Tracking Periodic Voltage Sags via Synchrophasor Data in a Geographically Bounded Service Territory

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***Abstract*—Existing methods for synchrophasor data analysis focus on oscillations that can be interpreted as a sum of sinusoids with or without damping, however, they are more difficult to apply when considering other types of waveforms. This paper investigates how to apply spectral estimation analysis methods when analyzing a periodic voltage sag whose waveform is comparable to a periodic pulse train. A methodology is proposed where the estimated power spectral density and spectrograms are used to detect the area impacted by a periodic sag and to identify its dominant propagation path, which helps with the localization of the disturbance's spread. The proposed methodology is applied to measurement data obtained from a region in Dominion Energy's service territory that is geographically bounded by other utilities, which validates the effectiveness of the proposed method in a real-world utility setting.**

Keywords—periodic voltage sags, power spectral density, spectral estimation analysis, spectrogram, synchrophasor data.

I. Introduction

Wide area monitoring systems (WAMS) keep gaining interest from the power industry due through their potential to support grid reliability with measurement data-based analytics capabilities [1], [2]. The synchrophasor data provided by the phasor measurement units (PMUs) are synchronized time series with high temporal resolution and geographically diverse locations that enables advanced applications for diagnosing the system's operating conditions, e.g. analyzing system dynamic features by the oscillation analysis on ambient data [3] and post-disturbance (mostly ring-down) data [4], [5].

The dynamic features embedded in the measurement data can be visualized and analyzed in the frequency domain, even for the system response that presents nonlinearities like periodic square waves and pulse trains. For instance, spectral estimation allows a high resolution representation in frequency domain [3], [6], [7], while wavelet analysis allows to select basis for a finer time-frequency representation instead of only using sinusoids as basis [8]. In this paper, nonparametric spectral estimation is used to investigate the dynamics of periodic voltage sags, which have been recorded in Dominion Energy's service territory, and can be roughly characterized as a periodic pulse train waveform. Specifically, power spectral density (PSD) and spectrograms are used to convert the time-domain data to the frequency domain [9], where the dynamic features of periodic voltage sags are extracted and interpreted.

The dynamic features extracted by spectral estimation can facilitate disturbance tracking within a geographically bounded service territory. For system operation, it is common for each utility to only have observations over its own service territory. When the disturbances occur, operators need to use measurements from different substations to diagnose either the disturbance source within its service territory or the crucial tie lines that introduce the disturbance from external service territories. Then, the utility can determine to either improve its own operation schemes or collaborate with the external entities outside its own service territory to address the issue. The dynamic features captured by the spectral estimation methods enable such applications since they can be used to identify the disturbance propagation path and narrow down the disturbance source. Briefly speaking, by comparing the PSD from different measurement locations, both the impacted area and the dominant disturbance propagation path can be identified [10]–[12], which will provide important insights on narrowing down the possible disturbance source. In this paper, spectral estimation is applied to the periodic voltage sags observed in the Dominion Energy's power grid to show its potential in the disturbance analysis.

The remainder of this paper is organized as follows. Background on spectral estimation methods is given in Section II, where PSDs and spectrograms are discussed. How to use spectral estimation to identify the dominant disturbance propagation paths and narrow the disturbance source is discussed in Section III. Then, in Section IV, spectral estimation is used to identify the dominant propagation path of the periodic voltage sag from the measurement data of Dominion Energy's power grid. The conclusions and future works are discussed in Section V.

II. Spectral Estimation Background

The underlying periodical dynamical behaviors of a stochastic process can be characterized by estimating the power spectral density (PSD) in the frequency domain. A PSD can be viewed as a snapshot of the spectral density of a signal within a specific time frame. The comparison of PSD from different time frames and measurement locations can give insight for disturbance analysis, e.g. identifying the impacted area of certain disturbances, tracing the disturbance propagation path, and locating the disturbance source.

A. Nonparametric Spectral Estimation

Nonparametric spectral estimation can be used to directly estimate the PSD without explicitly assuming a model. The key is to explore the relation between the PSD, $S(f)$, and the autocovariance sequence, s_τ.

$$S(f) = \Delta t \sum_{\tau=-\infty}^{\infty} s_\tau e^{-i2\pi f\tau\Delta t} \tag{1}$$

where f is the frequency and Δt is the sampling interval. The autocovariance sequence s_τ is estimated from a zero mean stationary time series of N observations for $\tau = 0, \pm1, \ldots, \pm(N-1)$:

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

By substituting (2) into (1), the estimator in (3) can be obtained, which is commonly referred to as periodogram.

$$\hat{S}(f) = \frac{\Delta t}{N}\left|\sum_{t=1}^{N} X_t e^{-i2\pi f\tau\Delta t}\right|^2 \tag{3}$$

The periodogram cannot be directly used due its high variance and bias caused by spectral leakage. Several modifications have been proposed to obtain an estimator with better variance and bias properties, among which the Welch's spectral estimator is considered in this paper. The major steps to obtain the Welch's spectral estimator are listed below.

1. Split the original N observations into N_B overlapping blocks with N_S samples each.
2. Apply a data taper, h_t, on each block. To reduce the bias due to spectral leakage, it is recommended that every block is windowed with a Hanning data taper.
3. Obtain a periodogram for each block.
4. Average the individual periodograms together to form an overall spectral estimate.

The resulting spectral estimator will be given by

$$\hat{S}(f) = \frac{\Delta t}{N_B}\left|\sum_{j=0}^{N_B-1}\sum_{t=1}^{N_S} h_t X_{t+jn} e^{-i2\pi f t\Delta t}\right|^2 \tag{4}$$

where n is an integer specifying the amount of overlap between each block. Note that a smaller block size will lead to not just lower variance but also lower spectral resolution in the PSD. With appropriate selection of parameters, Welch's estimator can be expected to produce high resolution PSDs with low variance and low bias, without using significantly large amount of data. Consequently, the Welch's estimator will give a good indicator of the frequency of the oscillation modes within a signal.

A spectrogram is essentially a time-frequency representation. It shows how the spectral density of a signal varies with time, and thus, shows the variations of the frequency components. To obtain a spectrogram with reasonable resolution, the individual PSDs must be computed with relatively few samples. In this case, we use 10 minutes of data with a 90% data overlap between two successive PSDs.

B. *Spectral Analysis of Atypical Power System Dynamics*

When analyzed using the PSD, certain time domain dynamics show specific modal characteristics in the frequency domain. Of interest for this work, power system dynamics observed by measurements include lightly damped sinusoid-like oscillations and periodical voltage sags resembling a pulse train, as illustrated in Fig. 1. The PSD of those signals are shown in Fig. 2. For the sinusoidal signal of 1.0 Hz, a peak at the frequency 1.0 Hz appears in the PSD. For the pulse train of 1.0 Hz, harmonics w.r.t. the fundamental frequency 1 Hz appear in addition to the fundamental. In isolation, these signal characteristics can be easily explained, however, this is more complex when a signal couples the dynamics of the sinusoidal signal and the pulse train as depicted in Fig. 3. When decomposed in the frequency domain, as shown in Fig. 4, it is difficult to separate the sinusoidal content from the pulse train, which is the case when dealing with real-world measurements.

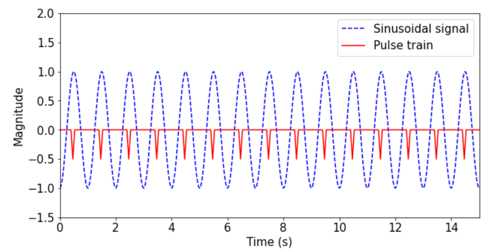

Fig. 1. Sinusoidal signal of 0.3 Hz and pulse train of 1 Hz in time domain.

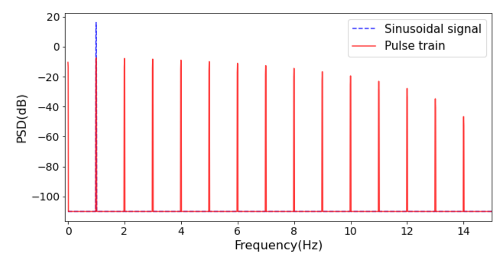

Fig. 2. PSD of the sinusoidal signal and pulse train in the frequency domain.

However, by analyzing the characteristics of the PSD in multiple locations, the dynamic behavior regarding a certain disturbance can be decomposed from the rest dynamics which reduces the difficulty in analyzing the disturbance and its propagation.

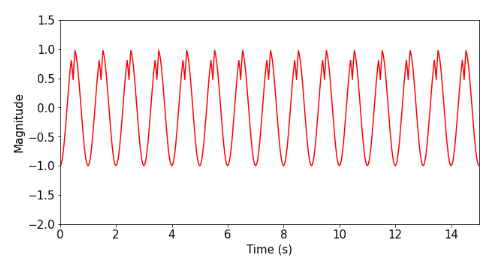

Fig. 3. Mixed signal in time domain.

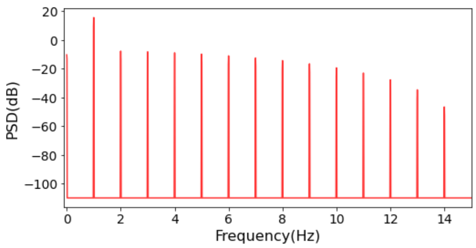

Fig. 4. PSD of mixed signal in frequency domain.

III. Spectral Estimation for Disturbance Analysis

A. Methodology

The spectrogram estimated for each measurement location allows to show the variation of the disturbance dynamics as the time evolves and across space. The locations of those measurements that show similar disturbance-induced dynamics can be classified as the impacted area. For a specific time interval, the severity can be computed and ranked by comparing the PSD values of those impacted measurements at the frequencies where the disturbance-induced dynamics appear. By doing so, the impacted area and the dominant disturbance propagation path can be identified, which will provide significant insights on how the disturbance penetrates in the network. 1. In fact, it is crucial to investigate all the relevant frequencies and not just the fundamental one because the PSD values at some of these frequencies may be potentially contaminated by the existence of other power system modes. Having a lower PMU sampling rate would potentially leave us with fewer frequencies to work with.

B. Disturbance Propagation Path

A power system disturbance propagates from its source to the neighboring substations via various transmission apparatus, which manifests in the variations in the voltage and current measurements from the impacted locations. Hence, the impacted area can be simply detected by applying the methodology outlined above on the voltage and current measurements and inspecting the dynamics exhibited in PSDs. Specifically, the spectrogram, of each measurement signal at each location, shows the variation of the disturbance dynamics as time evolves.

To identify the disturbance's propagation path, current magnitude measurements are used to track how the disturbance penetrates and spreads through different branches. The current magnitude measurements from different locations can clearly indicate the propagation path only if the disturbance propagates through the lines, otherwise it will not be observed for a current measurement where a line does not participate. In addition, at the system nodes, the current also indicates how disturbance-induced variations split or merge, following Kirchhoff's current law. The voltage magnitude measurements that can observe the disturbance-induced variations need to be used with care, some may not be on the propagation path as they may just passively follow the behavior of neighboring substations.

By investigating the spectral estimation of the current magnitude, the dominant disturbance propagation path can be identified as well as the related transmission devices. This is conceptually illustrated using the system in Fig. 5, where L1 and L2 are assumed to be stochastically varying loads with constant mean. Assume an unknown disturbance occurs in the proximity of load L1, and that the system remains under normal "ambient" conditions. In such case, the measured voltage of all the PMUs can observe the related dynamics, while only the measured current of PMU1 and PMU3 can observe the dynamics. Hence, the voltage magnitude measurement shows that the whole system is impacted by the disturbance, but the dominant propagation path identified by current magnitude measurement only includes the lines 3-4 and 1-2.

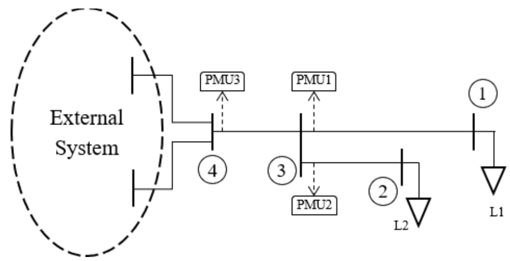

Fig. 5. 4-bus system

C. Disturbance Sources for a Geographically Bounded Service Territory

The identified propagation path can be used to narrow down the possible locations of the disturbance when other information is considered, e.g. system topology. This can also be illustrated with the previous scenario where disturbance occurs in the proximity of L1. Considering the system topology, the location of the disturbance can be narrowed down to the vicinity of load L1 because the measured current magnitude of PMU2 will likely not observe the dynamics of the disturbance.

A more relevant and practical scenario worth consideration is when the disturbance is introduced through the tie lines from the external system. In such case, all the PMUs can observe the disturbance and the comparison of PSDs on current magnitude can narrow down the disturbance source at the boundary Bus 4. Further, if only one of the tie lines connecting Bus 4 to the external system is the carrier of the oscillation, this will be also revealed by comparing the PSDs of the current from each line. While this is not the origin of the oscillation, for the transmission operator of this system whose observability is bounded by the geography of its service territory, the tie line represents the "source" within its system. This is critical information to understand where the disturbance enters the service territory and how it spreads. This understanding can enable the utility to deploy local means to minimize the impact of the disturbance. If this is not successful, this information would be crucial for collaboration with neighboring service territory is needed to keep narrowing down the disturbance's origin.

IV. Case Studies

To demonstrate the value of the proposed methodology, actual PMU measurements from the transmission system of Dominion Energy are taken under ambient system conditions. It is well known that the area under study experiences occasional voltage sag disturbances. This disturbance was first noted by field engineers and confirmed by performing spectral analysis, which showed the impact of periodical voltage sags every 1 minute. An anonymized excerpt of the single line diagram of the impacted area is shown in Fig. 6, due to security requirements, only a portion of the buses and the lines connecting those buses are shown. The subsystem is connected to the external system via the tie line connecting bus 1. The location of the installed PMUs and the power flow directions are also indicated. For the sake of convenience, each PMU is named as $PMU_{i\text{-}j}$ when placed on the line *i-j* on the side of bus *i*.

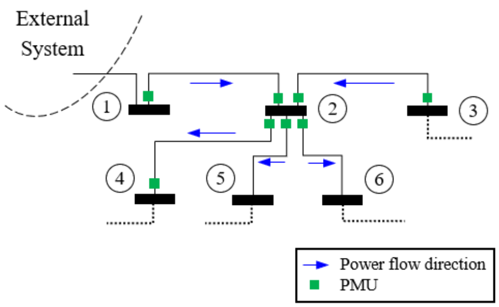

Fig. 6. Portion of Dominion's power network impacted by the voltage sags.

The data from 24 hours of a typical day in March 2021 is used to investigate the disturbance through the proposed methodology. Spectrograms of the voltage and current magnitudes at different locations show a set of harmonics with the fundamental frequency at around 0.167 Hz. For instance, the spectrograms of $PMU_{1\text{-}2}$ and $PMU_{2\text{-}5}$ within the frequency range of [0.05 Hz, 0.20 Hz] are given in Fig. 7 – Fig. 10. The harmonics are clearly shown the bright horizontal lines and appear during the entire day. The color denotes the oscillation energy in logarithmic scale.

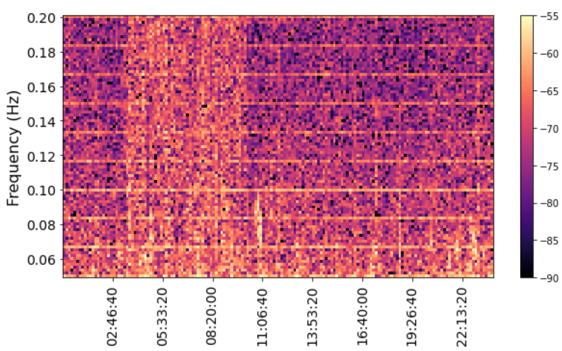

Fig. 7. Spectrogram on voltage magnitude of $PMU_{1\text{-}2}$.

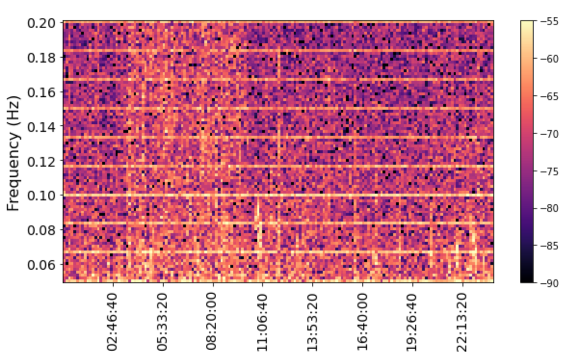

Fig. 8. Spectrogram on voltage magnitude of $PMU_{2\text{-}4}$.

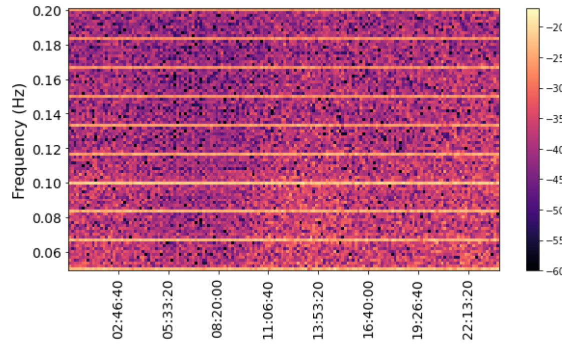

Fig. 9. Spectrogram on current magnitude of $PMU_{1\text{-}2}$.

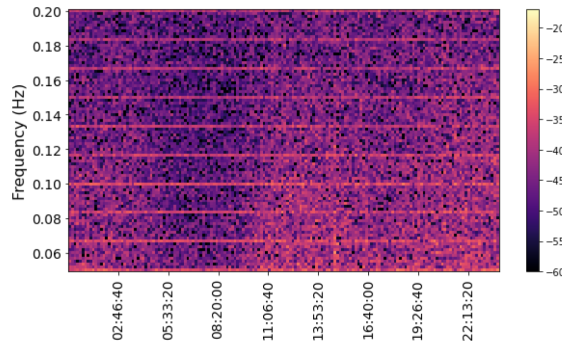

Fig. 10. Spectrogram on current magnitude of $PMU_{2\text{-}4}$.

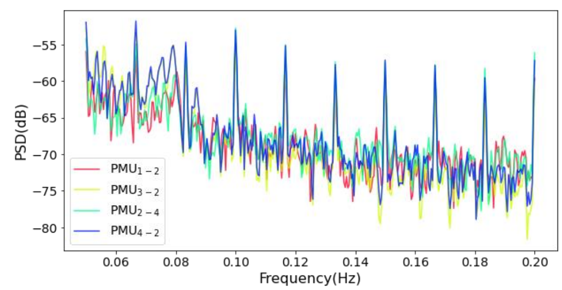

Fig. 11. PSDs from the voltage magnitudes within [0.05 Hz, 0.20 Hz].

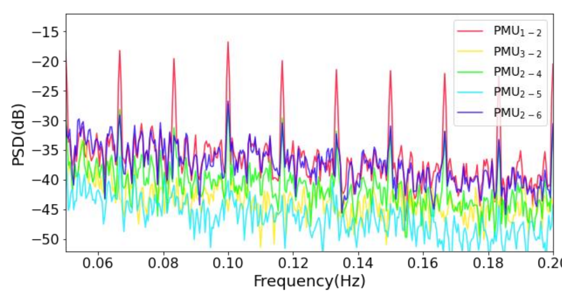

Fig. 12. PSDs from the current magnitudes within [0.05 Hz, 0.20 Hz].

For the sake of clarity, the PSDs of the sixth-order harmonic (at 0.1 Hz) are compared to inspect the impacted area and determine the propagation path. The PSDs from voltage and current magnitudes from all available locations within the range [0.097 Hz, 0.107 Hz] are shown in Fig. 13 and Fig. 14, respectively. Note that according to Fig. 13, all the buses are similarly impacted in terms of voltage magnitudes. However, in the case of the current magnitudes shown in Fig. 14, there are important differences in the severity of impact. Observe that the PSDs of $PMU_{3\text{-}2}$ and $PMU_{2\text{-}6}$ do not show a distinct peak at 1.0 Hz. Hence, only some of the lines are within the dominant path, which are shown in Fig. 15, marked in red and thicker line width.

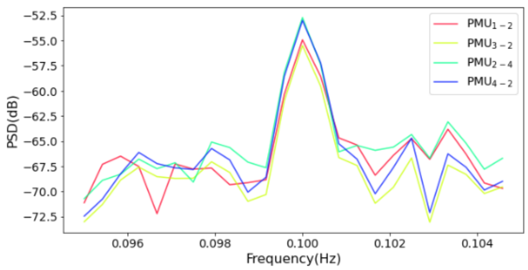

Fig. 13. PSDs from the voltage magnitudes within [0.093 Hz, 0.107 Hz].

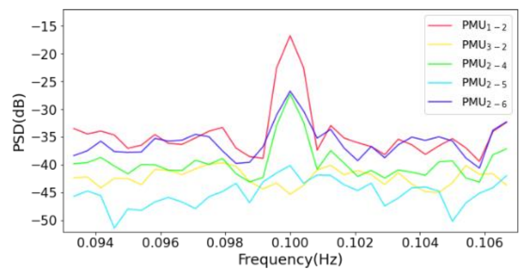

Fig. 14. PSDs from the current magnitudes within [0.093 Hz, 0.107 Hz].

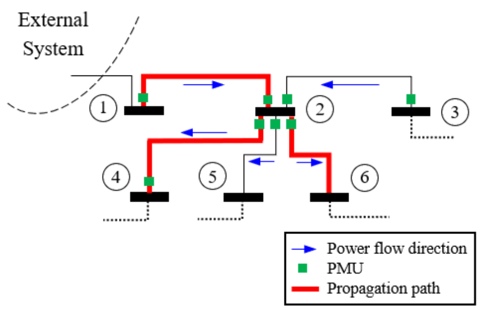

Fig. 15. Identified propagation path, marked in red and thicker line width.

Based on the comparison and ranking of PSDs, and the identified propagation path, it is possible to narrow down the disturbance source. Based on the comparison in Fig. 14, the line 1-2 is ranked as the one with the most energy. Observe that the total energy in line 1-2 is roughly divided among lines 2-4 and 4-6. From a geographically bounded service territory point of view, the disturbance source can be narrowed down to the tie line connecting bus 1 to the external system. From bus 1, the disturbance propagates to bus 2 through the line 1-2, and then, split up and propagate to bus 4 and 6. Outside of the service territory, the collaboration from other utilities is needed to identify the disturbance source or deploy local mitigation measures.

V. Conclusions and Future Works

Spectral analysis techniques transform time-domain measurement data to the frequency-domain. Methodologies can be developed in the frequency domain to extract information, such as exploiting PSDs, where the dynamics characterized by different frequency-domain features can be decomposed and investigated separately. In this work, a methodology based on spectral estimation is applied to investigate the dynamics of a periodic voltage sag observed by the real-world measurement data at multiple locations of Dominion Energy's power network. The impact area and the dominant disturbance propagation path identified allow to narrow down the disturbance's source, which in this case is geographically bounded by a tie line connecting the monitored service territory to the external system. Future works includes proposing a generic framework to apply the spectral estimation techniques for locating the disturbance sources across geographical bounds with inter-utility cooperation.

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