It also includes the parameters for spectral averaging. Finally the user is able to choose in the list box if both methods are to be used simultaneously or just one of them.

Once the configuration is set, the outputs of the algorithms are displayed in a *Module*, highlighted on Fig. 6. The graph on the right presents the power spectrum density, which is the output of the *Frequency Estimation* algorithm. It is scaled according to the parameters of the band-pass filter, highlighting the content of interest.

The graphical display on the left has several components, the most important are the three LEDs *Low Activity*, *High Activity* and *Danger!!!*, corresponding to the three thresholds defined in the general configuration tab. The comparison is



Type: Bandpass

Freq low: 0,11

Freq high: 1

AR Spectrum

Method: Burg-Lattice

AR order: 40

Frequency bins AR: 4096

Averaging

Averaging Mode: RMS averaging

Weighting Mode: Exponential

Number of Averages: 25

Both

Welch Parameter

Frequency bins W: 4096

window info

window: Hanning

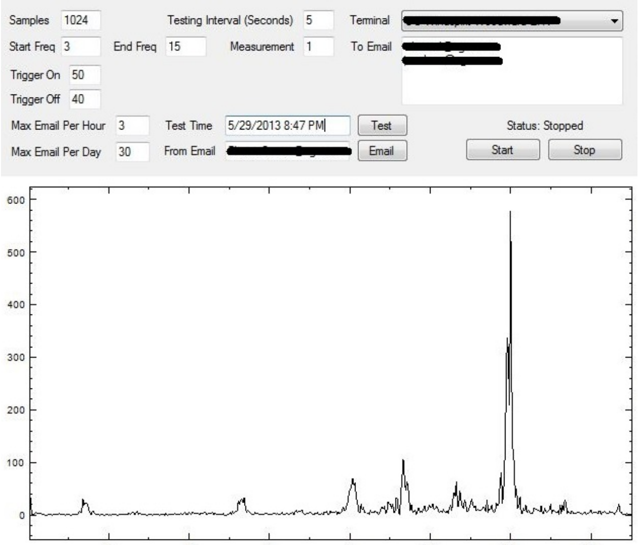
length: 350

overlap (%): 90

Figure 7. Screen shot of the configuration tab of one module of the *Monitoring Tool*

made on the latest sample, whose value is displayed by the field *Energy*. The graph provides a history to easily corroborate the energy computed with the input signal displayed. Given that the input signal is filtered by three FIR filters, the output signal is shorter than the input signal. Moreover the order of the filters have a strong influence on the length of the output signal. This can be modified by the user to adapt to their needs, measurement features and particular power network.

The *Monitoring Tool* presented in this paper was compared against an in-house tool developed by OG&E. OG&E's tool runs on a production-grade server and is shown in Fig. 8. It provides detection of the oscillations and email notifications. The application was developed in VB.net and utilizes the digital signal processing exocortex library for FFT oscillation detection[2]. It is configured via a set of parameters, which can be tested against archived data for assessing their relevance.



Samples: 1024
Testing Interval (Seconds): 5
Terminal: [redacted]
Start Freq: 3
End Freq: 15
Measurement: 1
To Email: [redacted]
Trigger On: 50
Trigger Off: 40
Max Email Per Hour: 3
Test Time: 5/29/2013 8:47 PM
Status: Stopped
Max Email Per Day: 30
From Email: [redacted]

Figure 8. Screenshot of OG&E's FFT tool

IV. REPLAY EXPERIMENT

In the previous Section the *Monitoring Tool* was introduced and all the options for its configuration have been presented. While the options related to connectivity aspects do not require knowledge about the power system analyzed, the configuration of the processing algorithms, especially for frequency estimation, have to be calibrated according to the properties of the power system. A good solution is to use archived data to run off-line experiments.

The original idea was to replay archived data from a PDC, broadcast it as an output stream and use the *Monitoring Tool*. The diversity of archive techniques and file structures raised the issue that a PDC, such as OpenPDC [17], was not flexible enough and not suitable to replay the archived data format available. This led to the development of the *Replay Tool*.

A. Replay Tool

The *Replay Tool* has been developed using the same code as the real-time tool. However, the software related to input measurements has been developed to use archived PMU data instead of real-time PMU data. The interface is almost identical to the *Monitoring Tool*. The processing algorithms are identical. This tool has specific additional features. For example it allows to scroll along the replayed data, which can be useful to get a quick overview of the content of the selected file. The *Replay Tool* works, otherwise, exactly like the *Monitoring Tool*.

B. Results

The experiments carried out with the *Replay Tool* used archived data obtained from OG&E, containing measurements from different locations during oscillatory events at a frequency around 13 Hz, as mentioned in the Introduction. These experiments served, during the development and implementation of the algorithms, to verify that the algorithms worked properly and calibrate their configurations for other experiments.

Figure 6 presents the *Replay Tool* during the replay of such oscillatory event. The beginning of the oscillatory phenomenon can be clearly identified in the frequency (display on the top left), as well as in both active and reactive power (displays on the top right). It can also be noticed that the *Module* on the bottom right, corresponding to the frequency range [12 - 15 Hz], that the *Danger!!!* indicator is activated only a few seconds after the beginning of the phenomenon. Additionally the oscillatory frequency is identified to 13.4 Hz on the PSD.

Figure 8 presents OG&E's tool analyzing the same archived data. As it can be seen on the screenshot a strong oscillatory activity, above the defined threshold, is occurring at 12 Hz. Additional oscillatory components can be noticed around 1.4 Hz, 5.5 Hz, 8 Hz, 9.4 Hz and 10.7 Hz. The main 12 Hz component is also detected with the *Monitoring Tool* and it activates the *Danger!!!* threshold as shown on Fig. 6. All the other components can also be identified on Fig. 6, validating the *Monitoring Tool*'s algorithms.

Additional testing and validation experiments have been carried out by using hardware-in-the-loop setups with real PMU devices in two different laboratory environments. One setup involved the use of a real-time digital simulator with a model reproducing the sub-synchronous oscillatory phenomenon [18], [19]. In the second setup, the simulator was replaced by power emulators, producing real power oscillations [20].

Finally, paper [21] evaluates the impact of a laboratory set-up when performing validation experiments on this tool.

V. CONCLUSION

This paper gives an example how synchonized phasor data applications can be developed to help grid operators in monitoring and control of renewable energy sources when unpredictable dynamic interactions arise.

In addition, the development of this PMU application showed that new applications can be conceived and implemented without relying on a monolithic software environment and within a relatively short time.

The paper did not cover the control actions that can be taken to mitigate the unwanted dynamics discussed, as the only available action at this time is to curtail the wind farm power output. One important aspect to further investigate is how the use of synchrophasor data can help in providing rich measurements containing information on sub-synchronous oscillations into the controls of Static Var Compensators, and other controllable devices. Recent applications to damping of low-frequency oscillations suggest that PMU-based sub-synchronous oscillation damping could be effectively applied [22].

ACKNOWLEDGMENT

The economical support of the institutions and funding bodies listed below is sincerely acknowledged:

- EIT KIC InnoEnergy through Action 2.6 of the Smart Power project.
- Nordic Energy Research through the STRONg^2rid project.
- Statnett SF, the Norwegian Transmission System Operator.

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[2] http://www.exocortex.org/dsp

- STandUP *for* Energy collaboration initiative.
- The EU funded FP7 IDE4L project

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