

# Application of ambient analysis techniques for the estimation of electromechanical oscillations from measured PMU data in four different power systems

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## SUMMARY

The application of advanced signal processing techniques to power system measurement data for the estimation of dynamic properties has been a research subject for over two decades. Several techniques have been applied to transient (or *ringdown*) data, ambient data, and to probing data. Some of these methodologies have been included in off-line analysis software, and are now being incorporated into software tools used in control rooms for monitoring the near real-time behavior of power system dynamics. In this paper we illustrate the practical application of some ambient analysis methods for electromechanical mode estimation in different power systems. We apply these techniques to phasor measurement unit (PMU) data from stored archives of several hours originating from the US Eastern Interconnection (EI), the Western Electricity Coordinating Council (WECC), the Nordic Power System, and time-synchronized Frequency Disturbance Recorder (FDR) data from Nigeria. It is shown that available signal processing tools are readily applicable for analysis of different power systems, regardless of their specific dynamic characteristics. The discussions and results in this paper are of value to power system operators and planners as they provide information of the applicability of these techniques *via* readily available signal processing tools, and in addition, it is shown how to critically analyze the results obtained with these methods. Copyright © 2010 John Wiley & Sons, Ltd.

**KEY WORDS:** power system oscillations; power system identification; power system parameter estimation; power system monitoring; application of signal processing techniques; synchronized phasor measurements; power system measurements; small-signal stability

## 1. INTRODUCTION AND BACKGROUND INFORMATION

With the application of advanced signal processing techniques to synchronized phasor measurements it is possible to obtain crucial information about power system dynamic behavior. This information when incorporated in energy management systems can aid in improving the operational reliability of interconnected power systems, and in addition, it may also be used to characterize power system dynamics. With the initiatives carried out in the Western Electricity Coordinating Council (WECC) [1] for over two decades and others (see references in References [2], and [3,4]), the application of advanced signal processing techniques to power system measurement data has been proven successful for the estimation of mode properties, i.e., mode frequency, damping, and more recently mode shape

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[5]. Estimates of mode frequencies and damping are indicators of a power systems stress, a declining value of these indicators point to a detriment on the capacity of a power system to operate reliably, and such condition may lead to a system break-up [1]. Mode shape estimates can give a direct indication of the major areas of a power system contributing to the oscillations in a specific mode frequency, and therefore may be used in the future for determining control actions [5]. There are several types of signal processing techniques available to provide these estimates, some are appropriate for transient signals (or *ringdown*) [6,7], others are adequate for *ambient* signals, and others are used when a known probing source is used to excite the power network [8]. Some of these techniques have been implemented in off-line analysis software [9], and are now being incorporated to software tools used in control rooms for monitoring the near real-time behavior of power system dynamics [10].

The techniques used on ambient signals are a subset of signal processing methods for linear prediction, optimum linear filters, and power spectrum estimation which have a relatively long history of their own [11,12]. The seminal works in References [13,14] introduced the basic assumptions needed to apply these methods to power system data and showed by solving the Wiener-Hopf linear prediction equations that power system modal frequency and damping estimates can be obtained from ambient data only. The fundamental assumption is that there are random changes, mostly comprised of load variations, which excite the small-signal dynamics of a power system. Hence, ambient data analysis can be used to estimate the inherent oscillatory modes of the power system when the main source of excitation of the system modes are random load variations resulting in a low amplitude stochastic time series referred to as “ambient noise” [2].

Under this basic assumption, non-parametric and parametric power spectrum estimation techniques can be used to estimate the power spectrum from synchrophasor measurements (phasor measurement unit (PMU) data). In this paper we focus on block-processing algorithms which encompass these two techniques. The first application of block processing is reported in Reference [14]. These algorithms operate on blocks of data, that is, a parcel of continuously-recorded time-synchronized PMU data usually ranging from 5 to 15 minutes. Using a fixed block length a new mode estimate is calculated for each block, all blocks being equally weighted. Updated mode estimates can be calculated as often as necessary, but they will need a block of the most recently measured data. The automated and continuous application of this identification process is known as a “mode meter” algorithm. From the available methods used in block-processing algorithms, here we focus on the use of a non-parametric method, the Welch Periodogram [11,15], and a parametric method, the Yule-Walker (YW) method [14,16]. As a result of applying these techniques and by focusing the analysis in the range of 0.1–1 Hz, the electromechanical modes are manifested as visible peaks in power spectrum density (PSD) estimate. Narrow peaks in the estimated spectrum indicate light damping, and broader peaks indicate a well damped mode. With any algorithm, there will be estimated modes that are *numerical artifacts*, and not true system modes. To discriminate between these two results, a “modal energy” method can be used to determine which mode in the inter-area mode range has the largest energy in the signal [16,17].

Spectral estimates may also be used for mode shape estimation; the cross spectral function (CSF) can be used to estimate both the phasing and coherence of the modes among the system generators [18]. As a result, mode shapes can be estimated [5]. Because these algorithms rely on block processing of data windows, they require several minutes of time-synchronized phasor data from different locations in the power network. Mode shape estimation is an active topic of research and is not illustrated in this paper; the reader is referred to References [5,17] for additional information.

Spectral processing techniques have been successfully applied to characterize the small signal oscillatory modes in the US WECC interconnection [1,16], the US Eastern Interconnection (EI) [19,20], as well as in the Australian power system [21,22]. In this paper we present results of the application of non-parametric and parametric methods for mode frequency estimation in several power systems. We have limited our discussion to the application of block processing techniques for mode frequency estimation only (a discussion on mode damping estimation can be found in Reference [16]). In this paper we emphasize the analysis of several hours of synchrophasor measurement data originating from the U.S. EI, the WECC, the Nordic Power System, and Frequency Disturbance Recorder (FDR) data [23] from the Nigerian power system. This paper intends to illustrate how commercially available signal processing tools [24] are readily applicable for PSD estimation (with the pre-requisite that users are knowledgeable of signal processing methods and are familiar with the

Matlab programming language [24]) and that they produce excellent results for estimating power system modes. A second goal of this paper is to share our knowledge on how to critically analyze the results from applying these techniques, and how to deal with several difficulties that may arise when analyzing PMU data. The discussions and results in this paper are of value to power system operators and planners as they provide information of the applicability of these techniques *via* readily available signal processing tools, and in addition, it is shown how to critically analyze the results obtained with these methods.

The remainder of this paper is organized as follows. In Section 2 we describe the main concepts used for ambient data analysis from a systems perspective. In Sections 3, 4, 5, and 6 we provide results from the ambient analysis of archived data from the WECC, the US EI, the Nordic Power System, and from Nigeria, respectively. In Section 7 conclusions are drawn, and in the Appendix we provide additional information about the software tools used in this paper.

## 2. MODE ESTIMATION FROM POWER SYSTEM MEASUREMENTS

### 2.1. Systems perspective

Analysis of small signal dynamics assumes that small changes in the power system can be described by a nonlinear differential-algebraic system of equations linearized about an equilibrium [2], i.e.,

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}_E u_E(t) + \mathbf{B}_L q(t) \\ y(t) &= \mathbf{C}\mathbf{x}(t) + \mathbf{D}_E u_E(t) + \mathbf{D}_L q(t) + \mu(t) \end{aligned} \quad (1)$$

where  $q$  is an hypothetical random vector perturbing the system,  $\mathbf{x}$  is the state vector which includes generator angle and speeds, and  $t$  is the time. Control actions that can be described as smooth functions of the state  $\mathbf{x}$  are embedded in the system matrix  $\mathbf{A}$ . Power system measurements are represented by  $y$  which contains measurement noise  $\mu$  which is comprised of effects from instrumentation, communication channels, data systems, and other similar devices; generally, measurement noise has a small amplitude. System topology changes may alter the matrix  $\mathbf{A}$  to various degrees.

The assumption for  $q$  is that it is a vector of small-amplitude random perturbations typically conceptualized as noise produced by load switching. It was proposed in Reference [13] that the load switching is primarily integrated stationary Gaussian white noise with each element of  $q$  independent. The system can be conceptualized as shown in Figure 1 where  $y_i$  is the  $i$ th element of  $y$  [1]. The MIMO (Multiple Input Multiple Output) system  $G$  is assumed linear. Network topology changes are represented by switches in dynamic gain matrices  $\mathbf{K}$  and  $\mathbf{K}'$ , which may or may not be deliberate. The response of this system can be classified as either transient (also termed *ringdown*) or ambient. In the

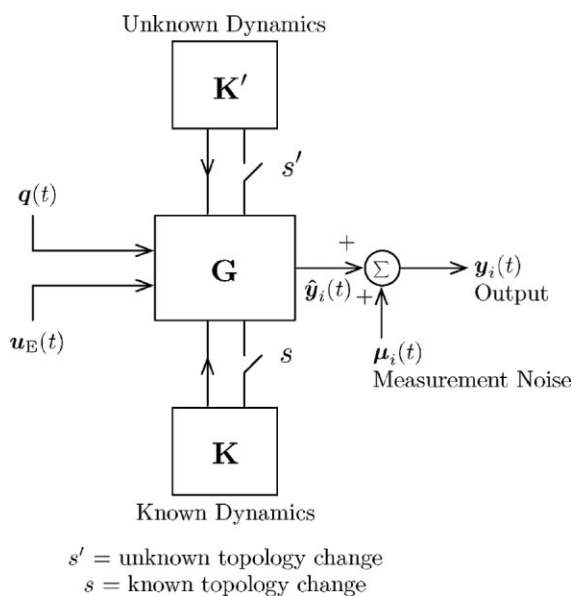


Figure 1. Structure for information sources in process identification [1,2].

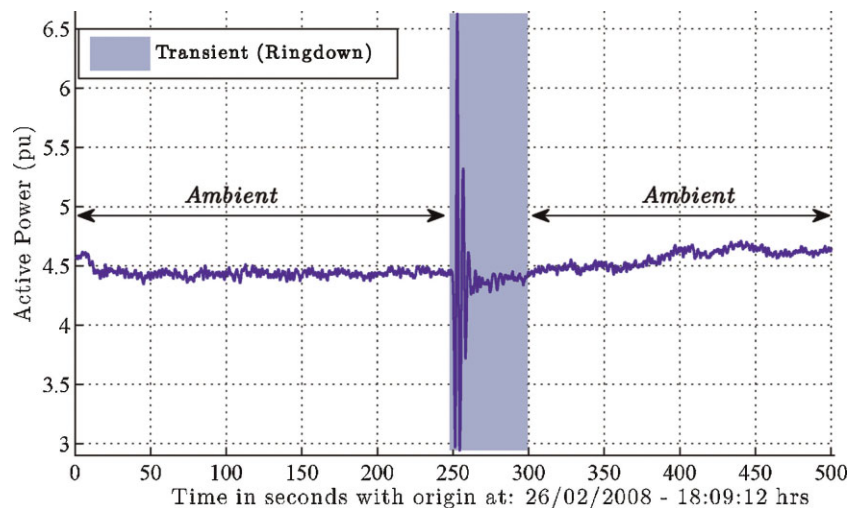


Figure 2. Active power flow on a transmission line in the US EI during the FRCC 2008 disturbance [25].

case of ambient conditions, the basic assumption is that the system is excited by low-amplitude variations at  $\mathbf{q}$  and that the variations are typically random in nature. This results in a response at  $y$  that is impregnated with the dynamics  $G$ . The input  $u_E$  can be used to inject low level probing signals into the system [8]. A transient response is typically larger in amplitude and is caused by a sudden switch at  $s$  or  $s'$ , or a sudden step or pulse input at  $u_E$ . The resulting time-domain response is a multi-modal oscillation superimposed with the underlying ambient response.

The different types of responses are shown in Figure 2, which shows a plot of the real-power flowing on a transmission line in the north of the EI during a system wide disturbance that originated in the Florida Reliability Coordinating Council (FRCC) Bulk Electrical System on February 26, 2008 [25]. Prior to the transient that starts at  $t = 250$  seconds, the system is in an ambient condition. The ringdown settles at approximately  $t = 300$  seconds and the system returns to an ambient condition.

It must be stressed that because the behavior of the power system contains a random component, no algorithm can exactly estimate the modal properties. In this paper we analyze ambient data for different power systems, in the next section we briefly describe the two main block processing algorithms used in our analysis.

## 2.2. Block processing algorithms

As discussed above block-processing algorithms operate on blocks of data. Using a fixed block length a new mode estimate is calculated for each block, all blocks being equally weighted. Updated mode estimates can be calculated as often as necessary, but they will need a block of the newest data of the same fixed length. To provide these mode estimates, block-processing algorithms implement non-parametric and/or parametric spectral estimation methods.

From the many available methods, here we focus on the use of a non-parametric method, the Welch method [15,11], and a parametric method, the YW method [14,16]. The Welch periodogram [11,15,26] is a specially robust non-parametric spectral estimation method which gives an estimate of a signal's strength as a function of the frequency; the spectrum is computed using the FFT (Fast Fourier Transform) algorithm. It does not assume an underlying model, and the estimated spectrum is based on a finite record of data. The algorithm allows for a fairly direct trade-off between frequency resolution (i.e., the ability to resolve closely spaced frequency components) and the statistical variability of the PSD estimate. The block of data is divided into shorter segments. The FFT of each segment is computed and the squared magnitudes are averaged. This averaging is what reduces the statistical variability in the estimates. The length  $N$  of each segment is what determines the frequency resolution  $\Delta f = 1/(NT)$  where  $T$  is the sampling period<sup>1</sup>. The segments can each be multiplied by a window

<sup>1</sup>For example, given a 10-minute block of data sampled at  $f_s = 5$  Hz, segments of 100 seconds are typically used. Thus, a frequency resolution of  $\Delta f = 0.01$  Hz is obtained.

function to reduce leakage. The segments can also be overlapping to further reduce the variability, but overlapping much beyond 50% has little extra benefit because of the lack of new data in each piece. The estimated modes are manifested as visible peaks in the PSD estimate. Narrow peaks in the estimated spectrum indicate light damping, and broader peaks indicate a well damped mode or modes that are closely spaced in frequency. Computational requirements of the Welch method can be found in Reference [11].

Even though non-parametric methods are very robust and insightful, because they do not assume an underlying model, they cannot provide numerical estimates of the damping ratio and mode frequency of the modes. On the other hand, parametric methods assume an underlying model whose parameters can be estimated from the measurement data. Once these parameters are estimated, the power density spectrum is computed from the model. As a result, the frequency resolution is much better than the one from non-parametric methods. A commonly used parametric method is the overdetermined modified YW algorithm [14,16] which is used to estimate the system modes using an autoregressive-moving-average (ARMA) model. Several variations of this method have been proposed in the literature [2]. In this paper the traditional YW algorithm was applied to an autoregressive (AR) model.

The resulting PSDs from these methods are complementary. When the YW method is used to provide mode estimates, the YW spectrum should be compared for consistency with the non-parametric Welch Periodogram spectrum estimate. If a strong similarity in the spectrum is not observed, the validity of the estimates can be questioned. The two methods discussed in this section are used for mode estimation in the following sections.

By repeating this process on several consecutive overlapping blocks of data, a time–frequency image of the Welch Periodogram can be constructed. We referred to this image as a “Welch spectrogram.” When the YW method is used, the time–frequency plot of the AR spectra of the sliding blocks of data is referred to as an “AR spectrogram.” These spectrograms provide crucial information about the changing dynamics of power systems.

### 3. MODE ESTIMATION FOR THE WECC

A 24-hour record of ambient data from June 2008 was obtained from PMUs in the WECC. The data were originally sampled at 30 samples per second, preprocessed to remove high frequency noise and low frequency trends, and downsampled to five samples per second. At approximately 8.5 hours into the data set, Alberta was disconnected from the rest of the system causing the system dynamics to change. With Alberta connected, there were two well-known North–South modes near 0.26 and 0.42 Hz. Upon the removal of Alberta from the WECC, the system is expected to be reconfigured to have a single North–South mode near 0.36 Hz.

To demonstrate the insight provided by the analysis of ambient data, frequency data (calculated *via* differentiating voltage angle data) from a PMU near the northern part of the system was used. The actual name and location of the PMU is hidden to honor confidentiality agreements. Both the Welch and YW methods were applied to the 24-hour data set, which was divided into overlapping 15-minute segments. For each segment, the PSD was calculated using each of the two methods. The results are shown in the time–frequency plots of Figure 3. An AR model of order 35 was used.

The high energy in the PSDs indicates areas where there is potential for observable electro-mechanical modes. High energy can also indicate the presence of forced oscillations or very low frequency trends not completely removed in the preprocessing of the data, as seen in the sub 0.1 Hz areas of Figure 3. Inspection of the PSDs reveal the obvious system change near 8.5 hours, where the highly observable 0.42 Hz mode lowers in frequency to 0.36 Hz. Note that the 0.25 Hz mode is not very observable at this particular PMU. To help interpret the information of Figure 3, the plots of Figure 4 were created. Figure 4a was generated using a single 15-minute segment of data from the time–frequency plots of Figure 3 during the time when Alberta was connected. Similarly, Figure 4b was generated using a single 15-minute segment of data from the time when Alberta was removed. Note the decrease in modal frequency is observable in the comparison of Figure 4a and b. Also note the good agreement between the Welch and YW results. The spectrograms of Figure 3 are three-dimensional plots that contain PSDs for every 15-minute segment of the 24-hour period.

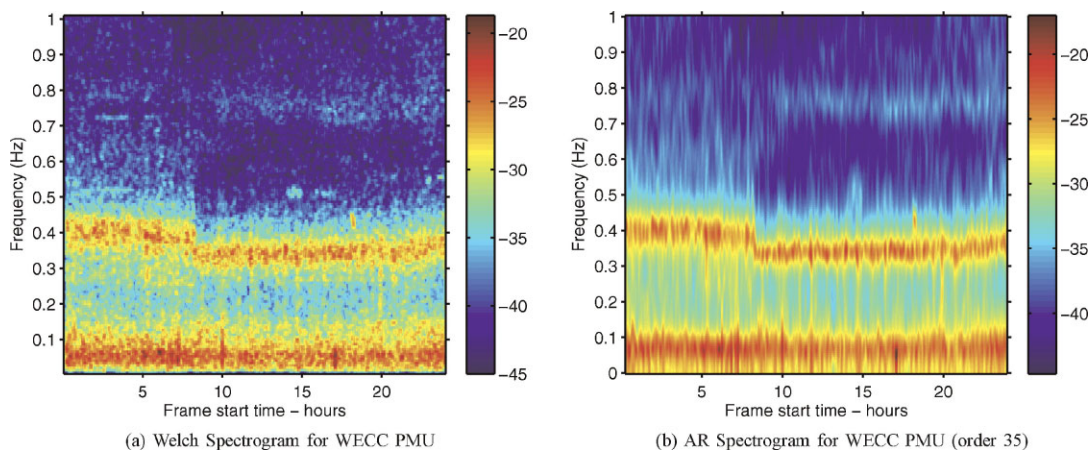


Figure 3. Spectrograms for the frequency data from the PMU of the WECC. The red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB]. (a) Welch Spectrogram for WECC PMU (b) AR Spectrogram for WECC PMU (order 35).

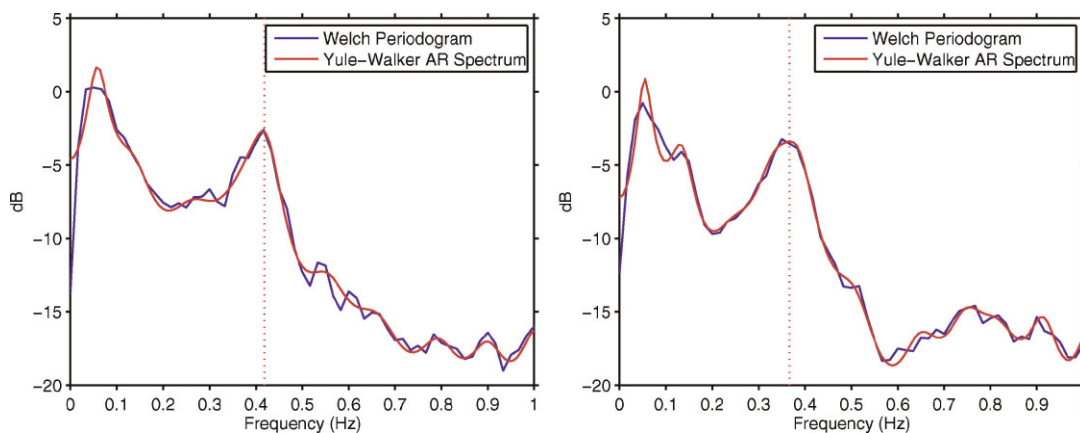


Figure 4. PSDs of the WECC data showing the shift in modal frequency when Alberta is removed. (a) PSD of WECC data with Alberta connected (b) PSD of WECC data with Alberta removed.

#### 4. MODE ESTIMATION FOR THE US EASTERN INTERCONNECTION

Nearly 19 hours of data from the US EI were obtained from PMUs during an event in which most of Florida disconnected from the rest of the system, resulting in a ringdown-type oscillatory response visible throughout the rest of the system. The PMU data were sampled at 30 samples per second and preprocessed in the same fashion as the WECC data. For illustrative purposes, a single PMU was selected in the Northeast portion of the system (the exact name and location hidden) and the same Welch- and YW-based PSD estimation techniques discussed above were applied. The results are presented in Figure 5.

The Florida Event is observed just after the 12-hour mark as the high energy region that is narrow in the time domain. The area of very low energy just before 5 hours is due to there being a section of missing data. The PSDs over the time of missing data were set to be equal to zero, so in the dB scale of Figure 5 they show up as the minimum energy of the dB coloring scale. The area of high energy from approximately 0.18–0.4 Hz indicates one or more highly damped electromechanical modes. Damping is proportional to the thickness of the energy in the frequency domain; wide band signals imply high

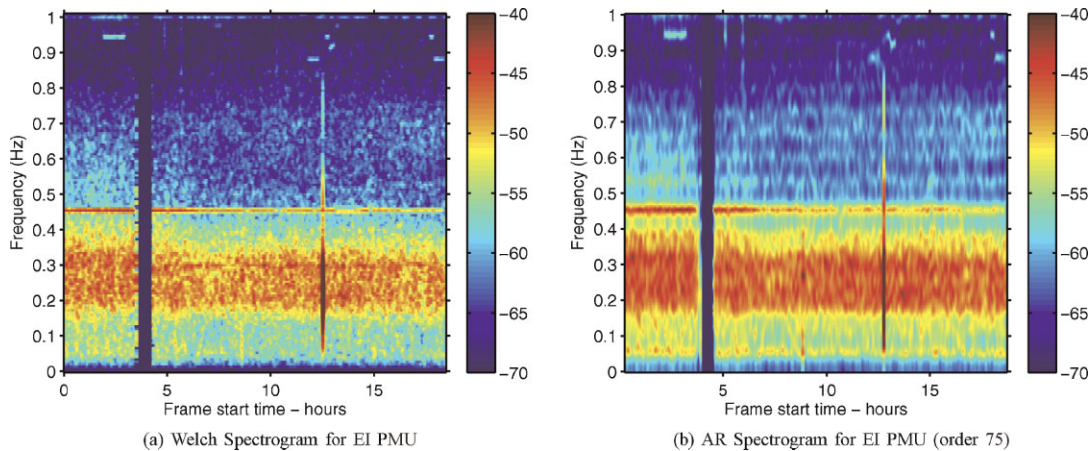


Figure 5. Spectrograms for the frequency data from the PMU of the EI. The red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB]. (a) Welch Spectrogram for EI PMU (b) AR Spectrogram for EI PMU (order 75).

damping or closely spaced overlapping modes and narrow band signals imply low damping. Note then the very narrow band signal near 0.45 Hz. At first glance this could be interpreted as an electromechanical mode with dangerously low damping. Further studies suggested that it could actually be a forced oscillation.

The strongest piece of evidence that the energy at 0.45 Hz is thought to be from a forced oscillation and not a mode is that the frequency of the energy was constant over the course of the day while the amplitude and phasing changed. As the day progressed, subtle changes in the power system due to configuration and loading caused electromechanical modal frequencies to slowly vary with the system changes. These subtle system changes would have contributed to the variable amplitude and phase of a forced oscillation while its frequency would have remained constant.

Also supporting the fact this was an oscillation is that it was observable throughout the EI on the day of the Florida Event in both PMU and FNET data, as well as in PMU data from November 2007 at precisely the same frequency. This was verified by performing a Welch Periodogram on long data segments that used FFT lengths that were approximately a whole number of periods of  $1/0.45$  seconds. One such periodogram is shown in Figure 6 where the frequency of the oscillation is estimated to be 0.4539 Hz. When applied to the other data sets, the frequency was always estimated to be 0.4539 Hz.

Lastly, the fact that this phenomenon at 0.45 Hz is extremely narrow in the frequency domain points to the fact that it is a forced oscillation. Pure sinusoids in the frequency domain are represented as line spectra, that is they have no thickness. This can be interpreted as a signal with 0.0% damping. This can be difficult to model with a parametric method of low order. For the spectrogram of 4, the order of the AR model needed to be 75 (as compared to 35 in the WECC data where no forced oscillations were observed) in order for it to begin to match that of the non-parametric Welch periodogram. With the model order sufficiently high, the YW method did in fact begin to model a pole at approximately 0.45 Hz with 0.0% damping, further suggesting that this was a forced oscillation at 0.45 Hz and not an electromechanical mode. In Reference [27], oscillations near 0.4 Hz are reported as being first seen in the eastern system in 1991 and numerous subsequent observations. In all cases, the oscillation was lightly damped. Further analysis is required to confirm that this is the same oscillation observed in more recent data.

## 5. MODE ESTIMATION FOR THE NORDIC POWER SYSTEM

In this section PMU data obtained from two different substations of the Nordic power system located in Eastern Denmark are analyzed; their locations are shown in Figure 7. Data from the Radsted substation (RAD132, in Figure 7) were obtained during 03-20-2008 and 03-21-2008. Data for the Hovegård substation (HVE400, in Figure 7) were obtained during 04-15-2007 and 04-16-2007.

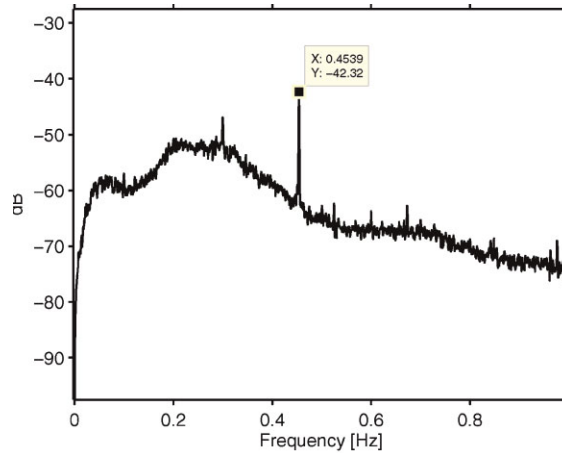


Figure 6. Welch Periodogram of long segment of EI data showing the 0.45 Hz oscillation.

The data are segmented in blocks of 10 minutes, and pre-processed for analysis. Active power flow signals are derived from the voltage and current phasors<sup>2</sup>, and bus frequencies are computed by taking the numerical derivative of the voltage angle. First linear trends are removed from these signals using the detrend algorithm. Because these analyses focuses on the inter-area mode range, a low-pass finite impulse response (FIR) filter with 2 Hz cut-off frequency is used to remove frequency components beyond this cut-off frequency. The data are downsampled to 5 Hz and a FIR high-pass filter with cut-off

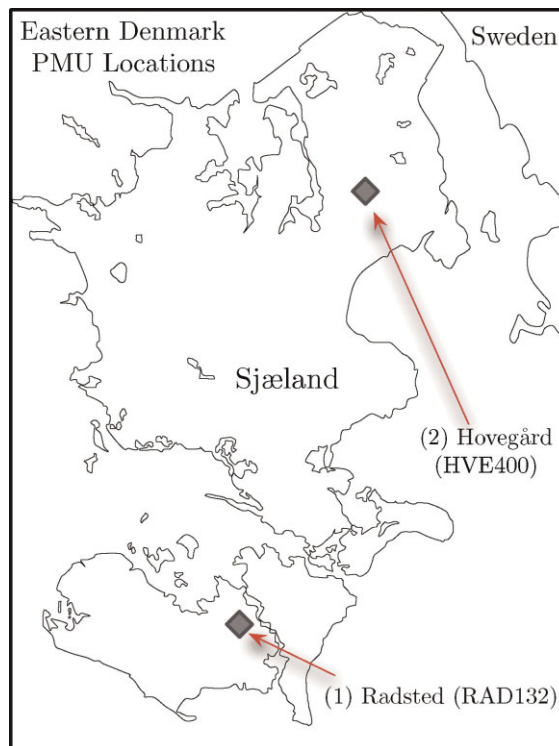


Figure 7. Eastern Denmark PMU locations.

<sup>2</sup>For convenience, pre-processed active power flow signals are denoted by  $P_i$ , where  $i$  is the line number from where measurements are made.



frequency of 0.1 Hz is used to remove frequency components related to governing control. To each 10-minute block of pre-processed data, the Welch and YW methods are applied. A summary of the signal processing tools used for these pre-processing steps is given in the Appendix.

First, the Welch method is applied to the pre-processed data to obtain estimated PSDs. We use 100 seconds for both the block segments and the number of FFT points used to calculate the PSD. To these segments a Hanning window with 50% overlap is applied. Figure 8b shows the estimated periodogram for the 10-minute data block in Figure 8a. Next, the YW method is applied. The estimated periodograms from Welch's method are used to refine the AR model order of the YW method by obtaining good agreement between the PSDs of both methods, while trying to maintain the model order as low as possible (in this case the order model is  $p = 40$ ). As a result, an excellent agreement was obtained between the PSDs estimated from each method. In Figure 8b the YW PSD is shown along with the one obtained by Welch's method. Notice the close agreement between both spectrum estimates.

Subsequently, both methods were applied to all the remaining signals from Radstead and Hovegård for a similar 10-minute block. Note that the estimates for Hovegård were obtained for a different date than those of Radsted. Common to all of the data sets were three dominant modes at approximately 0.36, 0.54, and 0.83 Hz, as indicated by the peaks in the spectra of Figure 8b. The presence of a low-frequency oscillatory component at approximately 0.277 Hz is discussed below.

Next, a time–frequency analysis for the whole 48-hour data set is performed, and the spectrograms in Figure 9 were obtained for the  $P_1$  signal, and in Figure 10 for the  $P_4$  signal of Radsted. For the  $P_1$  signal of Radsted, its Welch spectrogram is shown in Figure 9a, and its corresponding AR spectrogram in

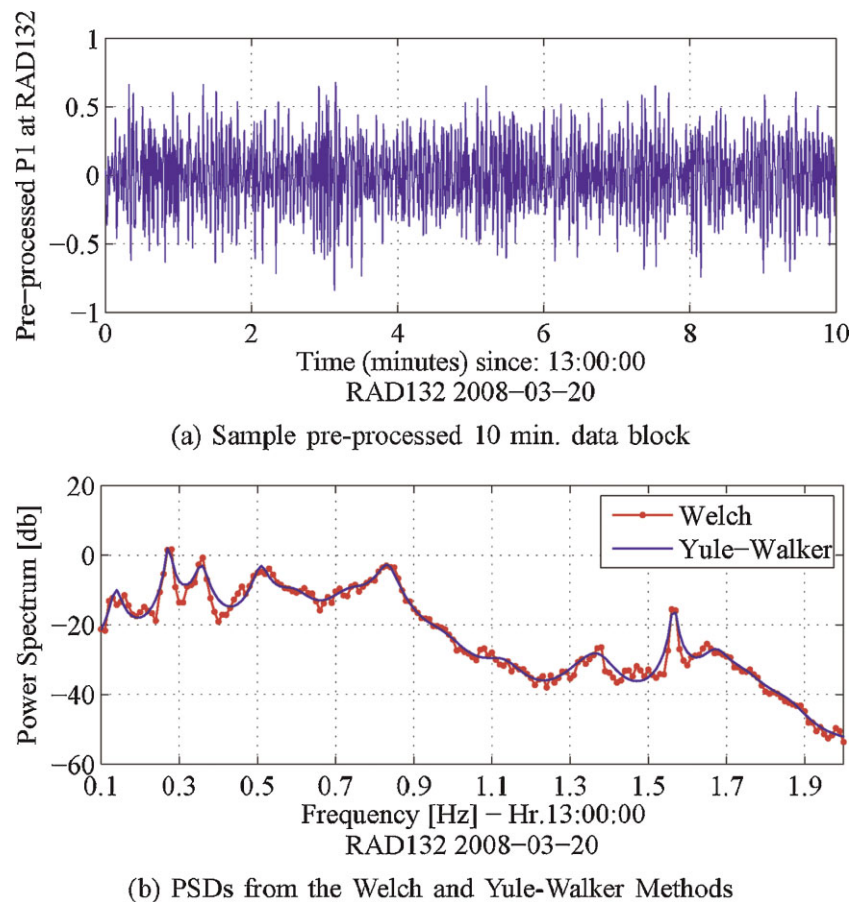


Figure 8. A pre-processed 10-minute data block of the  $P_1$  signal of Radsted, and its estimated PSDs using the Welch and Yule-Walker methods. (a) Sample pre-processed 10-minute data block (b) PSDs from the Welch and Yule-Walker Methods.

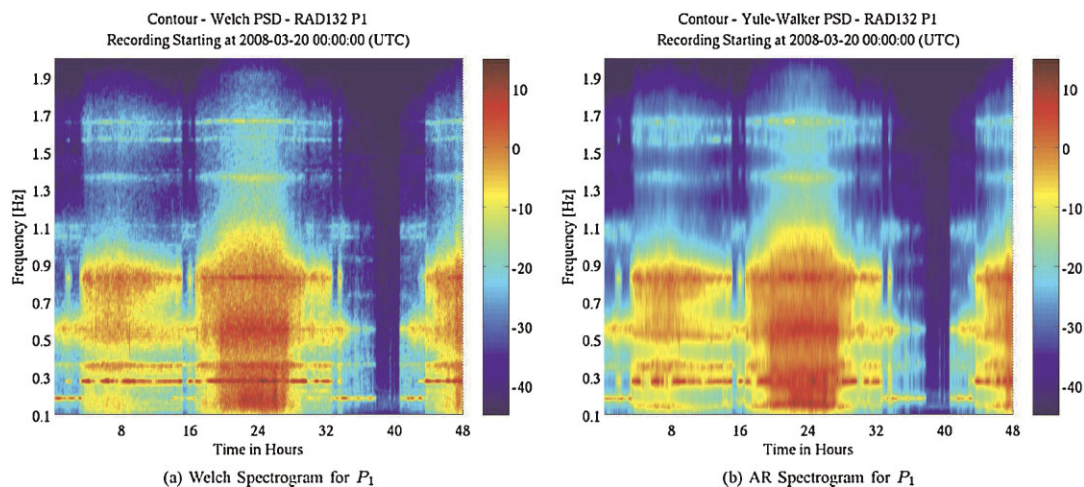


Figure 9. Welch and AR Spectrograms for the  $P_1$  signal from Radsted. The red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB]. The time is given in hours in (UTC) starting from 00:00:00 hours, local time is given in UTC + 1 hour. (a) Welch Spectrogram for  $P_1$  (b) AR Spectrogram for  $P_1$ .

Figure 9b. Observe the close agreement between both spectrograms confirming the existence of the modes discussed above. Similarly, the same modes were confirmed for the  $P_4$  signal by inspecting the spectrograms in Figure 10a and b.

The changing dynamics of the power system are revealed by the 48-hour spectrograms. Note that 03-20-2008 was a “typical day” (in terms of the power system loading), while 03-21-2008 was a national holiday with decreased loading. It is important to note that the frequency and damping ratio of the electromechanical modes are influenced by the system loading and configuration of the power grid. For example, Mode 2 (around 0.54 Hz) is present throughout 03-20-2008; however, it is not visible during the 32–42-hour segment (9:00 AM–7:00 PM in local time of 03-21-2008), which includes regular weekday working hours, it is likely that during this time frame there was a decrease on the system loading. It is interesting to observe that as a result of the different loading conditions, the frequency of Mode 2 varies during 0–32 hours. Similar behavior is observed by Mode 1 (around 0.36 Hz), and Mode 3 (around 0.83 Hz). The reader might be misled by the “blur” which appears around 24 hours in Figures 9 and 10 which is a result of the selected range of the temperature bar giving the coloring to the

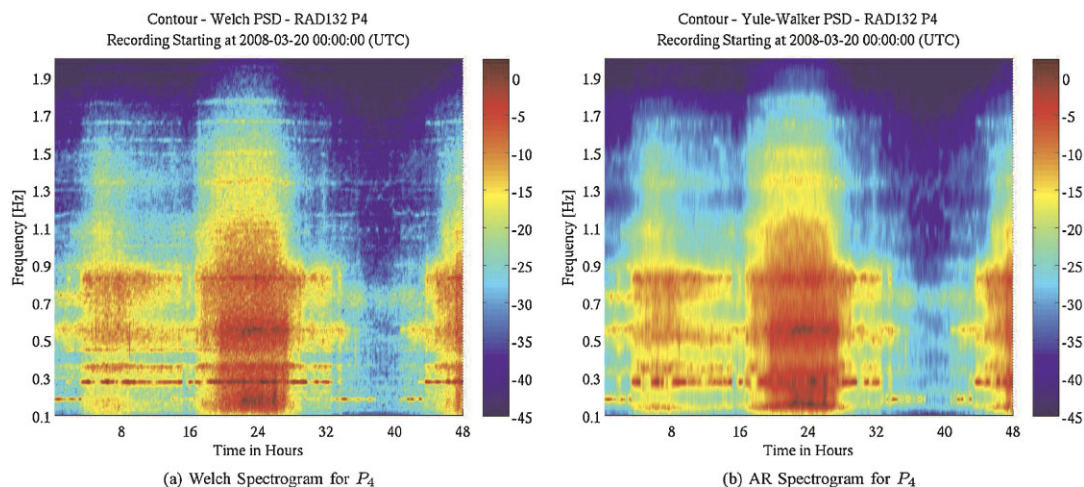


Figure 10. Welch and AR Spectrograms for the  $P_4$  signal from Radsted. The red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB]. The time is given in hours in (UTC) starting from 00:00:00 hours, local time is given in UTC + 1 hour. (a) Welch Spectrogram for  $P_4$  (b) AR Spectrogram for  $P_4$ .

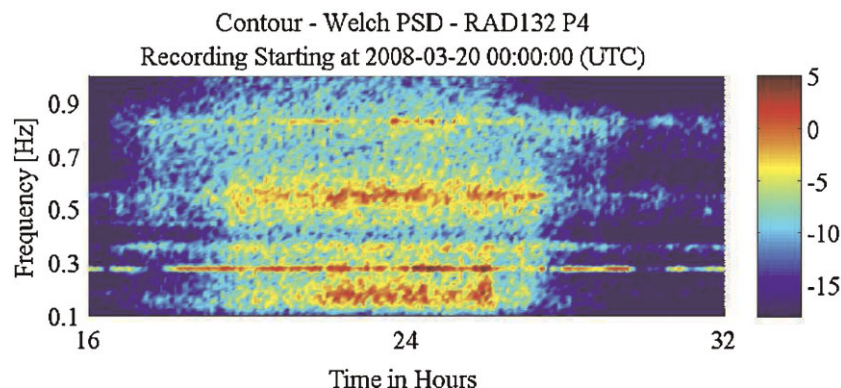


Figure 11. Enlargement of Figure 10a for  $t = [16-32]$ , centered at 24 hours. Note that the range for temperature bar has been also modified.

spectrogram. To clarify, in Figure 11, we show an enlargement of Figure 10a for  $t = [16-32]$ , centered at 24 hours and with a different setting for the temperature bar. Note that with this new range, the “blur” is not present longer and the modes discussed above can be clearly appreciated.

Close inspection of the Welch spectrograms for  $P_1$  and  $P_4$  (Figures 9a and 10a) reveals an important feature of this particular data set. As mentioned earlier, an oscillatory component is present at about 0.28 Hz. This component must be critically analyzed, and the Welch spectrograms serve to this purpose. The Welch spectrograms show that the 0.28 Hz component appears almost persistently at a very narrow band, centered at approximately 0.28 Hz, from hours 3–32 and 42–48. Also important to note is that the intensity of this component is quite consistent through the time frames mentioned. To further discuss the nature of this component, an enlargement of Figure 10a is shown in Figure 12.

Note that from Figure 12 the behavior of the 0.28 Hz component is much different from the one observed of Mode 1 where the mode has a broader variation frequency range and change of intensity. By inspecting 12, it becomes apparent that the 0.28 Hz component has a narrower and better defined frequency band.

The behavior shown by this 0.28 Hz oscillatory component corresponds to what is expected of a sinusoid or forced oscillation. A more careful inspection of the Welch spectrograms reveals that presumably another sinusoid is present at about 0.18 Hz for the time frames of 0–3, 32–37, and 40–43 hours. At this point, it should be realized that it is very likely that both of these components are harmonics of a fundamental sinusoid of 0.09 Hz. In fact, it is possible to observe traces of other harmonics in Figures 9a and 10a at  $n = 2-6, 8-13, 15-19,$  and 21, where  $n$  is the number of the harmonic, with corresponding harmonic frequencies of  $f_n = 0.18, 0.28, 0.37, 0.46, 0.55, 0.74, 0.83, 0.92, 1.02, 1.11, 1.20, 1.39, 1.48, 1.57, 1.66, 1.76,$  and 1.94 Hz. The origin of the sinusoid and its harmonics is unknown; it could be possibly due to a process in the system (as a control system going into a limit cycle), aliasing from higher frequencies, or communication or measurements issues. It is important to note that some of the

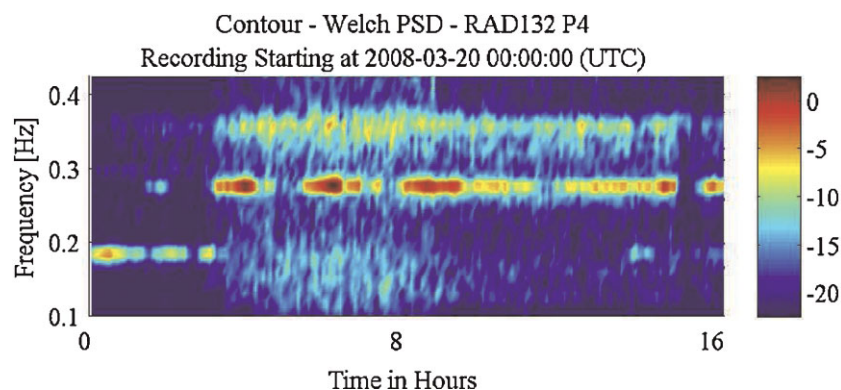


Figure 12. Enlargement of Figure 10a for  $t = [0-16]$  and  $f = [0.1-0.4]$  Hz. Note that the range for temperature bar has been also modified.

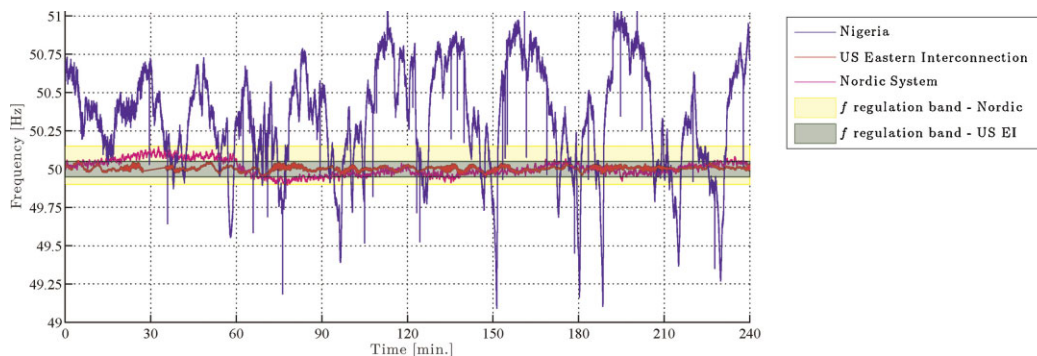


Figure 13. Comparison of the system frequency in different power systems over a 4-hour period. The steady state frequency at the US EI has been shifted by 10 Hz to coincide with the system frequencies of the Nigerian and Nordic networks.

sinusoid harmonics are superimposed over the “true” system modes. Regardless of their origin, these sinusoid harmonics will create difficulties to obtain accurate damping estimates of the true system modes. Mode meter algorithms [16] will have difficulties resolving the portion of the frequency spectrum that is due to ambient load variation from the portion due to the forced oscillations. This difficulty poses a new research challenge to improve the accuracy of mode damping estimates in mode meters.

## 6. MODE ESTIMATION FOR THE NIGERIAN POWER SYSTEM

### 6.1. A comparison of system dynamics observed from prolonged recordings

Differently from the power systems analyzed before, power systems constrained by insufficient generation capacity experience noticeable frequency changes when subject to disturbances or control actions. In these types of systems the primary concern is to maintain the load and generation balance, and therefore, frequency regulation is loose. Consider the frequency measurements taken for a time window of 4 hours as shown in Figure 13. This plot compares frequency measurements from two different types of power systems: a loosely regulated power system given by the Nigerian power system, and two tightly regulated power networks, the US EI and the Nordic Power System. The measurements of the US EI are derived from the voltage phasor angle of a PMU in the northern part of the EI, the measurements of the Nordic System were derived from the PMU in Radsted substation in Eastern Denmark, and the frequency measurements from Nigeria were obtained from a FDR [23] installed in Bauchi, Nigeria [28].

From these 4-hour recordings it is observed that the frequency regulation band in the US EI ranged from 59.95 to 60.05 Hz ( $\Delta f = 0.1$  Hz), while the frequency regulation band in the Nordic system varied from 49.9 to 50.15 Hz ( $\Delta f = 0.25$  Hz). Compared with these power systems, the frequency in Nigeria is loosely regulated with variations ranging from 49 to 51 Hz, a 1 Hz variation from the steady state of 50 Hz. In addition to the upper and lower bounds of frequency variation, it is also important to note that frequency can vary between these bounds in less than 10 minutes, with abrupt frequency changes of 0.4–0.5 Hz in 1 minute windows. In contrast, both the US EI and the Nordic System have a tightly regulated operation maintaining frequency variations closely between the frequency bands discussed above. Because the frequency variations in these systems are close to their steady state frequency, it is possible to obtain suitable “ambient data” for spectral analysis with standard pre-processing of the measurements as discussed in the previous sections.

### 6.2. Data pre-processing

Due the loosely regulated nature of the system frequency in the Nigerian grid, it is necessary to first condition the measurement data so that spectral analysis techniques can be applied. In Figure 14 a block diagram of a proposed pre-processing method is shown. Figure 15 shows the results of applying the method to a 10-minute data block from the Tuesday, January 23, 2007 (N17) recording.

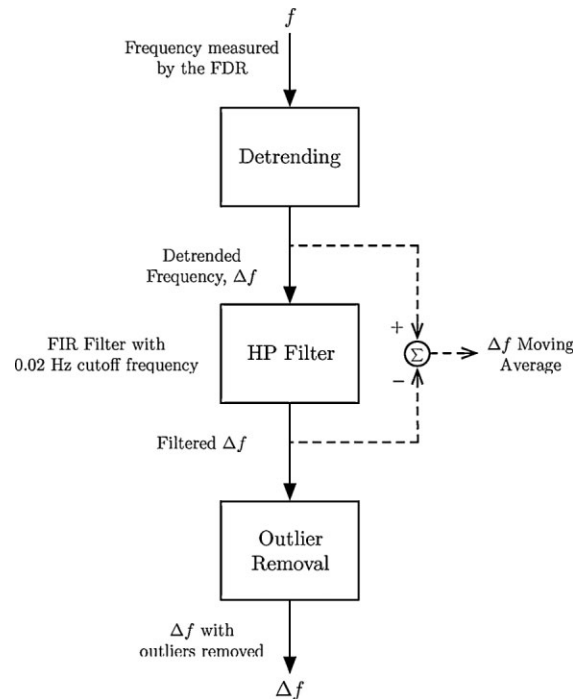


Figure 14. Proposed method for pre-processing FDR data from the Nigerian power system to be used in ambient data analysis.

The method starts by taking the raw frequency measurement from the FDR ( $f$ ) and removing linear trends from the data by using the detrend algorithm [24]. The result of applying this step to the 10-minute data block is shown in Figure 15a with a solid blue line (“Detrended Frequency” in the legend). The next step is to apply a high pass filter with cut-off frequency of 0.02 Hz to the data, which is shown by a red solid line in Figure 15a (“Filtered  $\Delta f$  Signal” in the legend).

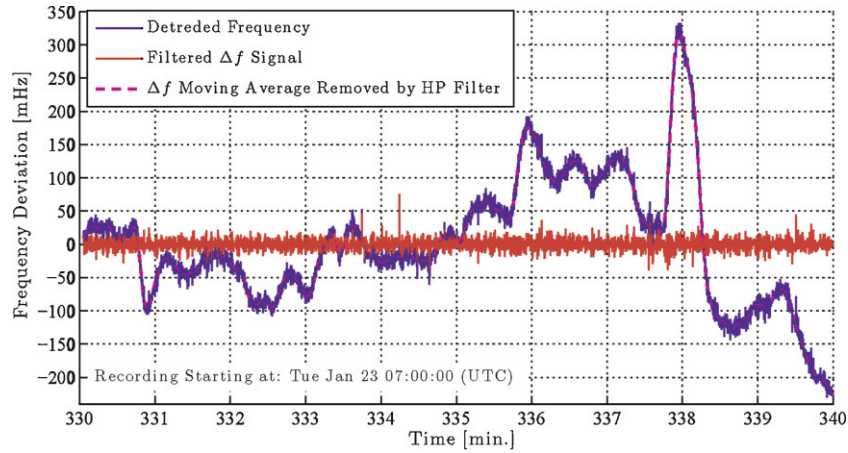
By applying this filter to the data, the moving average of the frequency, which corresponds to the slowest mode frequencies in the signals (below 0.02 Hz), has been effectively removed. In Figure 15 a magenta dashed line shows the moving average calculated by subtracting the “Detrended Frequency” to the “Filtered  $\Delta f$  Signal.” The frequency components removed by these steps correspond to the frequency of the process involved in balancing the load and generation in the Nigerian network. With this approach, we have obtained an ambient signal which consists of the electromechanical modes of the system.

The final step in the pre-processing method is to remove outliers from the filtered signal. To this aim the mean and standard deviation of the filtered signal are computed. Any point which exceeds the mean by 3.5 standard deviations is removed from the filtered signal. Figure 15b shows the removed outliers in red stems and the filtered signal with outliers removed in solid blue, the later is used for ambient data analysis. Next ambient analysis techniques are applied to prolonged frequency measurements from the Nigerian network, all of the data blocks involved in these calculations are subject to the pre-processing method described above.

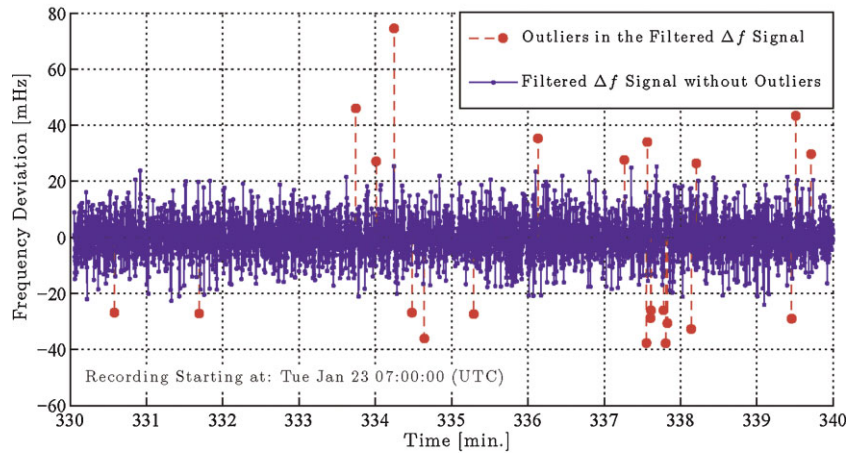
### 6.3. Mode frequency estimates

For this investigation, ambient data obtained during prolonged recordings resulting in data sets which range from 2 to 19 hours are used. Results are provided only for a subset of these data sets. Some of these data sets contained large gaps due to GPS signal loss. In addition, some portions of the data were corrupted by quantization errors, and thus removed for this analysis. The data are segmented in blocks of 10 minutes, and pre-processed with the method described in the previous section.<sup>3</sup> To each 10-minute block of pre-processed data, the Welch and YW methods are applied, and Welch

<sup>3</sup>For convenience, the pre-processed signals are denoted by  $\Delta f$ .



(a) Detrending and Filtering the frequency measurements



(b) Outlier removal and final  $\Delta f$  signal for 10 min. data block

Figure 15. Applying the pre-processing method to a 10-minute data-window from the Tuesday, January 23, 2007 (N17) data recording. (a) Detrending and Filtering the frequency measurements (b) Outlier removal and final  $\Delta f$  signal for 10-minute data block.

spectrograms and AR spectrograms are obtained. For the Welch method, 1000 points (100 seconds) data segments are used to calculate the FFTs involved in the averaging portion of the algorithm. To these segments a Hanning window with 50% overlap is applied. The AR model order used here is  $p = 30$ .

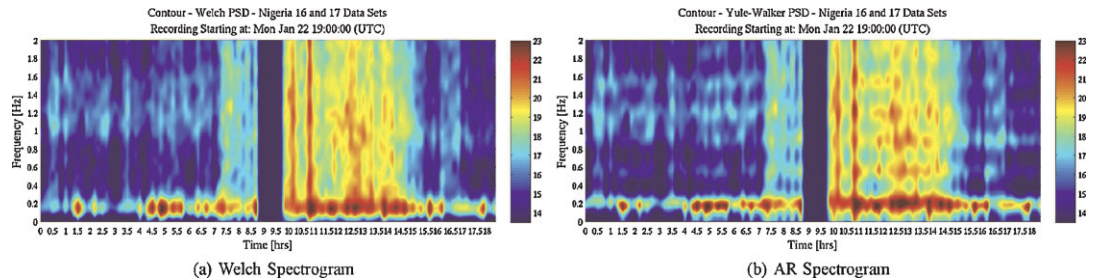


Figure 16. Welch and AR Spectrograms for the  $\Delta f$  signal obtained during Monday, January 22, 2007 and Tuesday, Jan 23, 2007 (N16 and N17). The red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB]. The time is given in hours in (UTC) starting from 19:00:00 hours, local time is given in UTC + 1 hour. (a) Welch Spectrogram (b) AR Spectrogram.

The resulting Welch spectrogram and the AR spectrogram shown in Figure 16. In the spectrograms, the red colors represent maximum values and the blue colors represent minimum values of the PSD [dB]. Note that the data sets N16 and N17 forms a continuous set of data recording, however between approximately 8.7 and 10 hours (shown as a blue band) there were quantization, GPS signal loss, and data drop issues. Therefore, the PSDs for this time frame were not computed and the PSD has been set to zero for all the frequencies within the time range.

The Welch spectrogram in Figure 16a clearly indicates the presence of a dominant inter-area mode with a mean frequency of 0.16 Hz ranging from 0.12 to 0.2 Hz. In this spectrogram, the variation of the modes with the system stress are quite noticeable with the modes showing large excitation between 10 and 15 hours, corresponding to 7–12 AM of Tuesday the 23rd, coinciding with the expected loading of the network for that given time range. Although both the modified (Figure 16a) and AR (Figure 16b) spectrograms suggest that two additional modes are present between 0.915–1.025 Hz and 1.15–1.3 Hz, further data analysis is needed to confirm this indication.

## 7. CONCLUSIONS

This paper has illustrated the application of ambient data analysis techniques for electromechanical mode estimation over multiple hours of data in four different power systems, and provided insight on how to critically analyze the results derived from these techniques. The WECC data analysis, showing the separation of Alberta, illustrates how these techniques are crucial for tracking the changing dynamics of inter-area modes in power networks. In addition, it is important to recognize that, as shown in the data analysis for the US EI and the Nordic Power System, ambient data analysis results should be closely examined for sinusoids or forced oscillations. The presence of these sinusoids will ultimately pose a challenge for mode meter algorithms to provide damping estimates, opening a further research window in this area. Finally, the data analysis of the Nigerian power system data is an interesting example of how to pre-process PMU data for ambient analysis to deal with difficult system dynamics.

## 8. LISTS OF ABBREVIATIONS

### 8.1. Abbreviations

AR	autoregressive
CSD	cross spectral function
EI	Eastern Interconnection
FFT	Fast Fourier Transform
FIR	finite impulse response
FRCC	Florida Reliability Coordinating Council
FDR	Frequency Disturbance Recorder
MIMO	Multiple Input Multiple Output
PMU	Phasor Measurement Unit.
PSD	Power Spectrum Density
WECC	Western Electricity Coordinating Council
YW	Yule Walker

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### APPENDIX A

A list of MATLAB and Signal Processing Toolbox commands for ambient analysis of PMU data is as follows:

- (1) *Pre-processing*:
  - (a) *detrend*: used for removing linear trends from a signal,
  - (b) *fir1*: used for designing low-pass and high-pass filters to remove undesired frequencies from the data,
  - (c) *filtfilt*: zero-phase digital filtering, used to filter low or high frequency components from the PMU data,
  - (d) *interp1*: used for linear interpolation through missing data.
- (2) *PSD estimation*:
  - (a) *pwelch*: estimates the PSD of a signal using the Welch periodogram,
  - (b) *pyulear*: implements the YW algorithm and computes the PSD of a signal,
  - (c) *hamming*: creates a hamming window for use with the *pwelch* function.
- (3) *Construction of spectrograms*:
  - (a) *surface*: by setting view (0, 90), this function can be used to construct spectrograms,
  - (b) *contour*: used to create spectrograms.

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