Estimation of Electromechanical Oscillations in the Nordic Grid using Ambient Data Analysis

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***Abstract*—This paper presents an off-line analysis of ambient PMU data for the estimation of electromechanical oscillations in the Nordic Grid. The Yule-Walker method, as the representative of parametric methods, and two non-parametric methods (Welch and Multitaper) are evaluated using real-life data collected from four locations in the Nordic power system. Further, a real-time software application developed in the LabView environment using the PRL software development toolkit is described; this application implements the spectral estimators in a real-time platform.**

***Index Terms*—Wide area measurements, phasor measurement units, electromechanical oscillations, ambient data, mode estimation, Nordic power system.**

I. INTRODUCTION

Low-damped electromechanical oscillations have become an important concern in the Nordic power system. As a result, Phasor Measurement Units (PMUs) have been recognized as a key agent for efficient monitoring and control of electromechanical oscillations in the Nordic Grid [1].

Spectra of ambient data measured by PMUs provide information about existing oscillations in the system. Mathematically, these oscillations are the result of poorly damped system modes which are excited by random load variations [2]. Numerous algorithms for mode estimation have been developed in recent years [3]–[9]. In the seminal work published by Pierre et al. [10] an autoregressive model is used to describe the power system's dynamic behavior. Later, this method was extended to incorporate an autoregressive moving average models [11]. The electromechanical mode estimation problem can be considered as a system identification problem with, in the most general case, unknown inputs. Consequently, different system identification methods have been applied to tackle this problem, including: subspace methods [12] and frequency domain decomposition [13]. Useful overviews of the proposed methods are given in [2]–[4].

In this paper, the application of several methods is demonstrated with real-life data collected at four locations in the Nordic power system (Fig. 1). In these analyses, one parametric (Yule-Walker) and two non-parametric methods (Welch and Multitaper) are used. These methods revealed several electromechanical modes in the Nordic grid which should be taken into consideration for network extension and operation. Further, spectral estimators are implemented to operate in real-time. For this purpose, a vendor-independent software development toolkit named PRL is used for the implementation of these spectral estimators. Using the PRL, spectral estimation algorithms are developed in the LabView environment where PMU measurements are imported from a PMU connected to the low voltage distribution network or the outputs of an eMegaSim Opal-RT real-time simulator.

The remainder of this paper is organized as follows: Section II describes the necessary pre-processing steps before the spectrum of ambient data is estimated. Spectral estimation algorithms and tuning procedures are given in Section III and Section IV, respectively. Section V presents results of the applied estimators on measured data from Nordic power system. The developed real-time mode estimation application is described in Section VII whereas conclusions are drawn in Section VIII.

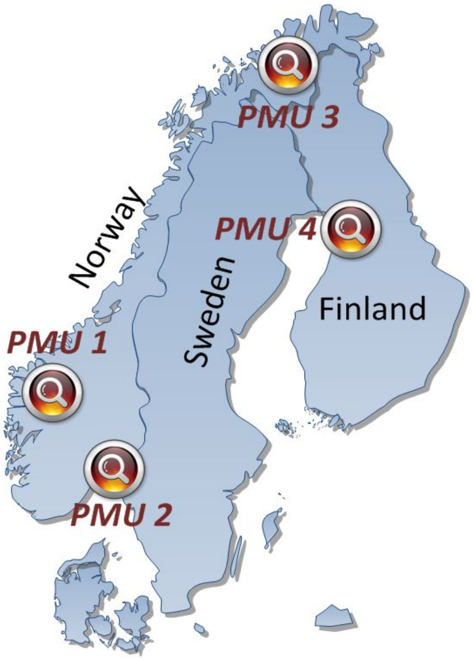

Fig. 1. Nordic power system and locations of used PMUs connected to the transmission network

II. PREPROCESSING

The use of a raw measurements from PMUs can lead to ambiguous results due to: 1) possible errors in some of the measured samples, 2) ill conditioned autocovariance matrices in the case of PMUs with high sampling rates (30Hz or more) or 3) existing trends in the signal which do not carry any information about system dynamics [8]–[9]. Because of these difficulties, before applying any of the spectral estimators, available data must be preprocessed.

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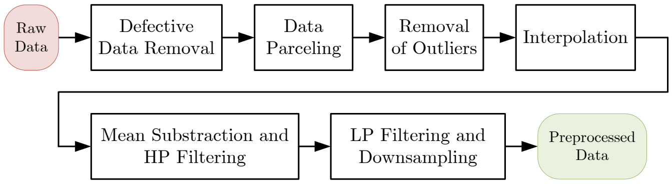

Fig. 2. Preprocessing algorithm

The preprocessing steps used in this paper are given in Fig. 2. The main goals of preprocessing stage are removal of erroneous data, trend removal, downsampling (recommended down to 5Hz for electromechanical oscillations) and data parceling. More details about preprocessing are given in [14].

III. SPECTRAL ESTIMATION ALGORITHMS

A. *Non-parametric methods*

Most non-parametric methods for spectral estimation are based on the well-known relation between the autocovariance sequence (s_τ) and the Power Spectral Density (PSD) function [15-16]:

$$S(f)=\sum_{k=-\infty}^{\infty} s_\tau(k)\, e^{-ik2\pi f\tau\Delta t}\,. \tag{1}$$

A comprehensive way to estimate the autocovariance sequence form the observation sequence (X_1, X_2, …, X_N) is given by

$$\hat{s}_\tau = \frac{1}{N}\sum_{t=1}^{N-|\tau|} X_t X_{t-|\tau|}\,, \tag{2}$$

where, $\tau = 0, \pm 1, \ldots, \pm(N-1)$ and N is the number of samples in the analyzed observation. This kind of the spectral estimator is called periodogram whose performances can be improved by appropriate tapering and estimate averaging. In this paper, two modifications are applied leading to the Welch's and Multitaper methods.

A.1. Welch's Spectral Estimator

The first step in Welch's method involves the partitioning of the data parcel to smaller blocks which are also allowed to overlap[1]. After partitioning, data tapers are applied on each block in order to reduce the negative effects of spectral leakage[2]. The final step is to compute a periodogram for each block and averaging all computed spectra into one final result. This is expressed by (3):

$$\hat{s}_\tau = \frac{\Delta t}{N_B}\left|\sum_{j=1}^{N_B-1}\sum_{t=1}^{N_s} h_t X_{t+jn}\, e^{-i2\pi f t\Delta t}\right|^2, \tag{3}$$

where h_t time series of the Hanning window and n is an integer specifying the amount of the overlap between two successive blocks. N_B and N_s are the number of overlapping blocks and number of samples in each individual block, respectively.

A.2. Multitaper Spectral Estimator

Multitapering is a technique similar to Welch's method but individual blocks are multiplied by several different windows and after that their spectra are averaged [15]. The tapering reduces bias in the estimator whereas averaging reduces the variance. The estimator is given by:

$$\hat{S}_\tau = \frac{1}{K}\sum_{k=0}^{K-1}\Delta t\left|\sum_{t=1}^{N} h_{t,k} X_t\, e^{-i2\pi f t\Delta t}\right|^2 . \tag{4}$$

To get a good reduction in both bias and variance it is of great importance to select a sequence of data tapers that not only have good leakage properties, but also have relatively uncorrelated eigenspectrums. For an orthogonal sequence of data tapers it is possible to obtain a sufficient degree of uncorrelation. In this paper, the discrete prolate spherical sequences (dpss) are used as the orthogonal sequence for tapering.

B. *Parametric methods*

Yule-Walker's method is the most commonly used spectral estimator from the group of parametric estimators [16]. The main assumption used in the Yule-Walker method is that a random process (ambient response) can be accurately described by an autoregressive model. The autocorrelation sequence of the analyzed signal is estimated using (2) and the well-known Yule-Walker equations [16] are solved in order to determine the coefficients of the underlying autoregressive model. Once the model of the process is determined, computation of mode frequencies and damping ratios can be carried out easily by extracting their values from the AR model.

IV. TUNING OF SPECTRAL ESTIMATORS

The accuracy of mode estimation heavily depends on the chosen parameters used in each estimator; however, methods for parameter tuning are not widely reported in the literature. The heuristic approach proposed in this paper consists in using a very long sequence of measured data (24 hours) to compute a reference spectrum. A spectrum computed from this amount of data is expected to have: (a) high frequency resolution, (b) low variance and (c) low bias, with the drawback that no information is provided on how the modes are changing over time. In other words, this kind of spectrum provides general information about persistent system modes. This can be seen in Fig. 3, where the presented spectrum was computed using Welch's method from 12 hours of frequency measurements from a PMU at Tampere University of Technology, Finland (not shown in Fig. 1).

After the reference spectrum is computed, parameters of spectral estimators are iteratively updated in a way that a

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[1] 50% overlap is recommended.

[2] A Hanning window is used data taper in this paper.

shorter time window of data (order of minutes) is chosen while preserving key properties of the reference spectrum such as variance, bias and frequency resolution.

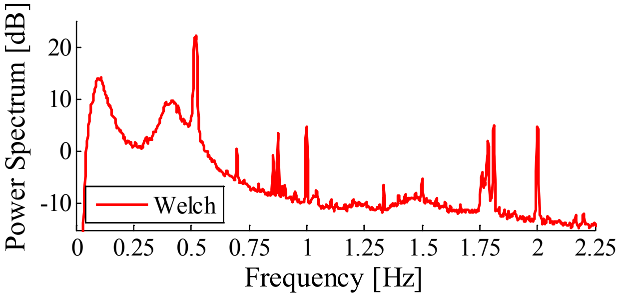

Fig. 3. Welch spectral estimate of 12 h. of data from Tampere's PMU and 1440 samples block size

A. *Non-parametric methods*

In the case of Welch's method, the time window is reduced until the variance, frequency resolution and bias performances are evidently decreased. It is found that window size of 500 samples (100 seconds) provides sufficiently good results (see Fig. 4[3]).

For the Multitaper method the same window size is selected. An optimal number of tapers is selected by gradually increasing the number of tapers and comparing to the reference spectrum. It is found that more than 8 tapers lead to unacceptable high variance (see Fig. 5).

B. *Yule-Walker Method - Model Order Selection*

One of the main advantages of the Yule walker method is relatively easy tuning. The only parameter which should be tuned is the model order, which can be empirically determined based on the required frequency resolution. In this work, a model order of 160 is adopted for spectrograms (Fig. 6). However, in the case of mode estimation lower model is preferred (up to 40). Result of the Yule-Walker spectral estimation is given in Fig. 6.

C. *Comparison of Spectral Estimators*

The main argument for using Multitaper over Welch's is that there is less spectral leakage for spectra having very high dynamic ranges. However, electromechanical oscillations do not have such high dynamic ranges. This is why both methods give similar estimates (Figs. 4 and 5). All major peaks, which are the most important for estimation of lightly-damped modes, are more or less identical. In the case of Yule-Walker's method, a high order method provides very similar results as with parametric methods, while lower order results in smoother spectrum with lower frequency resolution.

These results show that the frequency characteristics of power system measurements can be adequately captured by any of the described spectral estimators, and consequently, all of them can provide accurate information about existing oscillations in the system (Fig. 7).

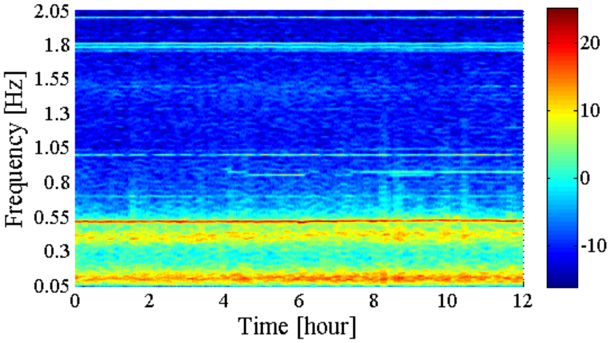

Fig. 4. Welch spectrogram with block size of 500 samples

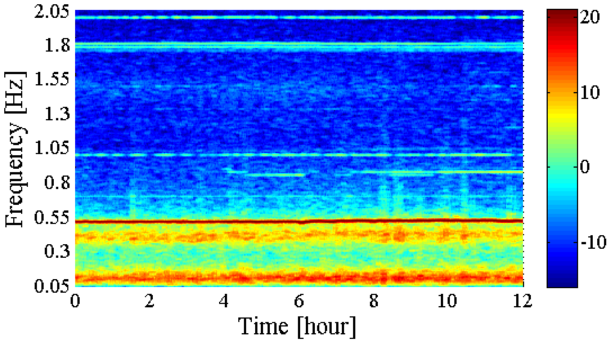

Fig. 5. Multitaper spectrogram with 8 tapers

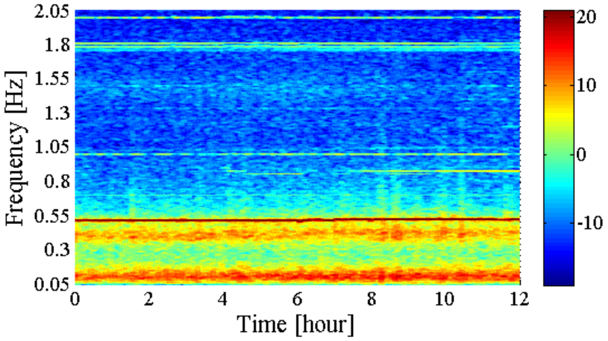

Fig. 6. Yule-Walker spectrogram with model order of 160

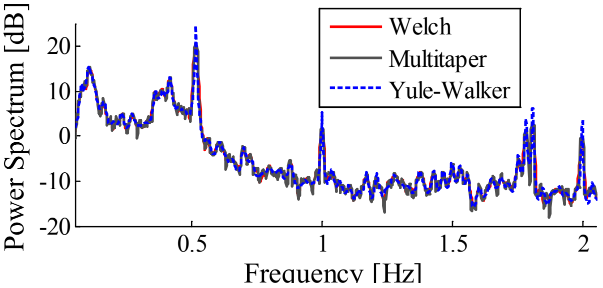

Fig. 7. Comparison of spectral estimators

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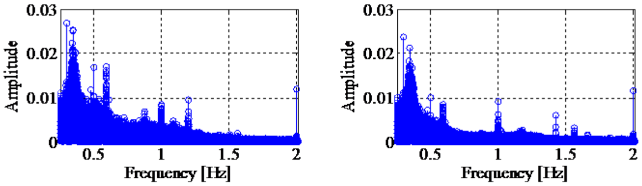
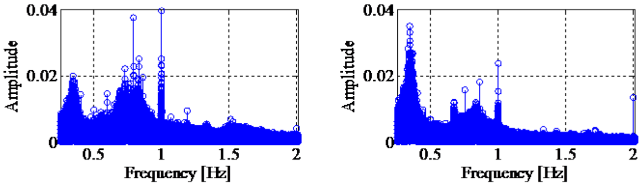
[3] For Figs. 4 – 6, the measurements start time is 08-Aug-2010 00:00:00 UTC. All spectrograms are obtained using 12 hrs of data from a PMU located at the low voltage distribution network of Tampere University of Technology and PSDs are estimated using 10 min. data parcels with 90% overlap.

V. MODE ESTIMATION WITH REAL SYNCHROPHASOR DATA FROM THE HIGH VOLTAGE NORDIC TRANSMISSION SYSTEM

The described methods are used to analyze the dynamic behavior of the Nordic Grid. Fourier transforms of four analyzed signals (from 4 different locations) are shown in Fig. 8. Note that there are several particularly narrow band peaks which presumably correspond to forced oscillations [8]. These oscillations are not a result of the system itself but of oscillatory behavior of particular elements in the system [8]. The same behavior can be seen in the spectrogram shown in Fig. 9.



(a) PMU 1 (b) PMU 2



(c) PMU 3 (d) PMU 4

Fig. 8. Fourier transforms of four signals from different locations in Nordic grid shown in Fig. 1.

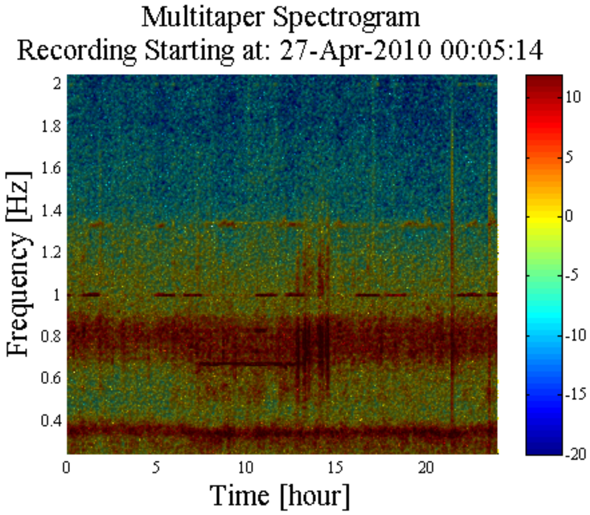


Fig. 9. Multitaper spectrogram computed with 24 hours with PMU at Location 3 (PMU 3 in Fig. 1.).

Spectrogram and FFT analysis have shown several modes, however not all of them can be observed in all locations. This is summarized in Table I.

VI. REAL-TIME IMPLEMENTATION OF SPECTRAL ESTIMATORS

A software development toolkit (SDK) named PMU Recorder Light (PRL) [17] is used as an interface between a Phasor Data Concentrator (PDC) which receives data from the physical PMUs, and a LabView-based Windows application, providing real-time access to PMU streams. This tool makes full scale testing in real-time easier for researchers, liberating them of time consuming synchrophasor data handling. This tool exploits the IEEE C37.118–2011 protocol making it independent of any specific equipment and their manufacturers.

The PRL has two major components as listed below:

1) Data Collector. This component reads the data from the PDC/PMU and stores them in buffers.

2) Data Extractor. This is a collection of functions (VIs) that allows the user to access the buffers and queues in the PRL. This component is a user interface for the PRL. It reads the data from the buffers and provides user with a control over the data streams in a suitable form for further processing (i.e. as a signal data type in LabView).

The general architecture of the PRL software development toolkit is shown in Fig. 10.

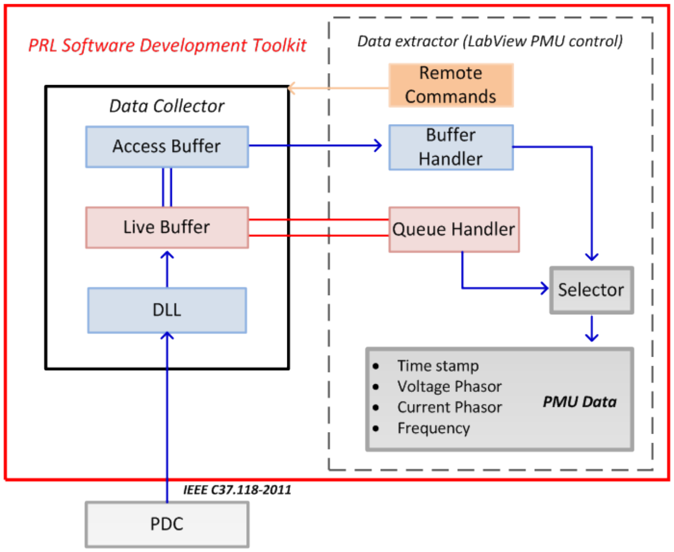


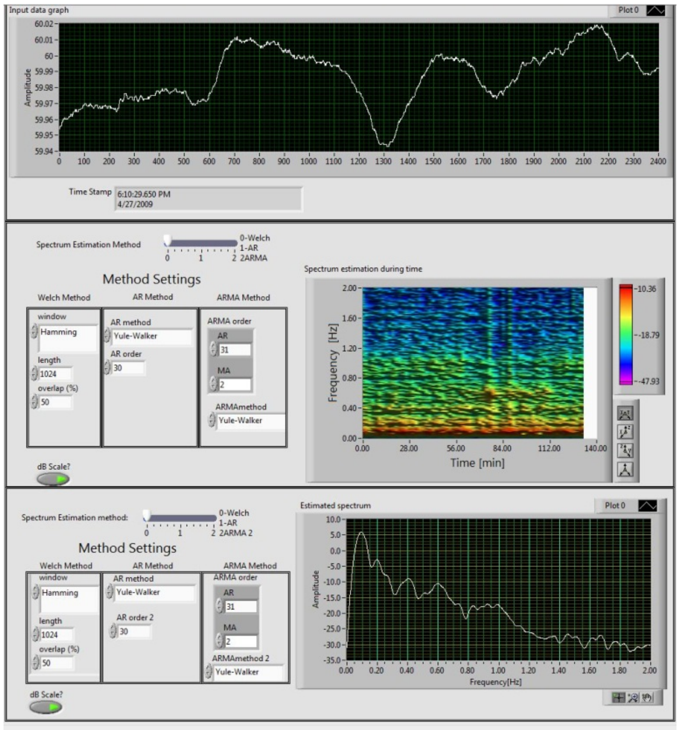
Fig. 10. Architecture of the PRL SDK

For the testing purposes, an experimental laboratory setup is designed where the PRL receives signals from a PDC. PDC receives data from PMUs connected to the amplified outputs of a real-time eMegaSim Opal-RT simulator or to the low voltage distribution network. Additional details on the experimental setup developed at KTH are described in [18].

Table I. Observability of the Nordic electromechanical modes

Mode Type	Mode *f* [Hz]	*PMU Locations and Mode Observalitiy*			
		PMU 1	PMU 2	PMU 3	PMU 4
Electro-mechanical	0.3	✓	✓	✓	✓
	0.8	✗	✗	✓	✓
	0.55	✗	✗	✓	✗
Forced Oscillations	0.6	✓	✓	✗	✗
	1.0	✓	✓	✓	✓
	1.2	✓	✓	✗	✗
	2.0	✓	✓	✗	✗
Short Period	0.7	✗	✗	✓	✓

The implemented LabView real-time spectral estimator employs algorithms described in the Section III. A graphical user interface of the developed application is depicted in Fig. 11. The upper part of the interface shows the measured signal in a time-moving panel (a frequency measurement in this case). The second part shows change of the spectrum over time (spectrogram). The bottom part of the interface shows average spectrum computed using longer data records (up to two hours). This figure gives an insight into average behavior of the system.



Time Stamp 6:10:29.650 PM 4/27/2009

window: Hamming
length: 1024
overlap (%): 50
AR method: Yule-Walker
AR order: 30
ARMA order: AR 31, MA 2
ARMAmethod: Yule-Walker

window: Hamming
length: 1024
overlap (%): 50
AR method: Yule-Walker
AR order 2: 30
ARMA order: AR 31, MA 2
ARMAmethod 2: Yule-Walker

Fig. 11. Graphical user interface of real-time spectral estimation application

VII. CONCLUSION

This paper demonstrates an application of spectral estimators for electromechanical mode identification in the Nordic Grid. Three methods, namely Welch, Multitaper and Yule-Walker, are compared and it is concluded that when appropriately tuned all the methods provide similar results. Further, these methods are applied in real-time using the PRL software development toolkit by developing a real-time mode estimation application. Real-time signals are taken from PMUs which are connected either to amplified outputs of an eMegaSim Opal-RT simulator or from a PMU directly connected to the distribution network feeding the laboratory. Future work will focus on utilizing the described methods and other techniques in real-time applications integrated in an early warning system for power system stability monitoring and measurement-based stability assessment.

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