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Spectral Estimation of Low-Frequency Oscillations in the Nordic Grid using Ambient Synchrophasor Data under the Presence of Forced Oscillations

Luigi Vanfretti, *Member, IEEE*, Sebastian Bengtsson, Vedran S. Perić, *Student Member, IEEE*, Jan O. Gjerde

***Abstract*—Spectral analysis applied to synchrophasor data can provide valuable information about lightly damped low-frequency modes in power systems. This paper demonstrates application of two non-parametric spectral estimators focusing on mode frequency estimation. The first one is the well-known Welch spectral estimator whereas the application of Multitaper method is proposed here. In addition, the paper discusses mode estimator tuning procedures and the estimators' performances in the presence of "forced" oscillations. The validity of the proposed application of the non-parametric estimators and tuning procedures is verified through both simulated data and PMU data originating from the high-voltage grid of the Nordic power system. Special attention is given to the analysis of the behaviour of different low frequency modes present in the Nordic grid, including that of forced oscillations.**

***Index Terms*—Inter-area oscillations, forced oscillations, PMU, mode estimation, mode meter, power system parameter estimation, Nordic Power System, Nordic Grid**

I. INTRODUCTION

Lightly damped modes in the power systems reduce transfer capacity and, in some cases, lead to unstable system operation [1, 2]. Therefore, continuous tracking of modes properties is of great importance for power system operators. It has been shown that ambient responses, which is a result of random changes in power systems, can provide real-time information about mode properties [3].

Software tools used for mode properties identification are called mode meters [1]. These tools perform digital signal analyses on ambient responses which are present in measured variables such as frequency, powers, voltages and currents.

Several mode meter algorithms have been recently developed. The first work in mode estimation based on ambient data was proposed in [4], where an Autoregressive model of ambient data is used. This method was later extended to incorporate the Autoregressive Moving Average (ARMA) model [5] and the Autoregressive model with spectral analysis [6]. State space based tool for mode identification is proposed in [7] and discussed in [6]. Adaptive tuning of autoregressive models by adaptive filtering techniques enables continuous modes tracking. This technique is introduced in [8] and further improved in [9]. A relatively new method for output-only mode identification, refereed to as Frequency Domain Decomposition (FDD), has also been applied for mode estimation in power systems [10]. Another approach for mode estimation that employs Stochastic Subspace methods, proposed in [11]. Useful overviews of the proposed methods are given in [1, 12, 13].

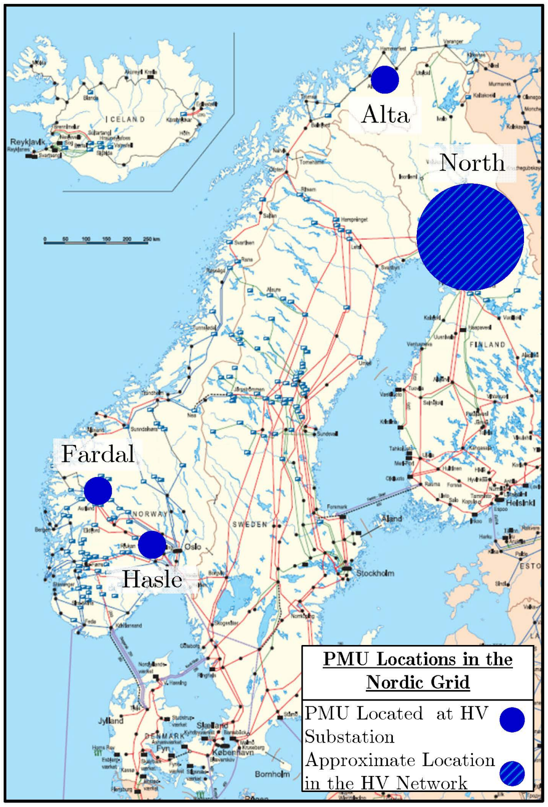

Fig. 1. Nordic Power System with locations of PMU measuremens

This paper proposes an application of a multitaper spectral estimator for mode frequency estimation. The Multitaper spectral estimator [14] is characterized by low bias and spectral leakage. On the other hand, the variance of the estimate is slightly higher comparing to other non-parametric methods. However, taking into account relatively slow changing of modes in normal power system operation, this disadvantage can be overcome by using longer data parcels.

The Welch and Mulitaper spectral estimators [14, 15] are applied to 72 hours of synchrophasor data captured at four locations in the Nordic power system (Alta, North, Hasle and Fardal, see Fig. 1). The first step in mode estimation (preprocessing) is the extraction of a clear ambient data from measured variables. This step ensures consistent data sets and consequently appropriate data quality which is necessary for an accurate mode estimation. After the data has been preprocessed, mode estimator parameters are to be determined. The problem of the parameters selection must consider the trade-off between variance, bias, resolution, etc. This paper proposes descriptive and visual methodology for tuning both spectral estimators. The validity of the Welch and Multitaper methods with adopted tuning procedures is verified by using synthetic data from a power system simulation.

In the performed analyses, special attention is given to identification and classification of the existing modes in Nordic

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L. Vanfretti, S. Bengtsson, and V.S. Perić are with the Electric Power Systems Division, School of Electrical Engineering, KTH Royal Institute of Technology, Teknikringen 33, SE-100 44, Stockholm, Sweden. E-mail:luigiv@kth.se

J.O. Gjerde is with the Norwegian TSO, Statnett SF, Research and Development, Hysebybakken 28 B, N-0302 Oslo, Norway. E-mail: jan.gjerde@statnett.no.

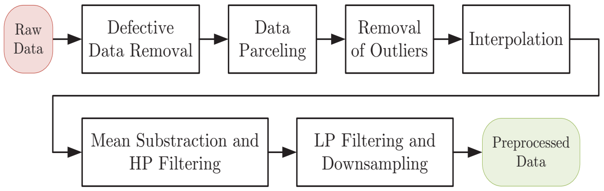


Fig. 2. Preprocessing algorithm

power system. It is identified that some modes have temporary character (modes disappear after some time) whereas some are permanent, furthermore, some identified modes are not result of the system itself but of forced oscillation which are caused by oscillatory behaviour of some elements in the power system [16, 17, 18, 19]. An analysis on the impact of forced oscillations on damping estimation is provided by the authors in a separate publication [20].

The remainder of this article is organized as follows: Section II briefly summarizes the preprocessing algorithm used. The used spectral estimators are discussed in Section III whereas tuning procedures are proposed in Section IV. A comparison of spectral estimators and analysis of synchrophasor spectrograms are given in Section V. In Section VI the features of forced oscillations are highlighted, while Section VII mode estimation is carried out both on synthetic simulation data and PMU data from the Nordic grid. Section VII also analyses the different low-frequency oscillations identified in the Nordic power system. Finally, conclusions are drawn in Section VIII summarizing the main findings in the article.

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 [13]. Because of these difficulties, before applying any of the spectral estimators, available data must be preprocessed.

The block diagram of the preprocessing steps is shown 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 steps can be found in [21].

III. MULTITAPER SPECTRAL ESTIMATOR

As the name implies, the multitaper spectral estimator employs multiple tapers to improve the performance of the periodogram. For a sequence of K data tapers, $h_{t,k}$, K individual eigenspectrums can be computed as follows:

$$\hat{S}_k(f) = \Delta t \left| \sum_{t=1}^{N} h_{t,k} X_t e^{-i2\pi f t \Delta t} \right|^2 \tag{1}$$

The tapering reduces the bias of the estimator. In addition, by averaging the individual eigenspectrums, the variance of the resulting estimates is reduced. The estimator is given by

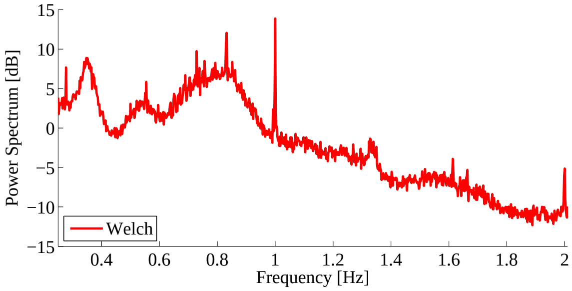


Fig. 3. Welch spectral estimate, 24 h data from Alta, 7000 samples block size

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

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. If the spectrums are highly correlated it is not be possible to obtain the desired reduction in variance. For an orthogonal sequence of data tapers it is possible to obtain a sufficient degree of uncorrelation.

$$\sum_{N}^{t=1} h_{t,j} h_{t,k} = 0 \quad j \neq k \tag{3}$$

In this paper, the discrete prolate spheroidal sequences (dpss) is used as orthogonal sequence used in tapering.

IV. TUNING OF SPECTRAL ESTIMATORS

The accuracy of the mode estimation highly depends on values of mode estimator parameters. Despite the importance of tuning of mode estimator parameters, to the knowledge of the authors, approaches to deal this problem are not reported in the literature. For a large amount of data (for instance 24 hours), a non-parametric spectral estimator is expected to produce high resolution PSDs with low variance and low bias. This kind of the estimator (using a large amount of data) is not able to provide information how the modes are changing in the real-time, but provide accurate information about existing modes in the system. This information can be later used for the tuning of estimators which update estimates more frequently and give information about mode variations through time and different operating conditions.

A PSD computed using Welch's method from 24 hours of data captured at the Alta substation is shown in Fig. 3.

A general approach for estimator parameter tuning is to visually compare PSDs computed using small parcels (for instance 1, 5 or 10 min.) with different parameters to one computed with 24 hours of data. When carrying out this comparison, the engineer must consider a trade-off between variance, bias and resolution of the resulting spectral estimate that uses a small data parcel. Appropriate accuracy of the estimate is accomplished by low variance, while adequate resolution requires sufficient amount of data (larger block size). This comparison can also be used for determining the

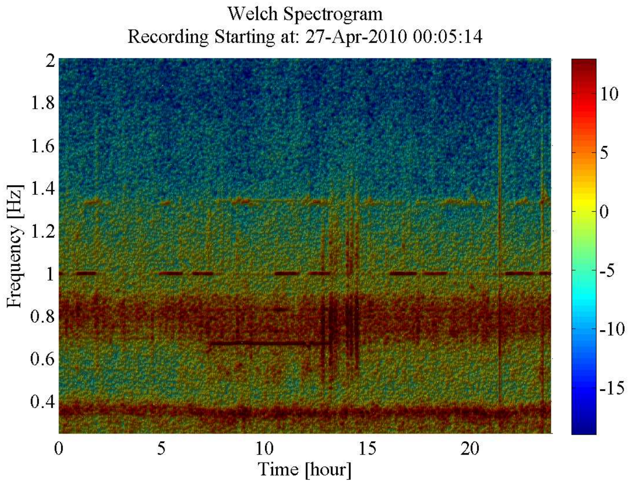


Fig. 4. Welch spectrogram, 24 h data from Alta and 700 samples block size

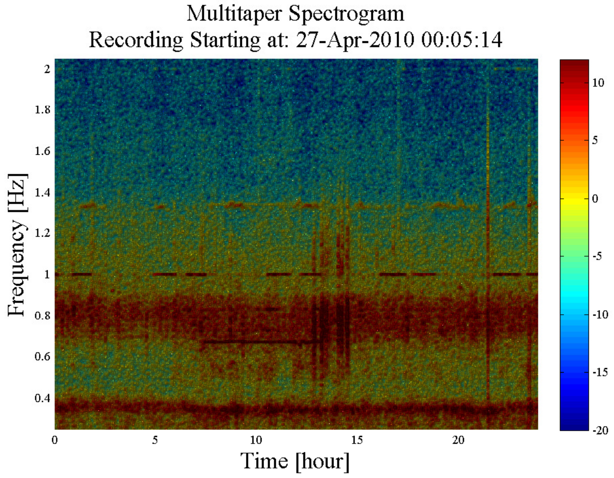


Fig. 5. Multitaper spectrogram, 24 h data from Alta and 8 tapers

appropriate block size required by Welch's method and number of tapers in the Multitaper method.

A. *Welch's Spectral Estimator - Block Size*

A decrease in block size leads to a decrease in variance and lowered spectral resolution. By starting with a large block size and slowly decreasing it until the modes can be distinguished from the variance, it is possible to obtain a PSD with acceptable variance while keeping the spectral resolution in acceptable limits. In the case of Nordic power system it is found that satisfactory results are obtained with 700 samples block size. A 24 h spectrogram with the block size selected with this methodology is shown in Fig. 7.

B. *Multitaper Spectral Estimator - Number of Tapers*

To determine an appropriate number of tapers an approach similar to method used for Welch's estimator can be used. Since the variance decreases as the number of tapers increases one can begin with a small number of tapers and increase until the smaller peaks can be discerned from the variance. In this case it is found that more than 8 tapers lead to unacceptable high variance. A 24 h spectrogram with the taper number selected with this methodology (8 tapers) is shown in Fig. 5.

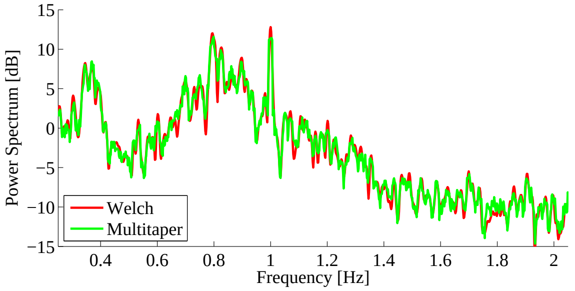


Fig. 6. Welch and multitaper spectral estimates, 10min of data from Alta, 700 samples block size and 8 tapers

V. COMPARISON OF SPECTRAL ESTIMATORS

Two non-parametric spectral estimators (Welch's and multitaper) have been used to compute spectrograms and PSDs for the same data set. In Fig. 6, the PSDs of both estimators are plotted together.

The main argument for using Multitaper over Welch's spectral estimator is that there is less spectral leakage for spectra having very high dynamic ranges. However, the system does not have such high dynamic ranges, so the estimators can be expected to have similar performance and as can be seen the estimators give similar estimates, all the major peaks, which are the most important for determination of lightly damped modes, are more or less identical.

VI. FORCED OSCILLATIONS

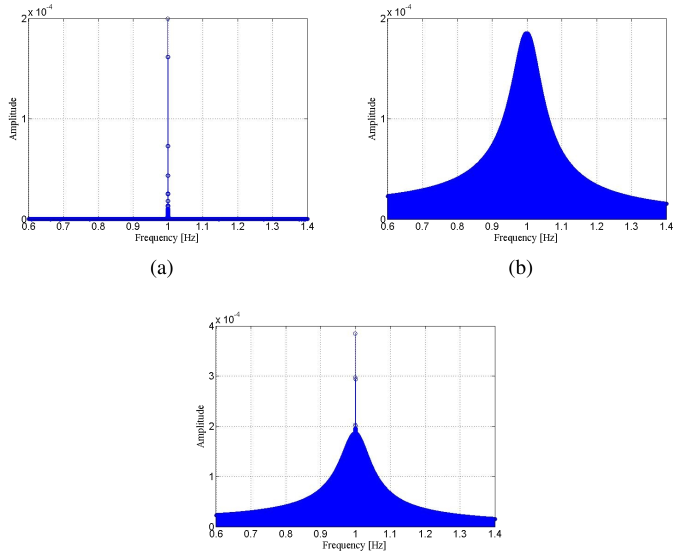
Forced oscillation phenomena in power system have sporadically appeared in the literature over the last 40 years [16]. There are different sources of these oscillations. Xuanyin et al. [17] reports that the regulation system of steam turbines can cause this kind of oscillatory behaviour. Other authors have investigated the impact of cyclic loads in the system [16, 18]. Vournas et al. [19] report diesel generators as one of the possible causes for forced low-frequency oscillations.

Regardless of cause, all types of forced oscillations have some common characteristics which can be used for their identification. Considering that a forced oscillation is a perpetual oscillation with a specific frequency, its spectrum is characterized by a very narrow frequency with high amplitude peak. Hence, a forced oscillation will have most of its spectral content concentrated in one small frequency bin, while for a mode the spectral content is spread around the main peak, in Fig. 7 this is illustrated. Observe in Fig. 7a how the spectral response of a forced oscillation at 1 Hz has all of its spectral content in a single frequency bin, while a damped oscillation has a more spread spectral content centered at 1 Hz as shown in Fig. 7b. Finally, it is interesting to observe in Fig. 7c the resulting spectrum from the combination of the two above oscillations. This is similar to the spectrum which one should expect from a forced oscillation overlaying an *true* system mode. This behavior is present in the Nordic power system which is closely analyzed in Section VII.B.

VII. SPECTRAL ESTIMATION OF LOW-FREQUENCY MODES USING SIMULATED AND REAL SYNCHROPHASOR DATA

A. *Mode estimation with simulated data*

A simplified seven bus model of the Southern/Southeastern Brazilian power system is used for validation of the proposed



(a) (b)

(c)

Fig. 7. FFTs computed with simulated data showing (a) forced oscillation (b) damped sinusoid (c) combination of a damped and forced oscillation.

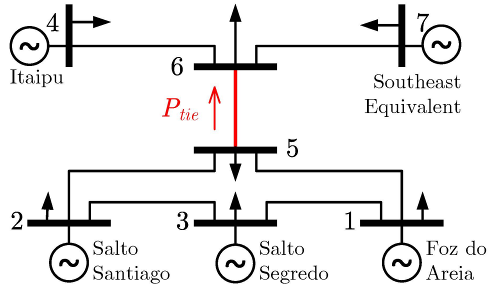
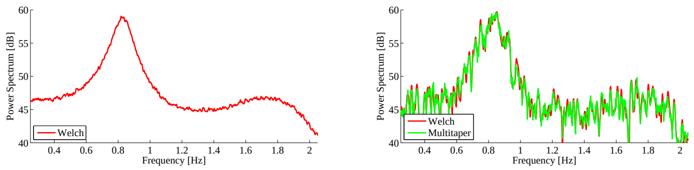


Fig. 8. Single-line diagram of the simulated power system

TABLE I
MODE FREQUENCIES AND DAMPING RATIOS OF THE SIMULATED SYSTEM

Mode Frequency [Hz]	Damping [%]
0.8308	6.9316
1.7869	14.5385

application of the two non-parametric estimators and the proposed tuning procedures [22] (see Fig. 8). The model represents the Itaipu hydro power plant which is connected through a 765kV line to the load area. Four 500kV buses (buses 1-5) which form a ring with 3 generators are connected to Itaipu power station by a 765kV tie-line (line between buses 5 and 6). All generators are modelled by a fifth order model. All model parameter data can be found in [22].

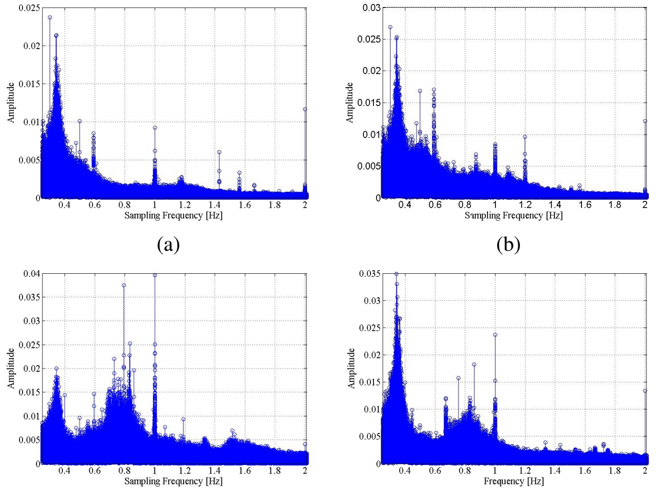


(a) (b)

Fig. 9. Spectral estimates computed using (a) 24 h., (b) 10 min. of simulated data

A classical small signal stability study reveals two electromechanical modes with frequencies of 0.83 Hz and 1.79 Hz, and damping ratios of 6.9316% and 14.53%, respectively (Tab.I).

Ambient data is synthesized through simulations where uniformly distributed pseudo-random values are used (white noise[1]) as inputs in all load buses of the system. A signal of the tie-line active power, which is sampled with frequency of 50 Hz, is used to create data parcels to be used with the spectral estimators.



(a) (b)

(c) (d)

Fig. 10. FFT containing forced oscillations, computed with 24h of data from: (a) Hasle (b) Fardal (c) Alta (d) North.

Spectral estimates of the tie-line active power, computed by Welch's and Mulititaper methods, are shown in Fig. 9. Figure 9a shows resulting spectra which were calculated using 24 hours of simulated data. The estimates shown in Fig. 9a data parcels are reduced to 10 minutes and parameters computed with the procedure in Section V. Note that the 1.79 Hz mode has poor observability in the tie-line active power, as it is not an inter-area mode, as a result it is not possible to obtain a high resolution when using data parcels as small as 10 min. However, for the 0.83 Hz inter-area mode where the tie-line power bears high observability the methods, using both 10 min and 24 hrs. of data, provide spectral estimates with adequate resolution.

B. Mode estimation with real synchrophasor data from the Nordic grid

In order to gain insight of the Nordic power system's behaviour, data from different locations must be used. In the performed analyses, synchrophasor data from four locations has been used. These locations are Alta, North, Hasle and Fardal (shown in Fig. 1). Spectra of the signals, calculated based on 24 hours of data are shown in Fig. 10.

There are forced oscillations of unknown origin in the data from the Nordic grid. These oscillations show up as narrow frequency bands in the FFTs computed from 24 hrs. of data from each location (see Fig. 10), and can be identified at 1 Hz, 1.2 Hz and 2 Hz. The presence of forced oscillations requires much care when selecting parameters for spectral estimators as explained in Section V, and have a negative impact in damping estimation [13, 24].

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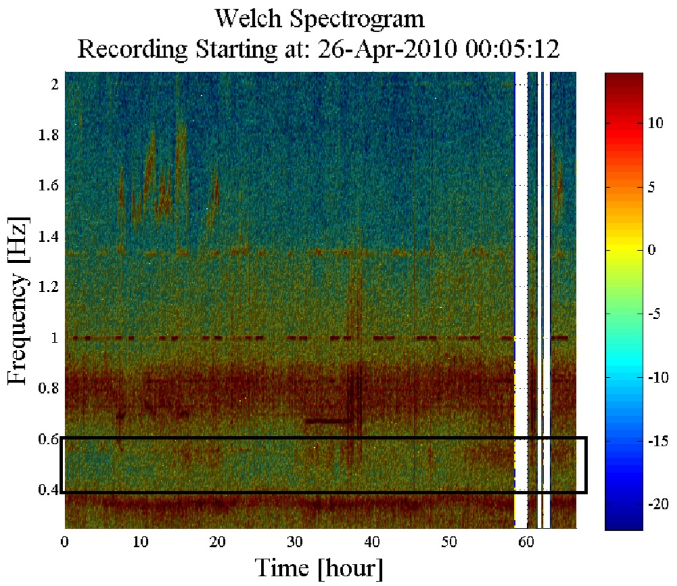
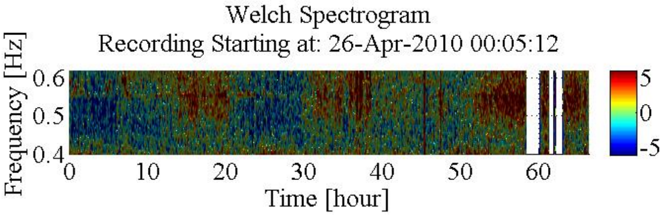
[1] Uniformly distributed pseudo-random values are drawn from the standard uniform distribution using Matlab's `rand` command.



(a) Welch spectrogram, 72 h data from Alta



(b) Detail of the Welch spectrogram with 0.5Hz mode

Fig. 11. Welch spectrogram, 72 h data from Alta and 700 samples block size, full spectrogram and extracted detail.

The variation of the system modes during the time is analysed with computation of spectra using 10 minutes block of data, with a 9 minute overlap. All these individual spectra are computed for 72 hours of data and are put together in order to form spectrogram. The four corresponding spectrograms are shown in Fig. 11-14.

These spectrograms reveal important information about Nordic power system. It can be noticed that there are three dominant electromechanical modes with frequencies of 0.3 Hz (inter-area) and 0.8 Hz (local). A mode with frequency of 0.55 Hz can also be identified, despite low observability, at Alta. Fig. 11b provides an enlargement of Fig. 11a where this mode can be readily identified. These results are in accordance with the results from small-signal analysis of a large non-linear model reported in [23]. The modes identified from the spectrograms are summarized in the Table.II.

In addition, there are many changes in the system dynamics, a particular case is when modes appear for a few hours and later disappear from the spectrogram, as it can be observed at Alta and North in Figs. 11a and 12, respectively, where a 0.7 Hz mode "pops-up" only during $t \approx [\ 31\ -\ 38\ ]$ hours. This behaviour is a result of the significant change of the operating point which are usually cased by topology change (line connection/disconnection) or some other change such as load/generator tripping or start-up.

As a result, the modes in Table II are classified into three groups [24]. The first group represent electromechanical modes which are permanently observable (0.3 Hz, 0.55 Hz, and 0.8 Hz). As explained previously, the 0.55 Hz mode [2] has a very low observability at most locations used in this study. The second group of the identified modes are result of forced oscillations in the system which are characterized by very narrow spectrum (1Hz, 1.2Hz and 2Hz). Beside these modes there is 0.7 Hz mode which has a temporary character. It appears only during the 7 hours in analyzed period ($t \approx [$ 31 - 38 $]$ hrs.) at Alta and North substations.

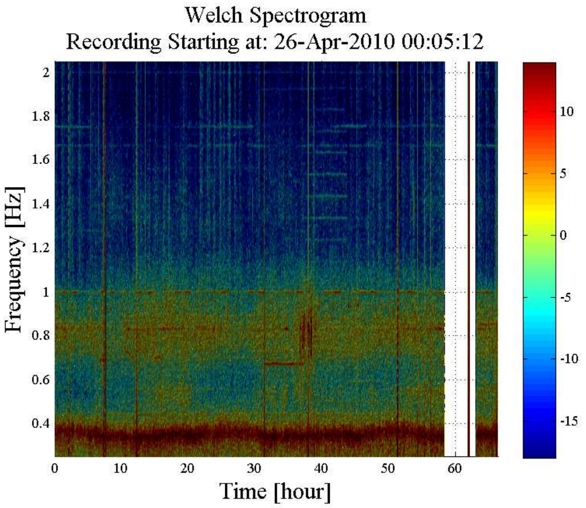


Fig. 12. Welch spectrogram, 72 h data from Finland North and 700 samples block size.

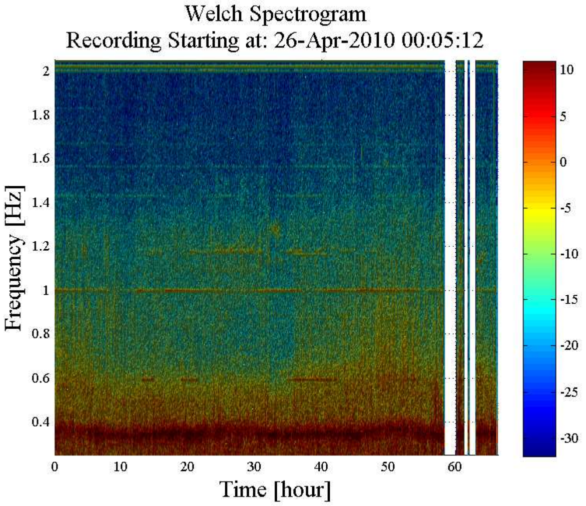


Fig. 13. Welch spectrogram, 72 h data from Hasle and 700 samples block size.

VIII. CONCLUSIONS

The paper demonstrates the application of two non-parametric methods for mode estimation from ambient data using both synthetic data from simulations and *real* PMU measurements from the Nordic grid. Two important steps in mode estimation namely data preprocessing and spectral estimator tuning are described. The tuning procedure starts by computing spectral estimates with large parcels of data, and allows to obtain proper spectral estimates for smaller parcel

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[2] This mode is also reported in the literature [23, 13].

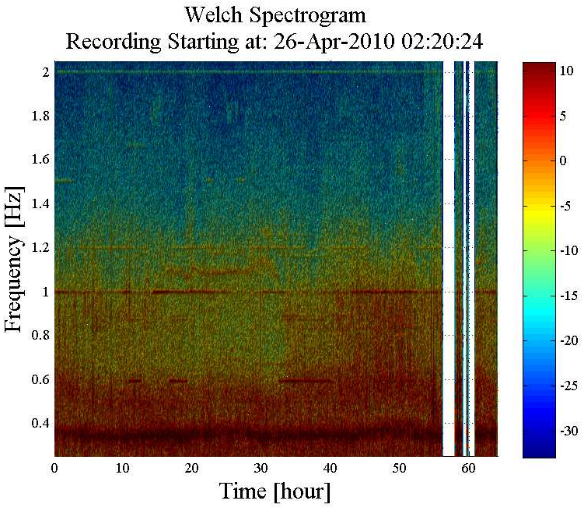

Fig. 14. Welch spectrogram, 72 h data from Fardal and 700 samples block size.

TABLE II
MODE ESTIMATES AND OBSERVABILITY AT DIFFERENT LOCATIONS
(YES-OBSERVABILE, NO-NOT OBSERVABILE)

Mode Type	Mode f [Hz]	PMU locations and observability			
		Alta	Hasle	Fardel	North
Electro-Mechanical	0.3	Yes	Yes	Yes	Yes
	0.8	Yes	No	No	Yes
	0.55	Yes	No	No	No
Forced Oscillations	0.6	No	Yes	Yes	No
	1.0	Yes	Yes	Yes	Yes
	1.2	No	Yes	Yes	No
	2.0	No	Yes	Yes	No
Short Period	0.7	Yes	No	No	Yes

sizes with adequate resolution. This is shown to be useful when building spectrograms that allow analysis of different modes present in the Nordic grid. Moreover, the presence of forced oscillations requires proper tuning of these estimators so that each type of modes can be properly identified.

From the performed analysis it can be concluded that modes in the system change during the day. While inter-area modes are persistent through most operating conditions, other modes appear only for a limited duration of time. This fact emphasizes importance of the continuous real-time monitoring of the power system modes. In addition, it is worth to mention that PMU measurements from different locations in the system should be considered in order to identify all dominant poles in the system.

Finally, what is most relevant to note is that the application of the estimators and tuning procedures proposed in this article allow to determine the existence and persistence of the each of the forced oscillations identified. Note from Table II that while the 1.0 Hz oscillation is ubiquitous, all other forced oscillations are confined to the South of the Nordic Grid. Such knowledge, previously unavailable, may help in characterizing the behaviour of forced oscillations in the Nordic grid more in detail in further studies. An analysis on the impact of forced oscillations on damping estimation is provided by the authors in a separate publication [20].

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