Estimation of the Nigerian Power System Electromechanical Modes using FDR Measurements

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***Abstract*—This paper reports on an ongoing research effort between researchers in North America and Africa on the study of the dynamics of loosely regulated and rapidly growing power systems, with focus on the Nigerian power network. A description of the implementation of Virginia Tech's FDR (Frequency Disturbance Recorder) at Bauchi, Nigeria is provided. We discuss the nature of the frequency dynamics observed throughout multiple hours of a day in Nigeria and other power systems. To cater to the loosely regulated nature of the system frequency in Nigeria, we propose an appropriate method for signal conditioning which prepares the data for ambient analysis. Parametric and non-parametric block processing techniques are applied to prolonged frequency recordings ranging from 8 to 19 hours, and estimates of modal frequencies and damping are obtained by computing power spectrum densities and applying a mode meter algorithm to the ambient data. The estimated modes from ambient analysis are in agreement with other studies based on power system models.**

***Index Terms*—frequency disturbance recorder, power system identification, power system monitoring, power system parameter estimation**

I. Introduction

Rensselaer Polytechnic Institute (RPI) and Abubakar Tafawa Balewa University (ATBU) have established a collaboration to study the dynamics of loosely regulated and rapidly growing power systems, with particular interest in the Nigerian power system. A frequency disturbance recorder (FDR) has been installed at ATBU and several recordings have been made. In two previous papers we have reported on FDR data analysis from disturbance events and proposed a university-based frequency monitoring network for the Nigerian power system [1], [2]. Here we focus on the estimation of electromechanical modes from prolonged frequency recordings using spectral techniques. First, we provide a summary of the implementation of the FDR at Bauchi, Nigeria, and analyze the nature of the system frequency over prolonged recordings. Compared to system frequency measurements of other interconnected power networks, the loosely unregulated nature of the Nigerian frequency posses a challenge for appropriately applying mode estimation techniques that have been used with data from tightly regulated power networks.

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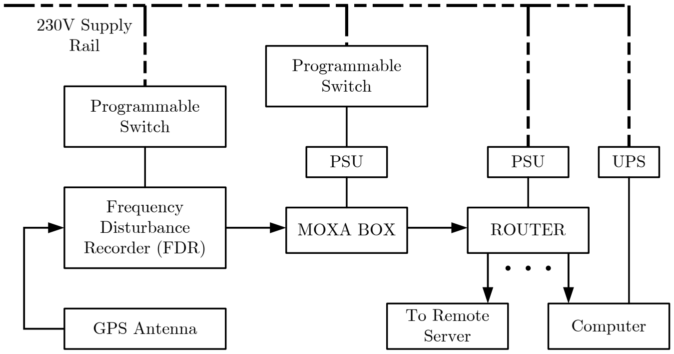
Spectral analysis techniques have been successfully applied to characterize the small signal oscillatory modes in the US WECC interconnection [3], [4] and more recently in the US Eastern Interconnection [5]. Ambient data analysis is used to estimate the inherent oscillatory modes of the power system 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" [6]. Non-parametric and parametric techniques, such as the Welch periodogram [7], [8], [9] and Yule-Walker method [10], [4], can be used to determine system modes, which are visible peaks in the spectrum estimate. Spectral estimates may also be used for mode shape estimation, the cross spectral function (CSD) can be used to estimate the phasing of the mode among the system generators, and coherency can be determined by the squared coherency function [11], [12]. 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. This study focuses on the application of block processing spectral techniques for mode estimation only. Due to the loosely unregulated nature of the frequency in the Nigerian network we propose a pre-processing method that prepares the data for use with the mode estimation techniques discussed above.

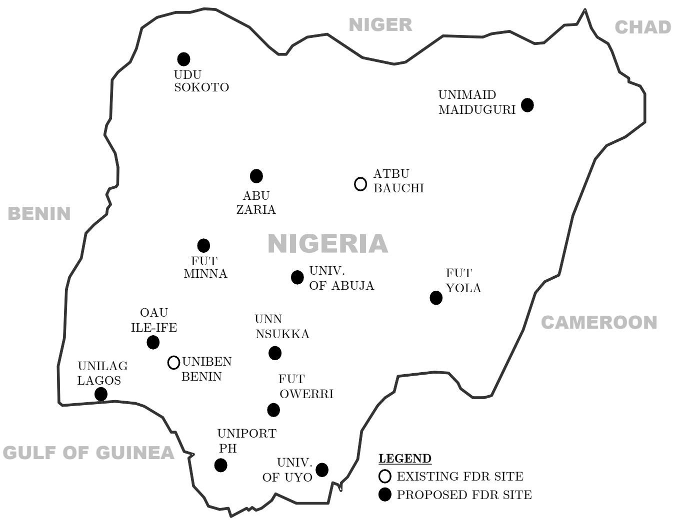
Finally, we compare the mode estimates obtained from ambient data analysis to those obtained from a model-based mode estimation study [13] which uses ringdown techniques on simulated data. Although the model used for this study is a simplified representation of the Nigerian power network, there is a good agreement for several of the modes estimated with ambient analysis techniques. Further studies will be needed to determine the nature of the modes that were not observed in the simplified Nigerian power system model. This paper should be seen as an initial step on developing techniques for electromechanical mode estimation that cater to the loosely regulated nature of the power system data obtained from rapidly growing power systems such as the Nigerian network.

II. FDR Implementation and Recordings

A frequency disturbance recorder (FDR) manufactured at Virginia Institute of Technology and State University was provided by researchers from RPI to ATBU researchers to obtain dynamic measurements of the Nigerian Power System. The FDR digitally records the voltage from a 230 V wall socket outlet. The voltage measurement is time tagged using GPS signals. From the voltage measurement, frequency is internally computed by the FDR. A data rate of 10 samples per second is captured with a personal computer and can be transmitted over the internet to the frequency monitoring



(a) ATBU FDR Installation Set-up



(b) FDR locations for the proposed FNET

Figure 1. FDR installation at ATBU, and proposed locations of additional FDRs that could enable a university-based frequency monitoring network

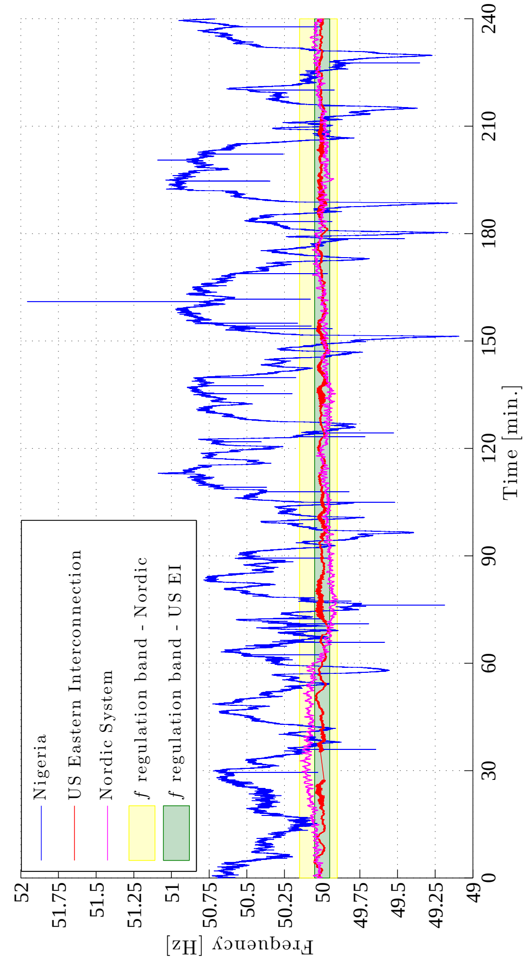


Figure 2. Comparison of the system frequency in different power systems over a 4-hour period. The steady state frequency at the US EI has been shifted by 10 Hz to coincide with the system frequencies of the Nigerian and Nordic networks.

network (FNET) server at Virginia Institute of Technology and State University VTech), Blacksburg, Virginia, USA.

Figure 1a shows the low-voltage power supply installation and data transfer set-up adopted by ATBU's researchers. The power supply for the FDR consists of a 230 V supply rail, two programmable switches, two PSUs (Power Supply Unit) and an UPS (Uninterruptible Power Supply). The programmable switches are used to switch on the FDR for scheduled data gathering. The PSUs are used to convert voltage and frequency from a 230V/50 Hz to a 110V/50 Hz supply. Note that the FDR was designed for operation at either power supply. The Ethernet devices (serial device server and router) used in the installation, however, are not designed for230V/50 Hz. The data transfer set-up consists of a serial device server (MOXA Box [14]) extracting data from the FDR through the serial port and sending it to a router. The router is enabled to send data to VTech's Information Management System (IMS) server and allows a dedicated PC to receive the information for local storage (local storage is preferred). The physical location of the FDR is shown in Fig. 1b along with the proposed locations of additional FDRs that could enable a university-based frequency monitoring network (FNET). A description of this proposed FNET is given in [2].

III. Frequency Dynamics Observed from Prolonged FDR Recordings

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 four hours as shown in Fig 2. 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 Eastern Interconnection (EI) and the Nordic Power System. The measurements of the US Eastern Interconnection are taken from a phasor measurement unit (PMU) in the northern part of the EI, and the measurements of the Nordic System where obtained from a substation in Eastern Denmark.

From these four hour recordings we observe that the frequency regulation band in the US Eastern Interconnection ranged from 49.95 to 50.05 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 full 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 min. 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 limited pre-processing of the measurements.

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. We discuss a methodology for this purpose in the next section.

IV. Mode Estimation from FDR Ambient Data

Ambient data analysis is 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" [6]. There is a significant array of different methods available to perform ambient data analysis [6]. Here, we limit the discussion to block processing non-parametric and parametric methods. Block processing algorithms can determine mode estimates from a window of data, each window providing a new estimate. Therefore, these methods require a large amount of phasor measurement data, and may not be suitable for real-time applications.

A specially robust non-parametric spectral estimation method is the Welch periodogram [7], [8], [9], which gives an estimate of a signal's strength as a function of the frequency. Here the dominant modes will be shown as significant peaks in the spectral estimate. This method is very insightful and uses limited assumptions. However, numerical estimates of the damping ratio and mode frequency are not directly provided. The most popular parametric method is the Yule-Walker algorithm [10], [4] 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 [6].

In this study we have used parametric and non-parametric algorithms, the Yule-Walker and Welch algorithms, respectively; to obtain spectrogram estimates of the *bus frequency* measurements at Bauchi, Nigeria. To obtain damping ratio estimates we use an energy technique implemented within a mode meter algorithm similar to [4], [6]. As a comprehensive discussion of the methods is beyond the scope of this paper, the reader is referred to the cited references for further details.

A. Data Pre-processing for Ambient Analysis

To cater to the loosely regulated nature of the system frequency of the Nigerian network we propose a method to pre-process the measurement data and obtain suitable ambient noise that can be used with the mode estimation techniques we described before. Figure 3 shows a block diagram of the pre-processing method, while Fig. 4 shows the results of applying the method to a 10 min. data block from the Tue, Jan. 23, 2007 (N17) recording.

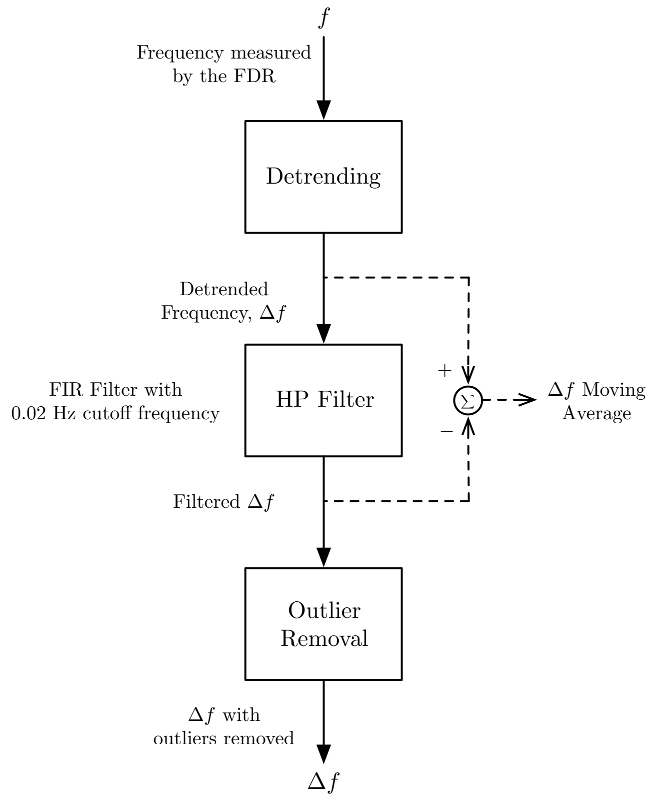
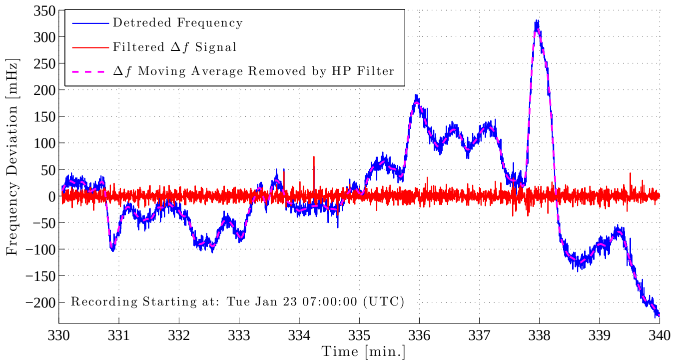


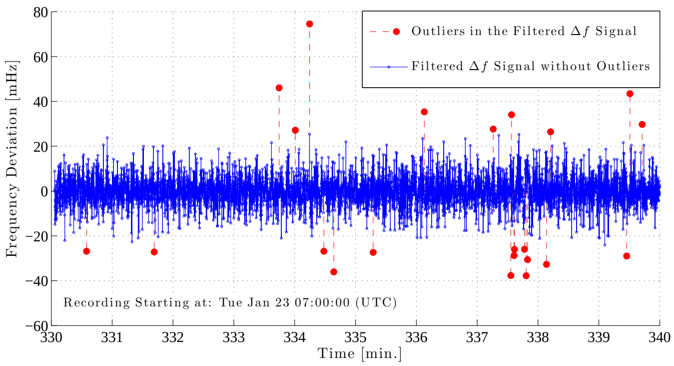
Figure 3. Proposed method for pre-processing FDR data from the Nigerian power system to be used in ambient data analysis

The method starts by taking the raw frequency measurement from the FDR (f) and applying a detrending algorithm [15] to remove the steady state bias from the data. The result of applying this step to the 10 min. data block is shown in Fig. 4a with a solid blue line ("Detrended Frequency" in the legend). The next step is to apply a high pass filter with cutoff frequency of 0.02 Hz to the data, this is shown by a red solid line in Fig. 4a ("Filtered Δf Signal" in the legend). By applying this filter to the data we have effectively removed the moving average of the frequency which corresponds to the slowest mode frequencies in the signals (below 0.02 Hz). In Fig. 4a we show in a magenta dashed line the moving average calculated by subtracting the "Detrended Frequency" to the "Filtered Δf Signal". The frequency components removed by this steps correspond to the frequency of the process involved in balancing the load and generation in the Nigerian network. Therefore, we have obtained an ambient signal which comprises mostly 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 we compute the mean and standard deviation of the filtered signal. Any point which exceeds the mean by 3.5 standard deviations is removed from the filtered signal (this point is not replaced by a zero). Figure 4b shows the removed outliers in red stems and the filtered signal with outliers removed in solid blue, the later is



(a) Detrending and Filtering the frequency measurements



(b) Outlier removal and final Δf signal for 10 min. data block

Figure 4. Appling the pre-processing method to a 10 min. data-window from the Tue, Jan. 23, 2007 (N17) data recording.

used for ambient data analysis. Next we apply ambient analysis techniques 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.

B. Estimated Power Spectrum Densities and Mode Frequency Estimates

For this investigation, we have used ambient data obtained during prolonged periods resulting in data sets which range from 2 hrs. to 19 hrs of continuous recording. We provide results only for a limited number of these data sets. Some of these data sets contained large gaps due to the loss of the GPS signal. In addition, some portions of the data was corrupted by quantization errors, and thus they where removed from the analysis. The data is segmented in blocks of 10 minutes, and pre-processed with the method described in the section above. [1] To each 10 min. block of pre-processed data we apply the Welch and Yule-Walker methods as described below.

We start by applying the Welch method to the pre-processed data in Fig. 4b to obtain its estimated periodogram spectrum. We use 150 points in the FFT to calculate the Power Spectrum Density (PSD) estimate. In addition, a Hanning window with 90% overlap is applied to the data. Figure 5 shows the estimated periodogram for the 10 min. data block in Fig. 4b.

Next, we apply the Yule-Walker method to the same block of pre-processed data. The estimated periodogram from Welch's method is used to refine the ARMA model order of the Yule-Walker method by comparing the PSD of both methods while trying to maintain the model order as low as possible. As a result, excellent agreement was obtained between the PSDs estimated from each method. In Fig. 5 we show the Yule-Walker PSD along with the one obtained by Welch's method.

Subsequently, we applied both methods to other 10 min. data blocks of pre-processed data from different dates in 2006 and 2007: Monday Jul. 3, 2003 (N02); Sunday Nov. 26, 2006, (N07); Tuesday Nov. 28, 2006 (N09), Saturday Dec. 02, 2006 (N13, N14); Monday Jan. 22, 2007 (N16); Tuesday Jan. 23, 2007 (N17); and Friday Jan. 26, 2007 (N19). We show all the estimated PSDs from the YW method in Fig. 6 where the dominant modes have distinctive peaks in the spectral estimate. Comparing all the PSDs we have determined eight dominant modes for the Nigerian power system that lie within the bounds shown in Fig. 6:

- Mode 1, 0.13 Hz with bounds of 0.12 - 0.2 Hz
- Mode 2, 0.40 Hz with bounds of 0.375 - 0.475 Hz
- Mode 3, 0.69 Hz with bounds of : 0.65 - 0.75 Hz
- Mode 4, 0.95 Hz with bounds of 0.915 - 1.025 Hz
- Mode 5, 1.20 Hz with bounds of 1.15 - 1.3 Hz
- Mode 6, 1.47 Hz with bounds of 1.4 - 1.55 Hz
- Mode 7, 1.74 Hz with bounds of 1.7 - 1.8 Hz
- Mode 8, 2.00 Hz with bounds of 1.95 - 2.05 Hz

[1] For convenience, the pre-processed signals are denoted by Δf.

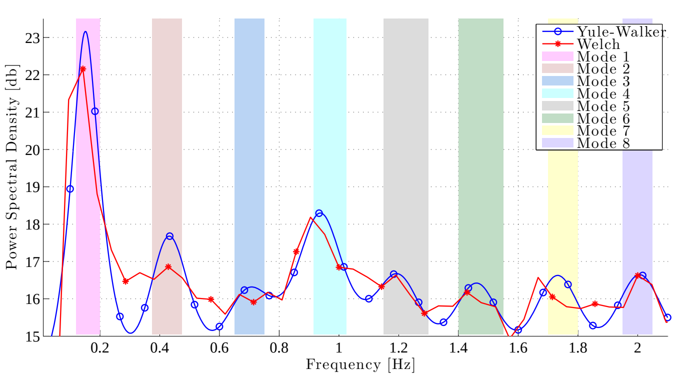


Figure 5. Welch and Yule-Walker estimated PSDs of a pre-processed 10 min. data block of the f signal measured by the FDR. The PSDs in this plot correspond to the Δf signal without outliers in Fig. 4b.

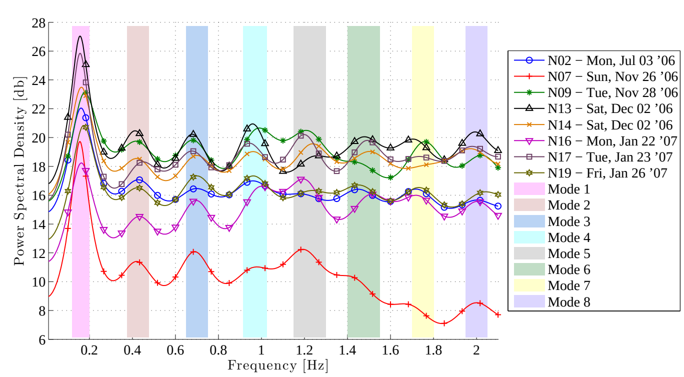
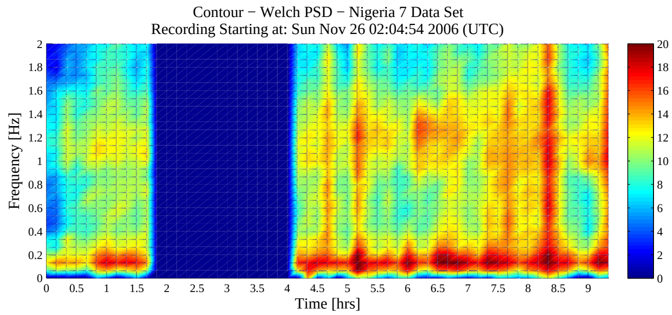
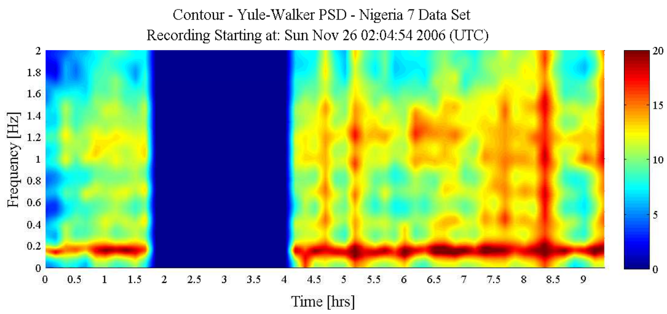


Figure 6. Yule-Walker PSDs for 10 min. data blocks of processed Δf signals from different measurement sets obtained in 2006 and 2007. The frequency bands show the modes that are common the recordings.

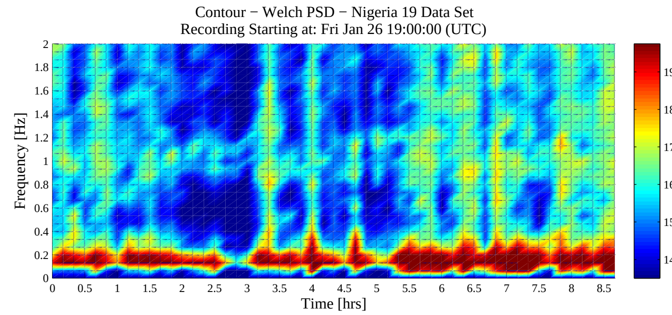


(a) Welch contour for the N07 data set

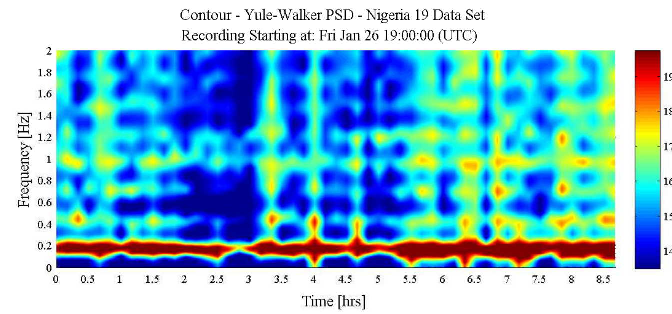


(b) Yule-Walker contour for the N07 data set

Figure 7. Welch and Yule-Walker PSD contours for the Δf signal obtained during Sun, Nov 26 ’07 (N07). 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 02:04:54 hrs, local time is given in UTC+1 hr.



(a) Welch contour for the N19 data set



(b) Yule-Walker contour for the N19 data set

Figure 8. Welch and Yule-Walker PSD contours for the Δf signal obtained during Fri, Jan 26 ’07 (N19). 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 hrs, local time is given in UTC+1 hr.

We repeat the process described above for all the 10 min. data blocks contained in the N07, N16, N17, and N19 data sets. As a result, we obtained the contours shown in Figs. 7, 9, and 8, respectively. Note that the data sets N16 and N17 form a continuous set of data recording. In the contours the red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB].

For the N07 data set the contour constructed with the PSDs from Welches’ method is shown in Fig. 7a, and the Yule-Walker contour in Fig. 7b. Observe that the Welch and Yule-Walker contours are in close agreement confirming the existence of the modes and bounds discussed above. The reduced mode frequency resolution in the Welch contours is a result of using large averaging in computing the PSD, however this does reduce the variability of the estimates. In the time frame from approximately 1.8 to 4 hrs the contours show a blue band, in this band there where data drops and quantization errors, and thus, we have not computed the PSDs for this time frame, i.e. the PSD has been set to zero for all the frequencies within the time range. 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. Even with the loss of data, the contour still aids in observing how the modes vary as the loading condition of the power system changes. Hour zero corresponds to 02:04:54 (UTC) (the local time is UTC + 1 hr.), the range from 5 - 9 hrs corresponds to 8:00 - 12:00 in local time. Hence, it is possible to see how as the loading of the power system increases, the modes become more pronounced.

Similarly for the N19 data set, the Welch contour is shown in Fig. 8a and the Yule-Walker contour in 8b. This contours cover the evening and night of a Friday where the system is subject to a less stressed operating condition, and hence the contours show a lower intensity on the modes (with the exception of Mode 1). Nevertheless, the modes and bounds discussed previously are also visible through this time period. From these contours it is important to note that all spectrum estimates are in agreement with regard to their dominant modes. Finally, we present the Yule-Walker contour for cases N16 and N17 in Fig. 9, which had a data gap between approximately 8.7 and 9.7 hrs. In this contour the variation of the modes with the system stress becomes more noticeable with the modes showing large excitation between 10 and 15 hrs., corresponding to 7 - 12 am of Tuesday the 23rd. This is consistent with the N07 data set where we observed a good degree of mode observability within that time window.

C. Mode Frequency and Damping Estimates

The Yule-Walker algorithm used above produced estimates for different modes. Some of these modes are true system modes, and others are numerical artifacts [6]. Here, we use a modal energy method to determine which modes have the largest energy in each of the ranges discussed above. An algorithm similar to the one reported in [4], [6] was used for this purpose.

In Fig. 10 and 11 we show the frequency and damping estimates for the Fri, Jan 26 ’07 (N19) data set. Similar results were obtained for the N07, N16, and N17 data sets. However we have omitted the corresponding plots due to space constraints. We plot the damping and frequency estimates

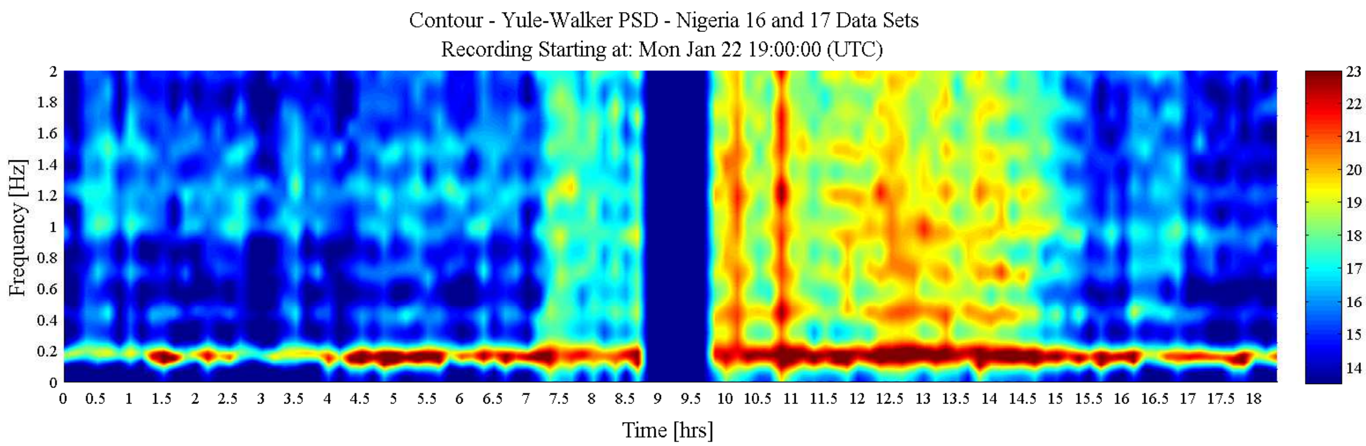


Figure 9. Yule-Walker PSD contour for the Δf signal obtained during Mon, Jan 22 '07 and Tue., Jan 23 '07 (N16 and N17). The red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB]. The time is given in hours in (UTC) starting from 19:00:00 hrs, local time is given in UTC+1 hr.

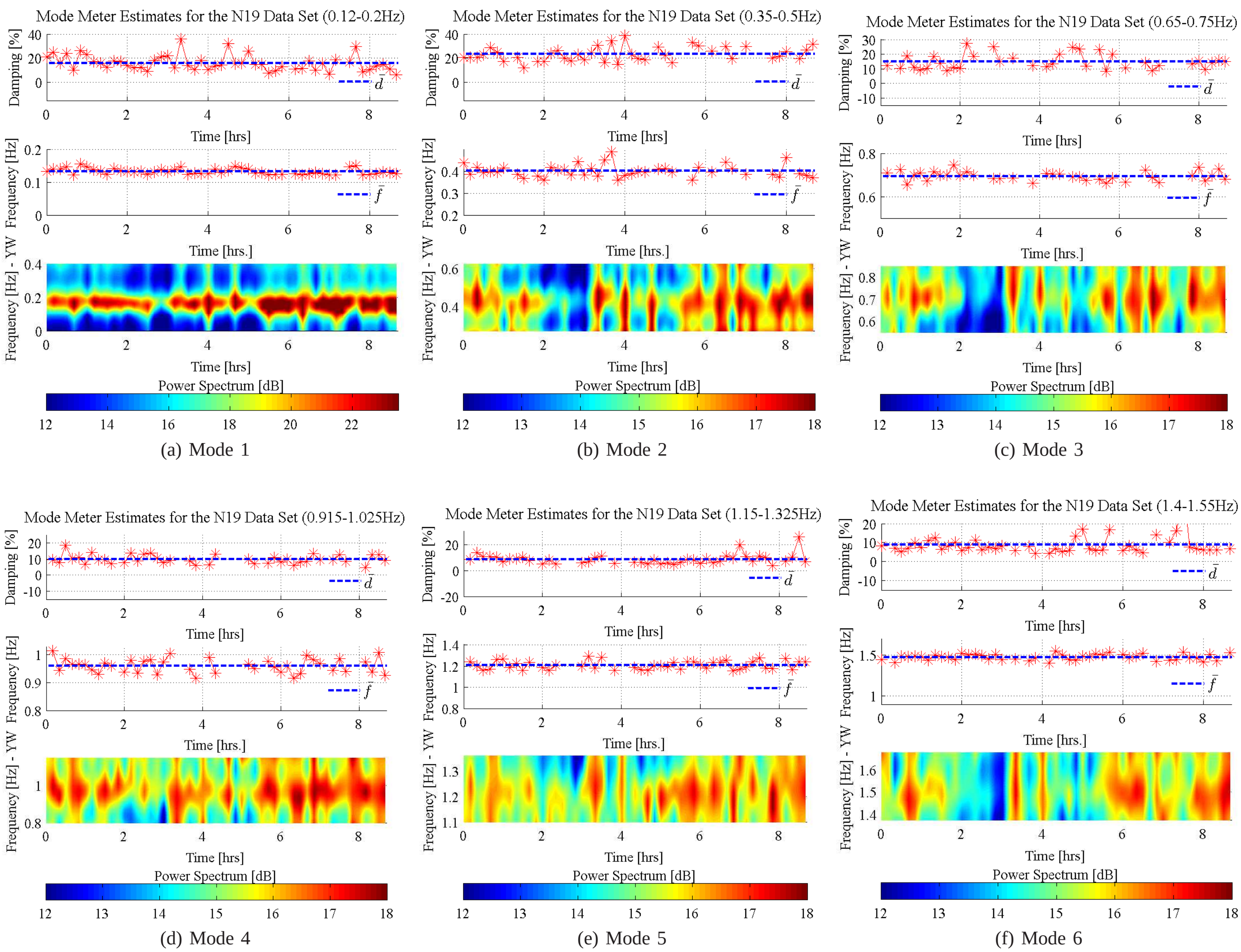


Figure 10. Mode frequency and damping estimates computed using the mode meter algorithm applied to the Δf signal obtained during Fri, Jan 26 2007. In the contours the red colors represent maximum values and the blue colors represent minimum values of the power spectrum density [dB]. The time is given in hours in (UTC) starting from 19:00:00 hrs, local time is given in UTC+1 hr.

Table I
MODE METER ESTIMATES FOR DATA SET OBTAINED DURING FRIDAY JAN. 26, 2007 (N19)

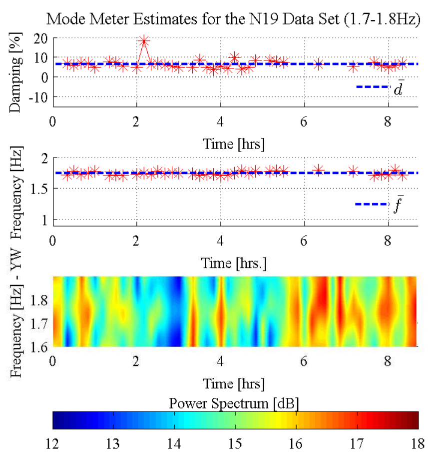
MODE	$\bar{f}$ (Hz)	σ_f	$\bar{d}$ (%)	σ_d
1	0.13212	0.00883	16.01679	6.43567
2	0.40013	0.02853	23.29541	5.90203
3	0.69430	0.02175	14.85070	5.20165
4	0.96062	0.02570	9.77720	2.78303
5	1.21054	0.03941	8.58043	3.89700
6	1.47489	0.03719	8.94971	6.27755
7	1.74164	0.02819	6.57345	2.49628
8	1.99151	0.02502	6.66627	6.75880

Table II
MODE METER ESTIMATES FOR DATA SET OBTAINED DURING SUNDAY NOV., 26, 2006 (N07)

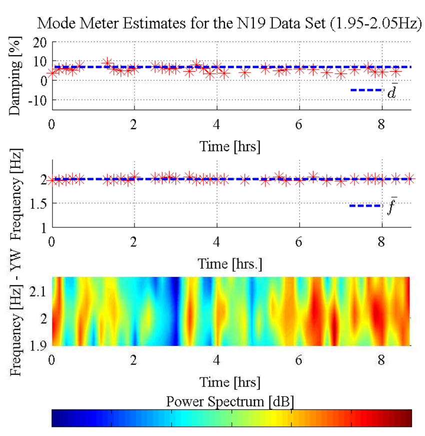
MODE	$\bar{f}$ (Hz)	σ_f	$\bar{d}$ (%)	σ_d
1	0.12896	0.00616	14.50442	5.49251
2	0.39317	0.02380	19.25457	5.57782
3	0.69352	0.02431	13.14500	3.46854
4	0.96624	0.02528	8.51961	2.57832
5	1.21058	0.03877	9.17073	8.84033
6	1.46013	0.04066	7.59083	4.41675
7	1.75755	0.02424	6.51783	1.67768
8	1.97501	0.02985	7.28166	5.57282

for each 10 min. block, and accompany them with their corresponding PSD contour from the Yule-Walker method. Observe that as a result of the load variation through the 9-hr. period the estimated frequency and damping ratio for each mode present changes. The most important characteristic to note is that the the damping estimates are less variable as the system becomes more stressed. In other words, the mode meter algorithm estimates are more reliable as the system stress is increased.

In addition, we have computed the average mode frequencies and damping estimates along with their standard deviations. We provide these statistics in Table I for Fri, Jan 26 '07 (N19) data set, and in Table II for the data set obtained during Sunday Nov., 26, 2006 (N07). Note that there is a close agreement in the mode frequencies and damping estimates computed for each different date.



(a) Mode 7



(b) Mode 8

Figure 11. Continuation of Fig. 10

The contour plots from Welch's method accompanying the mode frequency and damping estimates in Figs. 10 and 11 provide insight into the damping ratio of each mode. A broad frequency band in the contour as the one shown for Mode 2 in Fig. 10b (shown mostly in red between 0.35-0.5 Hz) corresponds to a high damping ratio, in this case the average damping ratio is between 19-24%. Conversely, a less distinctive frequency band will indicate a lower damping ratio. For example Mode 6 has slightly narrower frequency band approximately between 1.4 Hz and 1.55 Hz as shown Fig.10f (shown mostly in yellow and red). This band corresponds to a lower damping ratio whose average is between 7.5- 9%.

V. COMPARISON WITH ESTIMATED MODES FROM A SYSTEM MODEL

In [13] the authors have applied three different mode identification methods to determine the electromechanical modes of a simplified model of the Nigerian power system. Although this is a simplified model of the network, several of the modes identified in the study are also visible from the ambient data analysis presented in this paper. Estimates are provided for all the modes within the bounds defined in this paper, with the exception of Modes 2, 3 and 8 (0.4, 0.7, and 2 Hz). The damping estimates in [13] are more optimistic for Mode 1 which is determined to be the main interarea mode between hydro and fossil fueled generation areas.

Further analysis of a more elaborate power system model of the Nigerian power network will be necessary to determine the nature of Modes 2, 3, and 8 which were not present in the model-based study [13].

VI. CONCLUSIONS

We have reported on an ongoing collaborative research effort between researchers in North America and Africa to study the dynamics of loosely regulated power systems, with focus on the Nigerian power network. This paper focused on the application of spectral analysis techniques to ambient data obtained at Bauchi, Nigeria. Due to the loosely regulated nature of the Nigerian grid, we have proposed a methodology to condition the measurement data. With this methodology its possible to obtain ambient data suitable for use with ambient data analysis techniques.

Using parametric and non-parametric methods, we have computed eight dominant low-frequency modes that are consistent through several prolonged FDR recordings obtained during different dates in 2006 and 2007. The estimated modes are in close agreement with mode identification results obtained from a simplified model of the Nigerian power system. Further analysis of a more detailed power system model of the Nigerian system will be necessary to determine the nature of modes not present in the simplified model which where observed from the FDR data. In addition, the installation of additional FDRs will allow the creation of a wide-area frequency measurement network from which measurements can be obtained to compute the CSD, determine coherency, and obtain mode shapes. The results in this paper should be seen as an initial step on developing techniques for electromechanical mode estimation that cater to the loosely unregulated nature of the power system data obtained from rapidly growing power systems such as the Nigerian network.

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