Application of Wide Area Power System Measurement for Digital Authentication

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***Abstract*—The Electric Network Frequency (ENF) analysis of a digital recording is a two-step process. First, an ENF extraction algorithm is applied to the recording and the second step is comparing the extracted target sequence to subsequences contained in a grid reference database. In this paper, a new comparison algorithm is created that can remove the effects of oscillator errors from comparisons. Another study is to have a better understanding of the phenomenology by which sinusoidal grid signals find their way onto digital recordings. In addition, a study that uses both frequency and phase angle is done to determine whether tampering has occurred in digital recordings. Besides being able to determine the recording time, a study that distinguishes the frequency from different locations is performed to possibly determine the location of the recording.**

***Index Terms*—Power system measurement, Electric network frequency, Digital recording, Frequency localization.**

I. INTRODUCTION

The so-called Electric Network Frequency (ENF) Criterion is based on an observation made by Grigoras [1] in 2003. This observation concerns a "hum" that is frequently found in digital recordings. In his 2003 paper Grigoras showed that this hum is related to the sinusoidal voltage signal that runs through electric power grids. This sinusoidal voltage signal is approximately constant across the whole grid. The importance of this observation comes from the fact that the frequency of this grid sinusoidal voltage signal, at any instant of time, is dependent on the amount of power being generated and the amount of power being consumed across the grid. Since the amount of power that is consumed at any instant of time is random, a sequence of the frequencies of this hum will be a random process. Consequently, given the "uniqueness" of patterns that occur in random processes, it ought to be possible to extract a frequency sequence from a recording, the target recording, and compare this frequency sequence against a database of grid reference frequencies to determine the time when a recording was made.

The two step process proposed by Grigoras makes up what will be called the ENF analysis process. The first step, where frequencies are estimated from the target recording, will be called the ENF extraction step. The output of this step is the target sequence. In the second step, this target sequence is compared to subsequences from a grid reference database. This step usually involves some type of distance measure. The subsequence of the grid reference database which has the minimum distance (maximum distance) to the target sequence is considered to be the "matching" sequence in the grid reference database. The time that the matching sequence occurred is considered to be the time that the target recording was made. This whole process of taking the target sequence generated by the ENF extraction step and creating a "match" with a subsequence in the grid reference database will be called the ENF comparison set.

Since the ENF Criterion was first proposed, numerous papers [2-5] have been written on using this methodology for doing forensic authentication of digital recordings. Since there are relatively few tools for doing the forensic examination of digital recordings, the ENF Criterion seemingly represents a valuable new tool for doing this authentication.

The goals of this research are to improve the understanding of the whole ENF analysis process using the synchronized, widely deployed, and high resolution FNET system [6-9]. To this end four research studies have been conducted. These studies have resulted in the following:

- A new ENF comparison algorithm that removes the effects of oscillator error [10].
- A better understanding of the phenomenology of how grid sinusoidal voltage signals get imbedded into digital recordings [11].
- An ENF based algorithm for detecting tampering in digital recordings [12].
- A frequency localization study that may determine the location when the digital recording was made.

The rest of this paper is organized as follows. Section II gives an overview of the four studies. The methods used in each study are presented in Section III. Section IV highlights

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some of the results. Finally, the conclusions of this work are given in Section V.

II. OVERVIEW

In this section, each of the four studies is briefly described.

A. Removing the Effects of Oscillator Error from ENF Comparisons

Oscillators power all digital recorders. They are the fundamental element in the clocks that is used to time when analog-to-digital conversions are made. Most oscillators do not run exactly at their specified frequencies. These timing errors affect both the values of the frequency estimates as well as the times between frequency estimates. In fact, a number of investigators have observed offsets between the frequencies making up a target sequence and the frequencies making up grid subsequences. While the investigators seemingly did not know it at the time, these offsets were caused by oscillator errors. To address these offsets, one of these investigators suggested using the correlation coefficient as the comparison distance measure. The investigator did this because the correlation coefficient is seemingly insensitive to oscillator error. However, it has other problems associated with its use, e.g., it is not really a metric under the standard mathematical definition of this term. Consequently, it was decided that a different approach was needed to remove these errors. This led to the creation of a new comparison algorithm, one that can remove the effects of oscillator errors from comparisons. The algorithm developed is an iterative nonlinear least squares method that attempts to overlay a target sequence on a grid reference subsequence. It is called the Oscillator Error Correction/$d_{\overline{\sigma}}$ Metric algorithm. This algorithm was implemented and tested. It always converged when using it in millions of comparisons that were made.

B. Phenomenology of ENF

The phenomenology by which sinusoidal grid voltage signals find their way onto recordings made using battery powered digital recorders is not well understood. A better understanding of this phenomenology might prove useful in creating yet other ways to forensically verify the authenticity of digital recordings. Consequently, a study was conducted that used varying strengths of electric fields, varying strengths of magnetic fields, and sound shielding to determine which had effects on the strength or signal-to-noise ratio (SNR) of the grid sinusoidal voltage signal that appear in recordings. Varying the sound level involved using sound silencing material to build a "soundproof" enclosure. Tests were conducted outside the sound enclosure and then inside the enclosures. Varying the electric field involved changing the charge across two parallel electrical plates. Varying the magnetic field involved changing the current that flows through a coil. Measuring instruments were used to gauge the intensity of the electric field and the magnetic field. A number of different battery powered recording devices were used in this study. To assure that the signal being observed was actually a grid sinusoidal voltage signal, frequencies were estimated from the recording, and the frequencies were compared with Frequency Disturbance Recorder (FDR) data [7-8]. Interestingly, these studies suggest that the primary source for ENF in recordings appears to be an audible hum that seemingly comes from grid powered devices.

C. Tampering Detection in Digital Recordings

Since this is a rather new area of research with few papers on the topic, a good starting point for this study seemed to be to determine which parameters to use, i.e., parameters that vary when insertions or deletions occur. The results of this study seemingly indicated that both frequency and phase angle usually change values at deletion points and at the start and stop points of an insertion. This then led to the creation of an improved algorithm for doing this type of analysis. This Discrete Fourier Transform (DFT) based algorithm uses both frequency and phase angle to determine whether tampering has occurred in a recording. It is believed that the use of both frequency magnitude and phase angle increases the "detectability" of both insertions and deletions.

The tampering detection algorithm created has a frequency and phase angle extraction step and a target sequence/grid subsequence comparison step. However, since both frequency and phase angle information are used, the grid reference database must contain not only frequency data but phase angle data as well. This means that the comparison methods used to compare target data to grid subsequence data must involve both frequency and phase angle. This resulting algorithm underwent rather extensive testing that included different lengths of insertions and deletions and with variations in both the frequency and phase angle as the insertion and deletion points. It is hoped that this work, over time, will lead to a greater theoretical understanding of the tampering detection problem. It certainly proved that both frequency and phase angle must be included in any detectability study.

D. Frequency Localization Using FDR Data

The capability of previous research to determine the recording location is limited to the size of one interconnected grid. It is desirable to have a better spatial resolution. With the widely deployed FNET system (over 120 units in U.S.), it provides a great opportunity to look into this topic. The FDR deployment map in the North America is shown in Fig. 1.

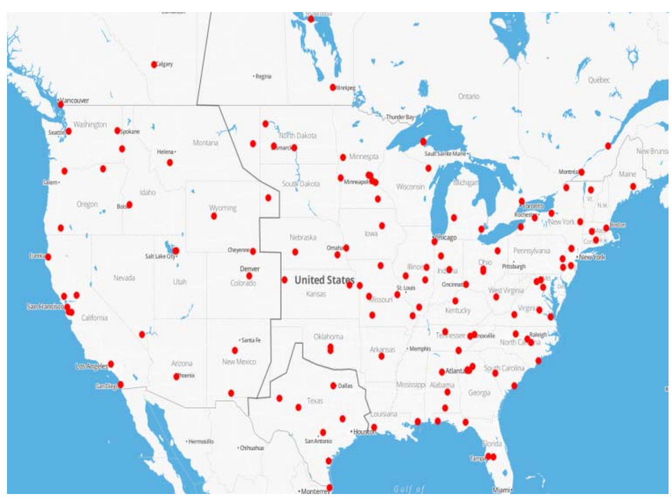

Figure 1. FDRs in North American power system

Variations among ENF signals within the same grid are due to the local load characteristics. These background noises at different places are recorded by the local frequency measurement devices such as FDRs. Thus by using the noise characteristics, the location of a target frequency signal can be identified by comparing it with historical data from different places. Wide area power grid frequency measurement system, such as FNET, can provide the historical data with high geography density and long time period, which can be used as a complete dictionary to identify the location of target frequency.

Three levels of spatial resolution, i.e., different states in one interconnection, different cities in one state, and multiple places in one city, are utilized to study the possibility of frequency localization.

III. METHODS

In this section, method used in each study is briefly presented.

A. Methods Used in the Oscillator Error Removal Study

This algorithm is based on an iterative Nonlinear Least Squares (NLS) procedure. The target sequence is modified. Then the distance between the modified target sequence and the subsequence of the grid reference data is computed. It will be called the deviation measure and will be denoted by $d_{\bar{\sigma}}$.

Both the estimated frequencies and time difference between consecutive frequency estimates, Δt, will be affected by the oscillator error. The NLS procedure attempts to make the value of $\bar{f}_T$, the average frequency of the target sequence, the same as the value of $\bar{f}_r$, the average frequency of the grid sequence. To do this the algorithm multiplies the value of $\bar{f}_T$ by a factor that is given by $\bar{f}_r/\bar{f}_T$. This same factor is used to correct the times. To do this, the algorithm divides Δt by this same factor. Doing so changes the time between consecutive frequency estimates to what it was measured to be, i.e., the correct value. After these corrections are made to the target sequence, the distance between the two sequences, i.e., the oscillator error corrected target sequence and the grid subsequence, is computed.

B. Methods Used in the Phenomenology Study

In the experiments studying the ENF source for battery-powered recordings, the procedure of confirming whether a recording has ENF or not is as follows:

1) Digital recordings are made in a non-laboratory environment, i.e., one without measures in place to attenuate electromagnetic radiation or sound waves.

2) The frequency spectrum of recordings is analyzed using an FFT (a 10-second moving window is used, then the results are summed and averaged). If a strong 60 Hz peak or a peak at a harmonic of this frequency exists, then the recordings may have ENF.

3) Extract the suspicious 60 Hz or its harmonic components using a short-time Fourier Transform (STFT) and compare the result with reference measurement data to confirm.

A number of experiments are conducted to study the effect of electric fields, magnetic fields, and audible hum on the grid sinusoidal voltage signals that appear in recordings separately.

C. Methods Used in the Tampering Detection Study

The method used in the new algorithm is a STFT-based approach. A STFT is a windowed Fourier transform where a signal is truncated by windowing function. This windowing function is moved through the signal in a manner that is specified by the hop size.

A coarse frequency estimation is firstly obtained using the STFT. Then a polynomial interpolation is applied. This procedure increases the frequency and phase angle resolution of the frequency and phase angle estimates. The procedure is then repeated for each frame until all the windows have been processed. After the frequency and phase angle are extracted from the audio file, the ENF is matched against the FNET frequency database using mean square error (MSE). Using both frequency and phase angle for tampering detection provides a more reliable detection.

D. Methods in Frequency Localization Study

To determine the location of the target signal, it basically needs two steps: 1) extracting the characteristics of the noise from target frequency, and 2) compare the extracted characteristics with historical data from different places. Therefore, a method needs to be developed to extract the characteristics of noises while filtering out the common part. In addition, a pattern recognition method needs to be used to identify the location of the target signal.

Here frequency domain analysis is employed to get the characteristics of signals. Due to the location dependent feature, the background noise shows different statistical characteristics in the frequency domain. To extract these characteristics, the “noise” is obtained by removing the common part, and then DFT is performed.

Neural network, as a novel and intelligent data analysis tool, can be used for pattern recognition. The frequency spectrum from historical data will be used to train the neural network, and the frequency spectrum of the target signal will be input into the trained network to identify its location.

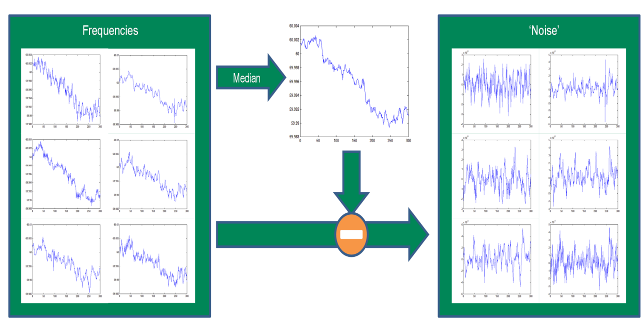

Figure 2. Approach of characteristics extraction

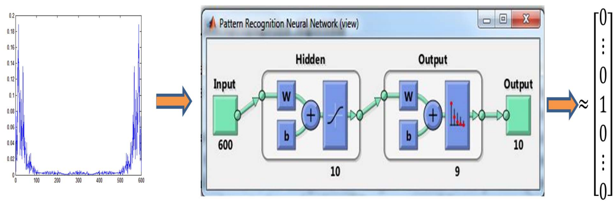

Figure 3. Approach of pattern recognition based on neural network

IV. Results

Some of the results from previous studies are highlighted and results of frequency localization study are shown.

A. *Results of Previous Studies*

Earlier studies have shown that grid frequency and phase angle data collected via FNET are able to match the frequency and phase angle extracted from digital recordings and voltage signals collected directly from electrical outlets as shown in Fig. 4 and Fig. 5.

These studies ranging from signal preprocessing, frequency and phase angle extraction and matching with reference database provide a solid foundation for future relevant work.

B. *Results of the Frequency Localization Study*

In the current study, the FDR data are used. Three levels of spatial resolution, i.e., different states, different cities in one state, and multiple places in one city, are utilized to study the possibility of frequency localization.

As the first step, the location identification ability of signals from different states is tested. Five cities of different states are selected in Eastern Interconnection (EI) and shown in Fig. 6. Frequency data recorded there are used as the historical data to train the neural network. A target signal from one of them measured at a different time is used to test if the developed technology can match it to the correct location of the five cities. 5-hour historical data are used to train the neural network. The target data length is 1 minute. Many samples of target data are tested to obtain the average matching ratio. Then, the localization area is reduced to a state (five cities of Missouri are selected) and same procedure is applied to obtain the results. Finally, five locations in the same city (Knoxville, TN) are tested.

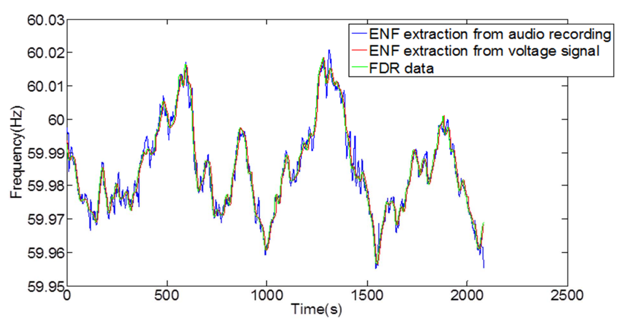

Figure 4. Power grid frequency data from audio recording and wall voltage signal at another location and FDR data from FNET

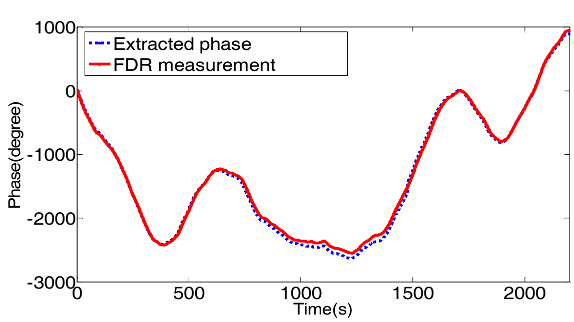

Figure 5. Comparison of extracted phase and FDR phase reference

For each of the three situations, different time intervals between target data and training data are considered, from 1 day to 2 years. This tested the effectiveness of the technology in different time scales. The results are listed in TABLE I.

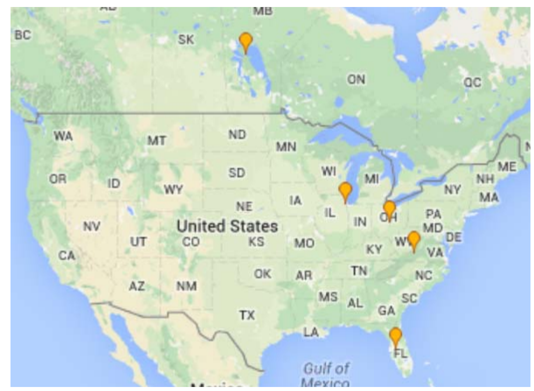

Figure 6. Location map of five states in EI

TABLE I. Matching Ratios for Frequency Localization

Area	Time Interval	Matching Ratio
Different states	1 month	99.3%
	1 year	80.0%
	2 years	72.2%
Different cities in the same state	1 month	94.9%
	1 year	24.7%
Different locations in a city	1 day	39.3%

It can be seen from the table that for different states scenario, the location of the target signal can be identified with a high matching ratio even if the time interval between the target and historical data is up to 2 years. However, the matching ratio decreases as the time interval increases. Thus recent data are preferred for the frequency localization study when they are available. Regarding different cities in the same state, the matching ratio of 1 month is lower, and the matching ratio of 1 year is too low to be useful. For the area as small as a city, the matching ratio even in one day is very low.

The reason is that in the same city, the background noise propagates to every outlet without too much attenuation. As a result, the frequency measurements show a very small difference between each other. That is, the “noise” extracted from the frequency is smaller than the resolution of frequency measurement devices which is ±0.1 mHz [13]. Therefore, the characteristics of different locations are submerged by the measurement uncertainty and thus cannot be distinguished. To identify the location within a city, higher measurement accuracy is required [14].

Though the location cannot be distinguished within a city, the results actually indicate that it is the local frequency characteristics of power grid rather than measurement unit difference that enable the distinguishability. Therefore, this technology is useful regardless of what measurement recording devices are used as long as they are accurate enough.

CONCLUSIONS

This paper presents an innovative application of wide area power system measurement for digital authentication using FNET system. Three research studies, i.e., oscillator error removal, ENF phenomenology, and tampering detection using both frequency and phase angle, are briefly reviewed and highlighted. Besides determining the recording time, a frequency localization study is performed to distinguish the frequency from different locations. Results show that the location of the frequency could be identified among states and cities. But it cannot be identified within one city.

Future work includes using different lengths of frequency data and extracted ENF for the localization study.

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