Spectrograms

A Tool for Data-Driven Dynamics Analysis

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Motivation

As power electronic converters replace synchronous generators, the fast dynamics of their feedback loops can lead to unstable oscillations, which can lead to power outages or damaged equipment.

In order to suppress these oscillations they must first be detected. In this talk I will describe the use of spectrograms for detecting oscillations in power systems.

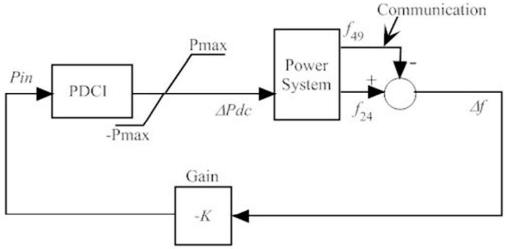


Fig. 3: PDCI control using relative frequency feedback.

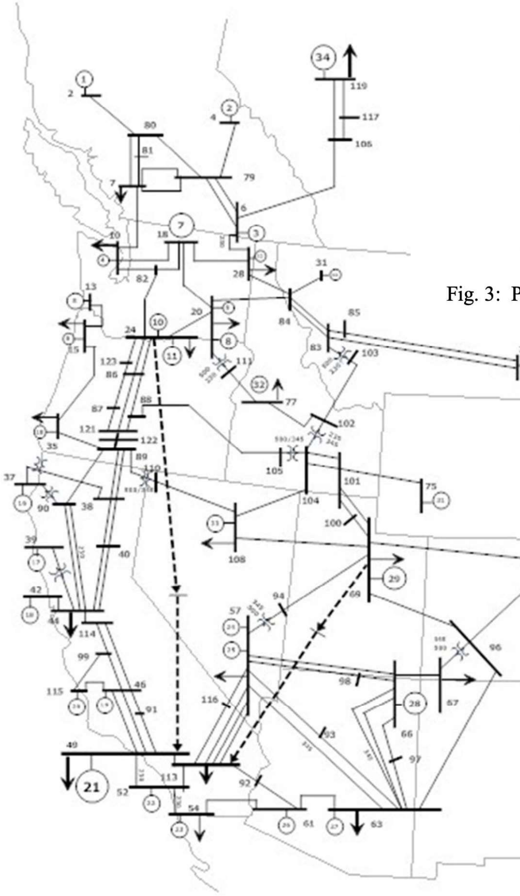


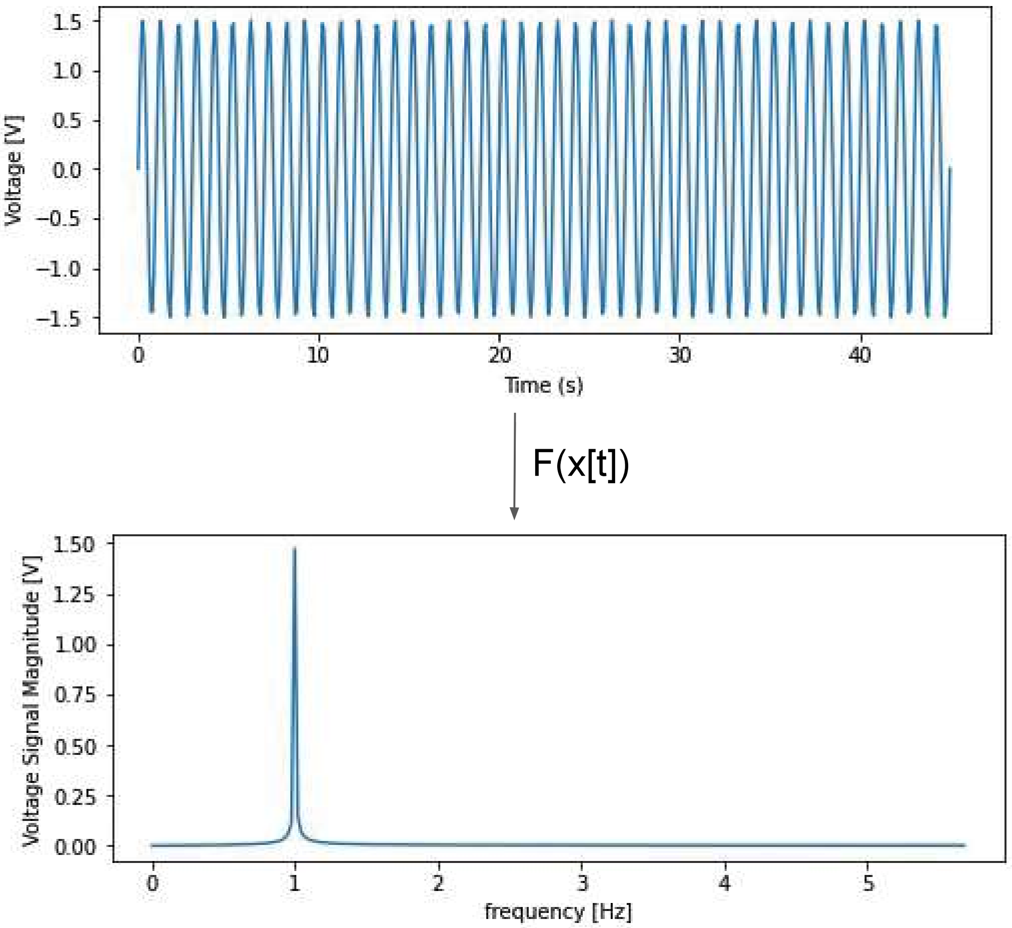
Fig. 1: High-voltage buses and lines of miniWECC model.

D. Trudnowski, D. Kosterev and J. Undrill, "PDCI damping control analysis for the western North American power system," 2013 IEEE Power & Energy Society General Meeting, 2013, pp. 1-5, doi: 10.1109/PESMG.2013.6672718.

Fourier Transform

The Fourier transform, F(x[t]) returns the frequencies present in a time-domain signal.

For example, a 1Hz sinusoid will have a single peak in the frequency domain.



Nyquist Frequency

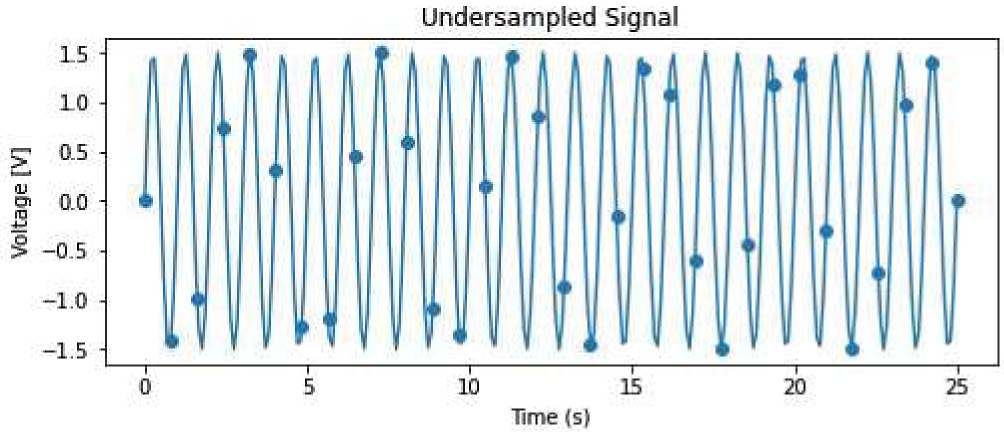
The sampling rate of your sensor must be at least twice the signal bandwidth.

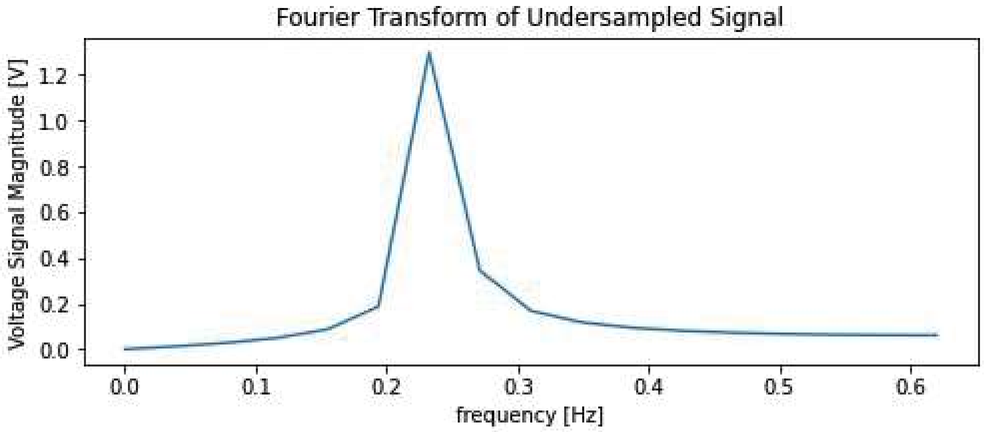
In this example, the sampling rate is

$$f_s = 1.2Hz < f_{nyquist} = 2Hz$$

So the Fourier transform does not report the correct frequency, **1Hz**.

This is an example of aliasing.

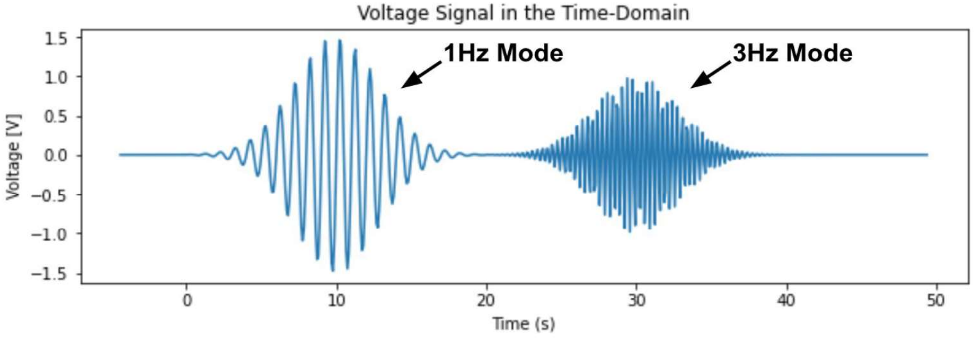


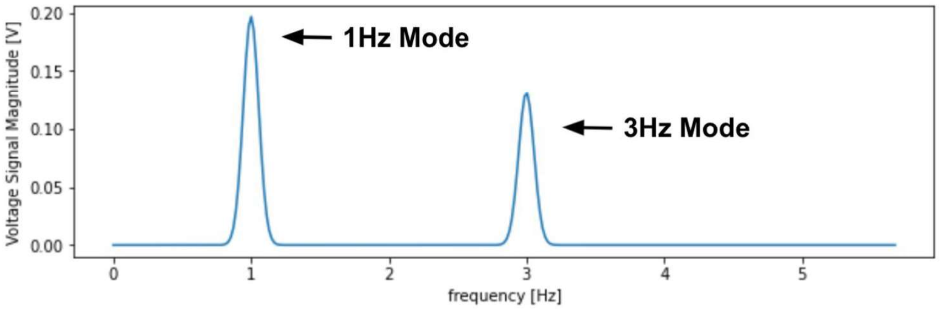


Two Wavelets of Different Frequencies

The Fourier transform returns all frequencies present in a time-domain signal.

However the Fourier transform does not provide any information on when the two wavelets occurred in time.





Fourier Transform Definition

$$X(\omega_k) = \sum_{n=0}^{N-1} x(t_n) e^{-j\omega_k t_n},$$

$$\omega_k = k\frac{2\pi}{NT}, \qquad k = 0, 1, \ldots, N-1$$

$N =$ number of samples

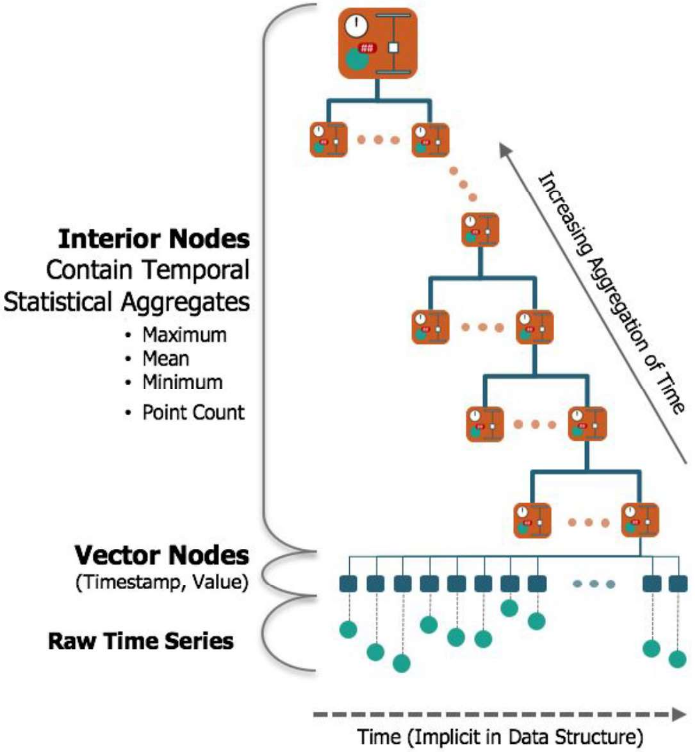
$T =$ sampling interval

$$\Delta\omega = \frac{2\pi}{NT}, \qquad \Delta f = \frac{1}{NT}$$

We use the Discrete Fourier transform (DFT) to compute a discrete set of frequencies present in the discrete time-domain signal.

The frequency resolution depends on the inverse of the window length, N*T.

Using Predictive Grid to Control Sampling Frequency



https://www.pingthings.io/platform.html

The Predictive Grid Platform stores time series data in a tree database.

Data can be easily accessed at different sampling periods, T, and time windows, N*T.

Thus we can control the frequency resolution of our DFTs by querying the database at different nodes of the tree.

Query at higher nodes to look at low frequencies over long time periods

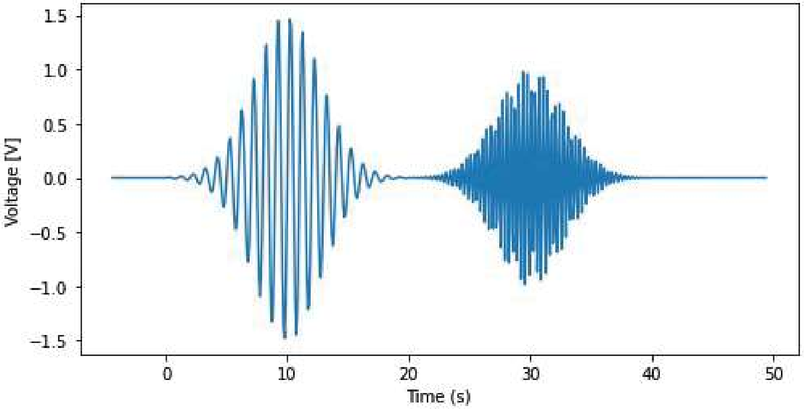
Query at lower nodes for higher frequency resolution,

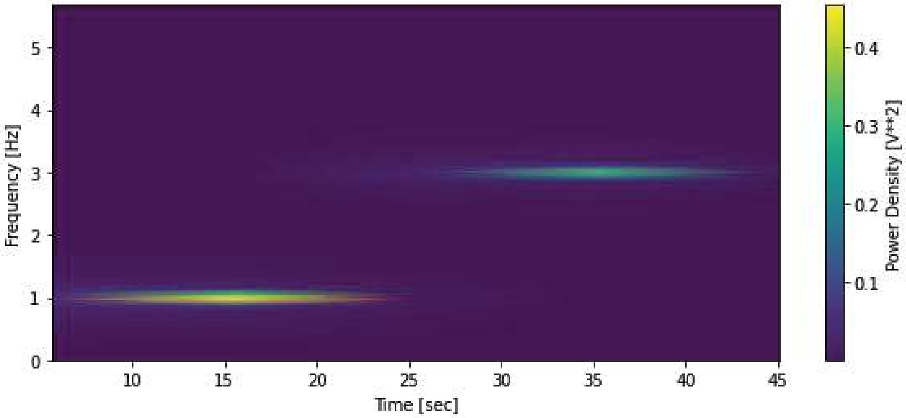
$$\Delta f = \frac{1}{NT}$$

Spectrograms

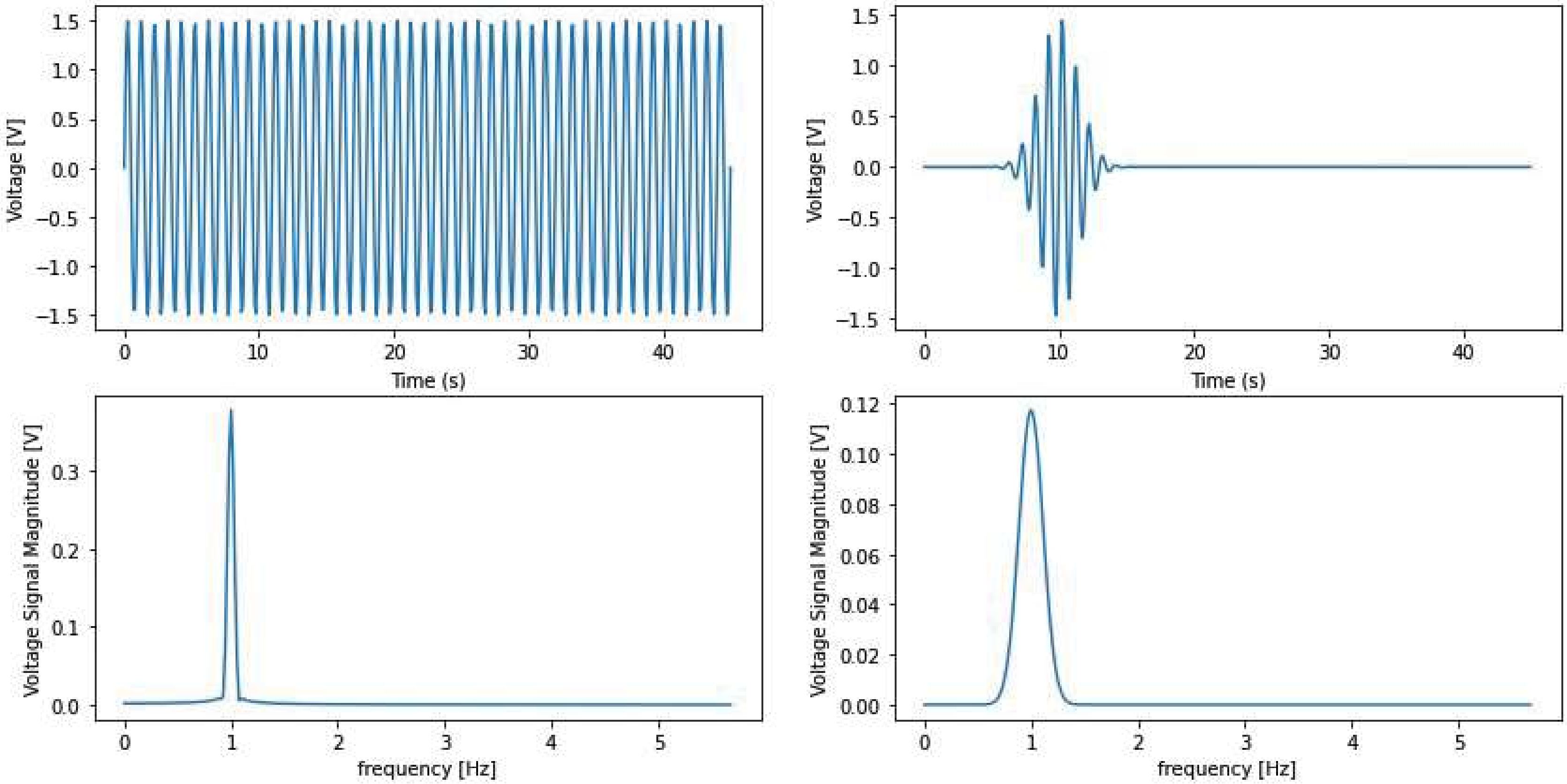
The spectrogram is a 2D plot that first divides the time-series data into multiple time windows and then computes the Fourier transform within each window.

Vertical slices of the spectrogram are the signal’s spectrum localized within one time window.

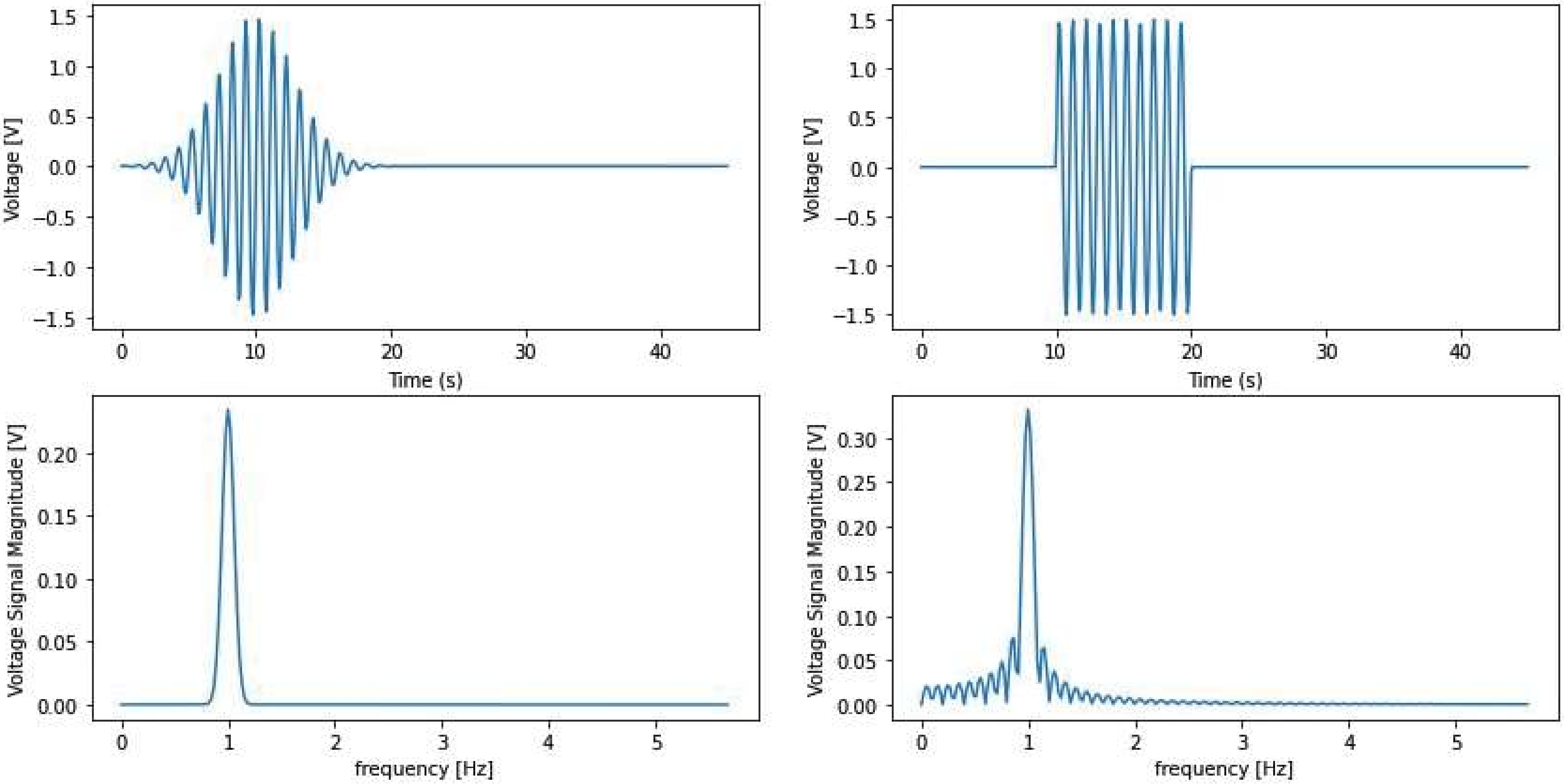




Windowing Decreases Frequency Resolution



Effects of Different Windows

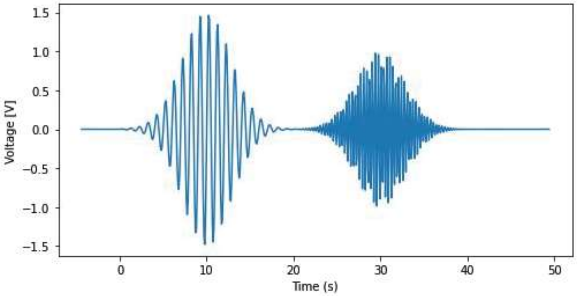


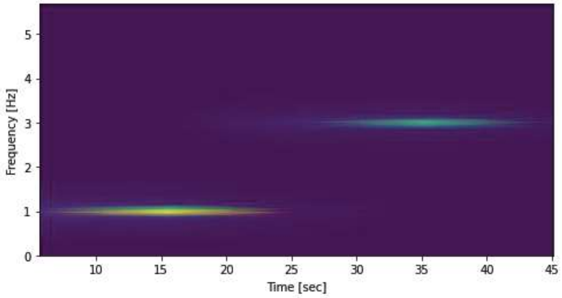
The Uncertainty Principle

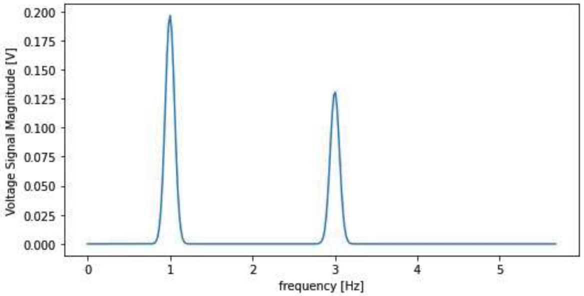
There is a trade-off between time resolution and frequency resolution.

The DFT uses the longest possible window and thus has the highest frequency resolution, but no time information. Conversely, the time series data has the highest time resolution.

The Spectrogram trades some frequency resolution to increase time resolution. We can control this trade-off by varying the window length of the spectrogram.





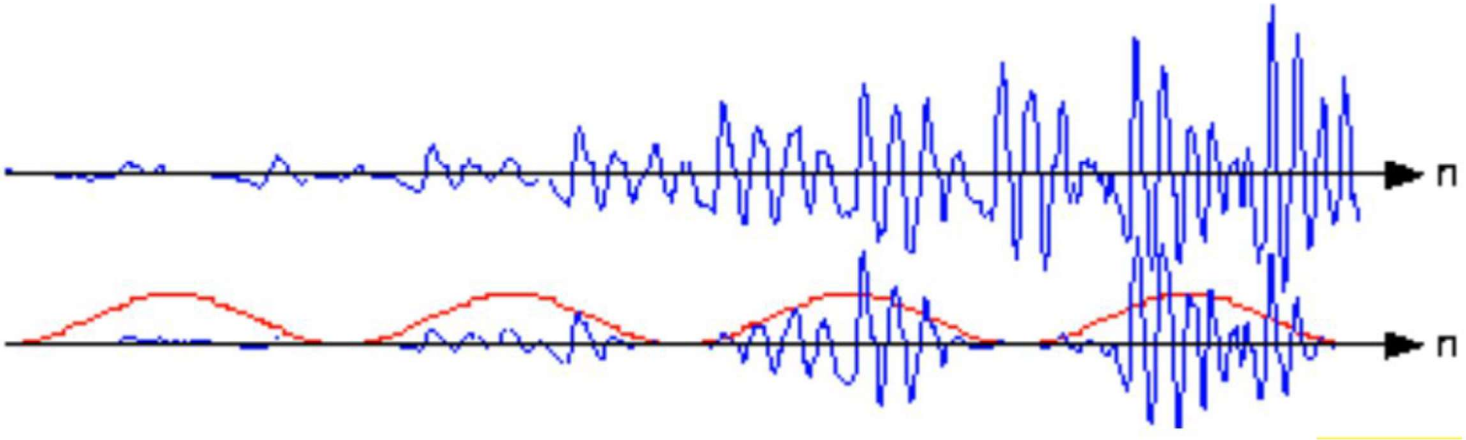


Increasing time resolution, decreasing frequency resolution

Increasing frequency resolution, decreasing time resolution

Window Overlap

When using windows with decaying tails, we need to overlap the windows. If we don’t we periodically suppress parts of the signal.



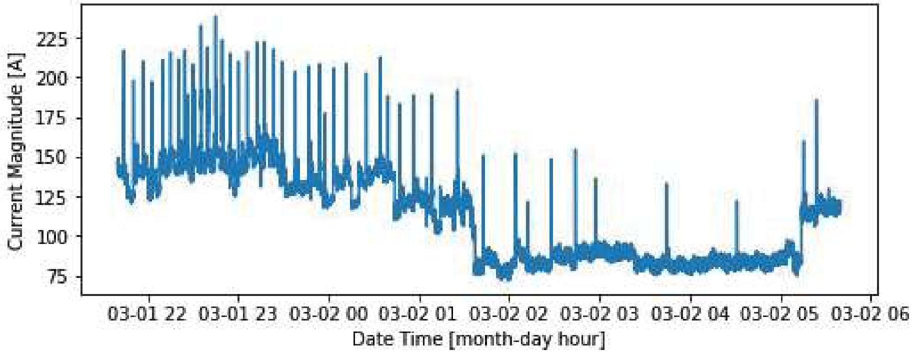
Spectrograms. (2020, May 18). https://eng.libretexts.org/@go/page/1828

Building Load Current Time Series and Spectrogram

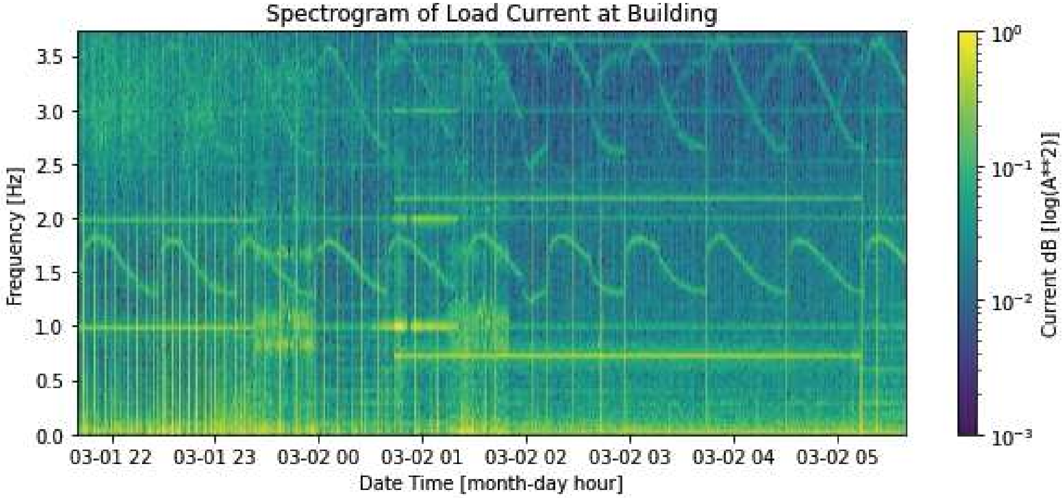
Time domain signals can be hard to interpret.

Spectrograms visually separate oscillations from multiple sources.

Loads may be more easily identified by their spectral signatures.



Spectrogram of Load Current at Building

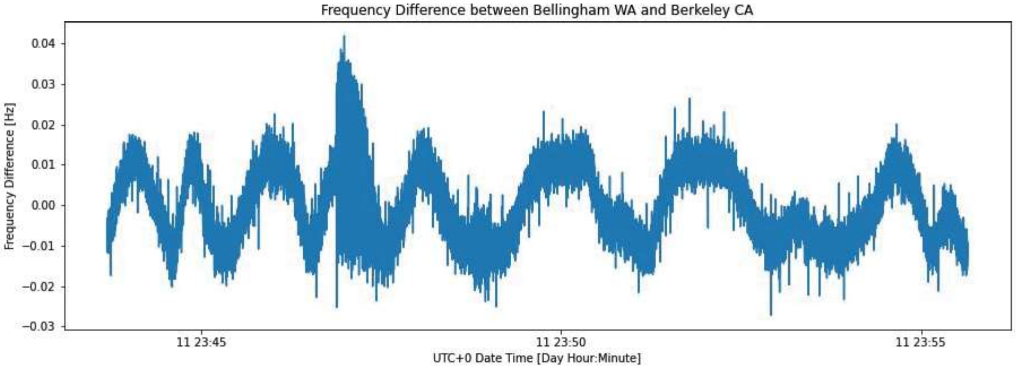


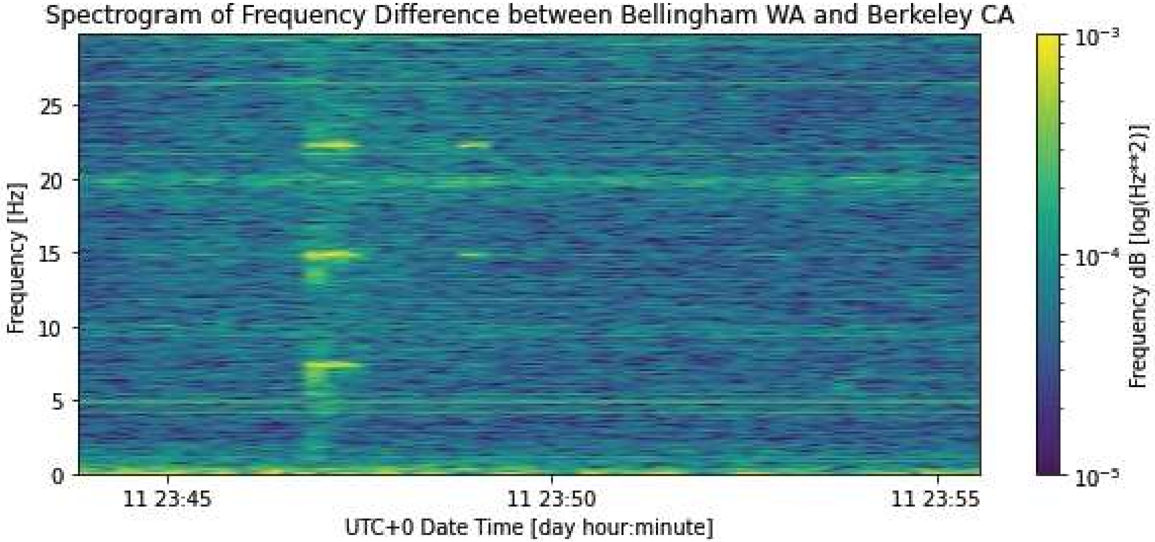
Wide-Area Oscillations

Wide area oscillations occur across large interconnected power systems.

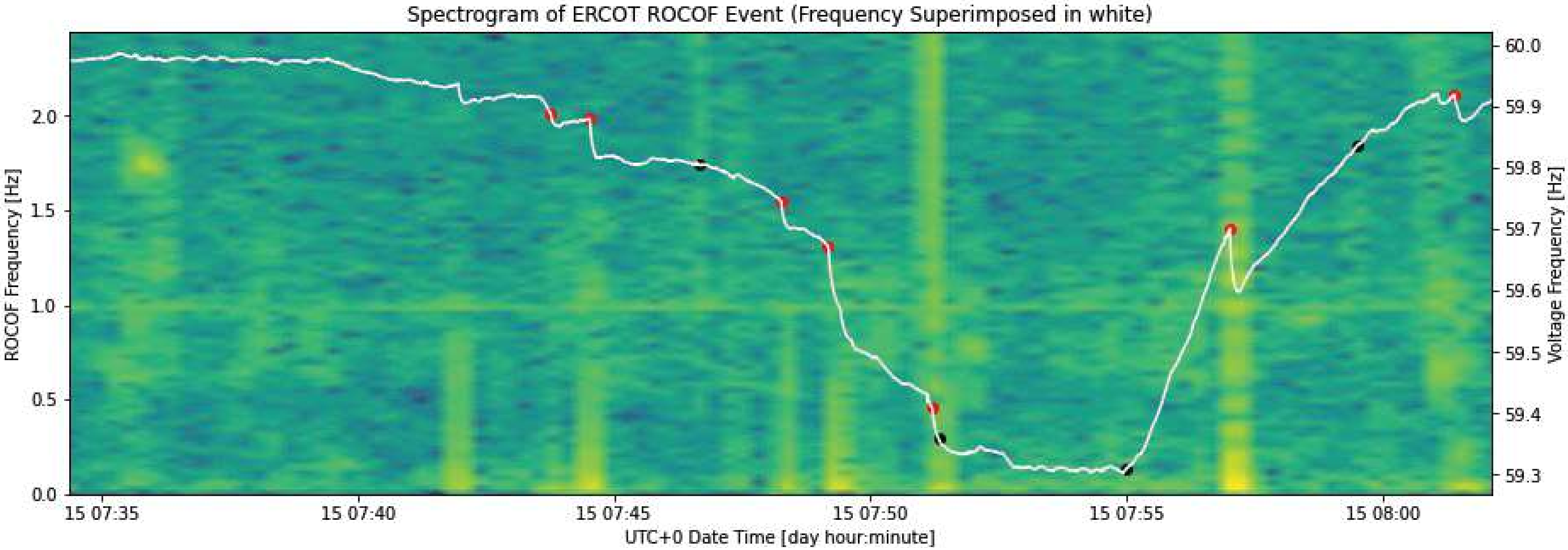
Here we visualize the frequency difference between Berkeley, CA and Bellingham, WA.

An event is visible in both the time series and spectrogram.


Frequency Difference between Bellingham WA and Berkeley CA


Spectrogram of Frequency Difference between Bellingham WA and Berkeley CA

ERCOT Frequency Event



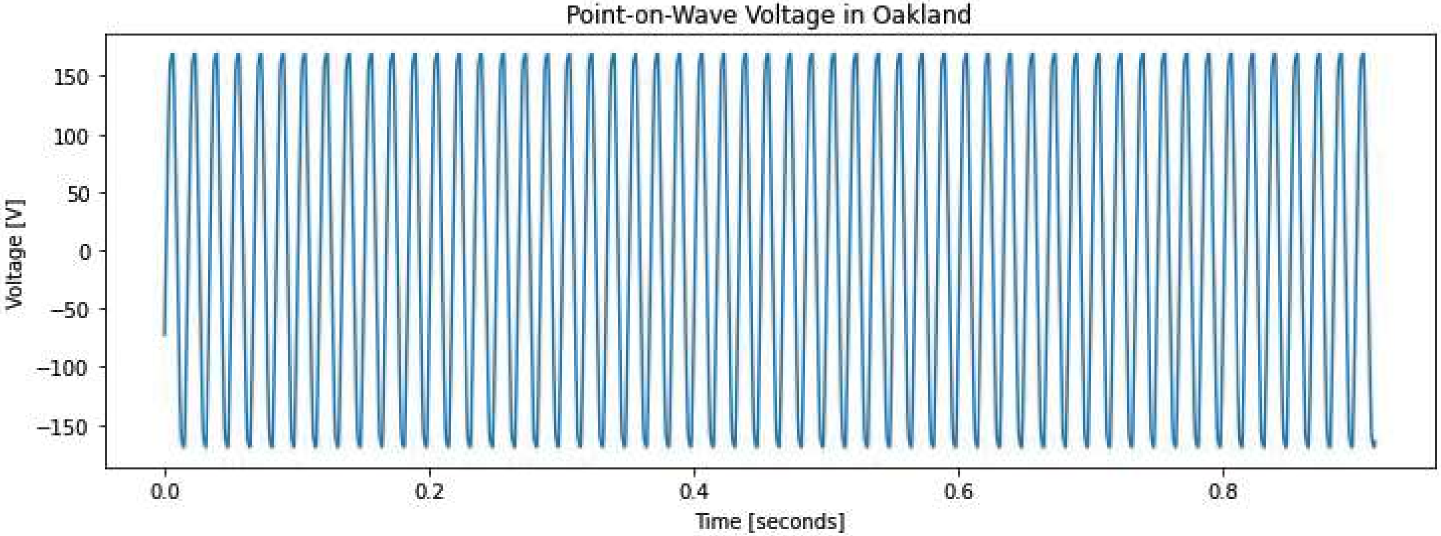
Generator loss events (labelled with red dots) are visible in both the time series (in white) and the spectrogram.

The spectrogram shows the frequency components during an event, which provides information on system dynamics.

Visualizing Point on Wave Data

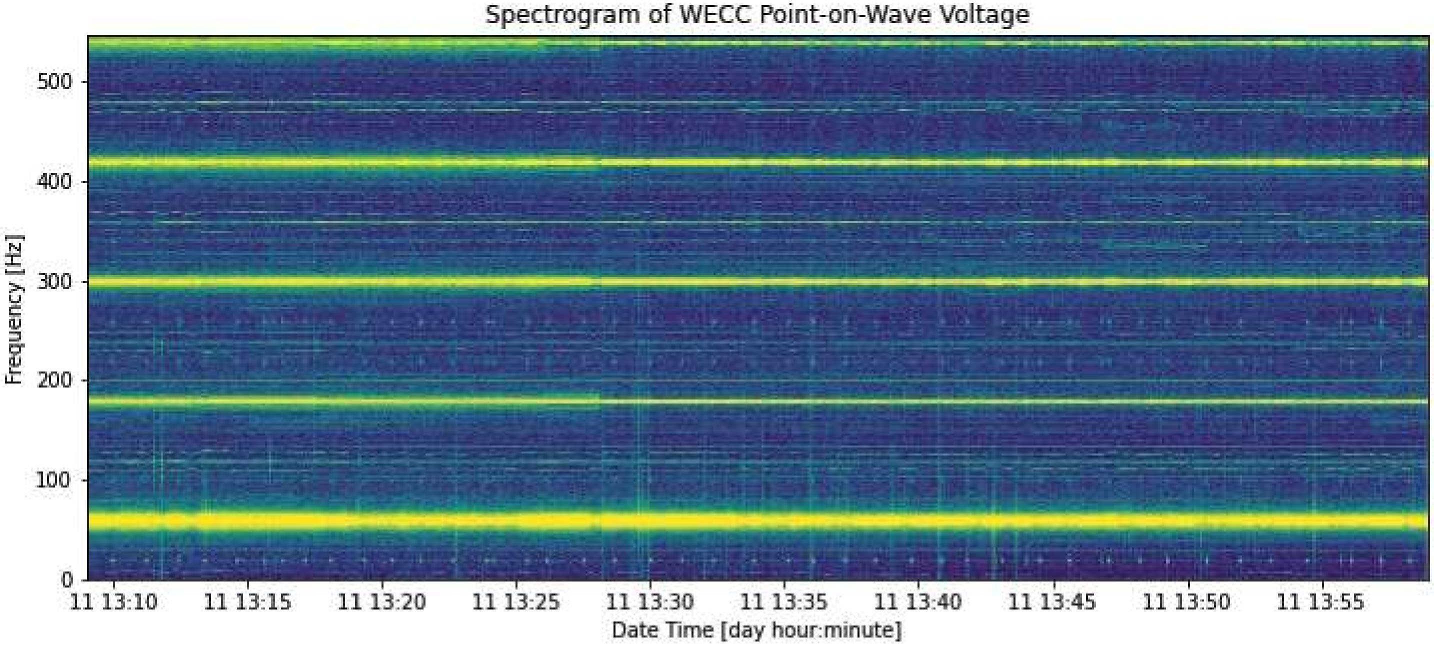
Below is a window of point on wave (POW) data from the GridSweep sensor, which has a sampling rate of 4.3kHz, measuring the voltage at a household in Oakland, CA.

Raw POW data is visually hard to interpret.



Data recorded during on-going U.S. Dept of Energy Project "GridSweep: Frequency Response of Low-Inertial Bulk Grids": 24 hours of GPS-time-stamped 4.3kHz point-on-wave sampling at 29-bit resolution, single-phase 120-volt nominal, recorded at Alex McEachern's residential kitchen in Alameda, California, USA on 2021/05/10 - 2021/05/11.

Visualizing Harmonics



7th harmonic

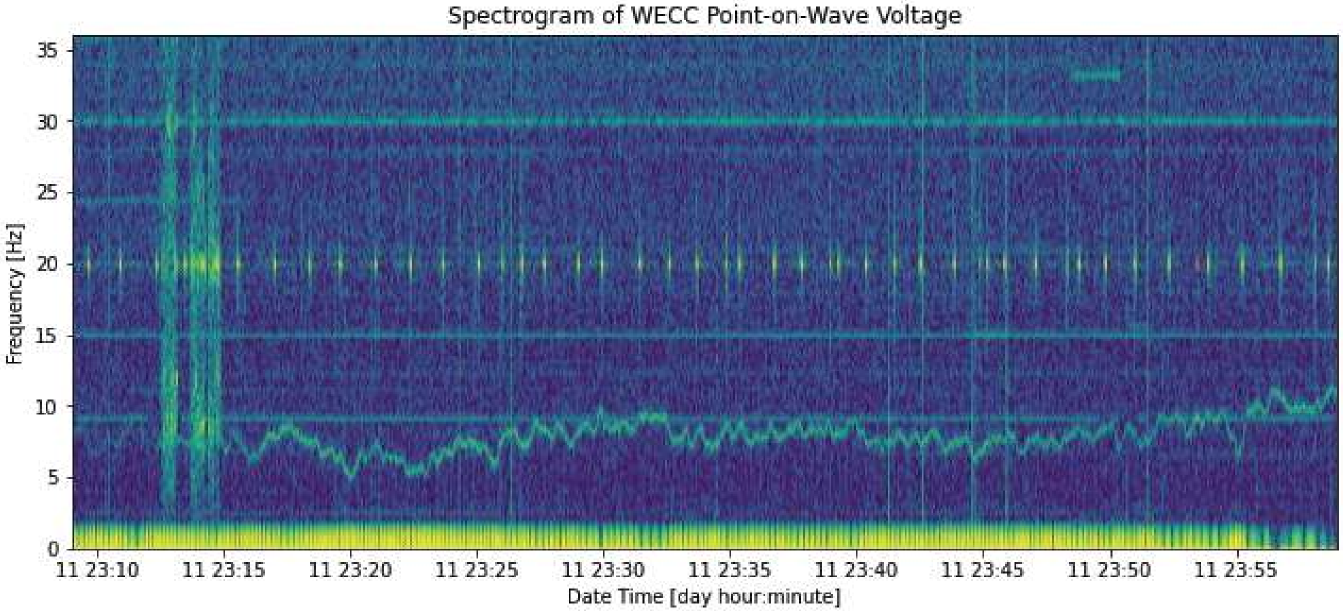
5th harmonic

3rd harmonic

Fundamental
Frequency (60 Hz)

Data recorded during on-going U.S. Dept of Energy Project "GridSweep: Frequency Response of Low-Inertial Bulk Grids": 24 hours of GPS-time-stamped 4.3kHz point-on-wave sampling at 29-bit resolution, single-phase 120-volt nominal, recorded at Alex McEachern's residential kitchen in Alameda, California, USA on 2021/05/10 - 2021/05/11.

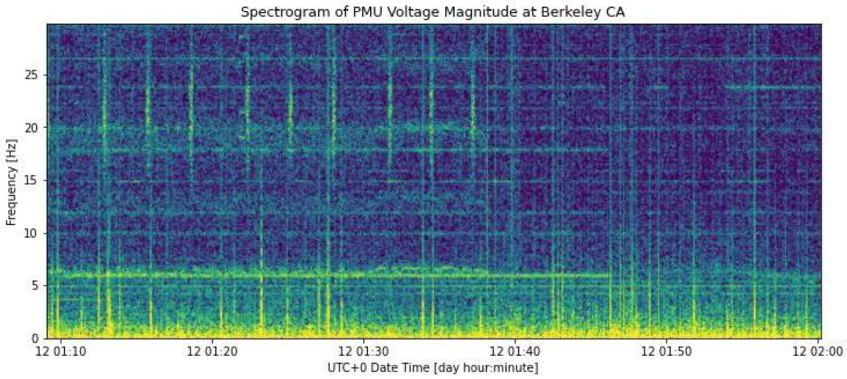
Detail in the Low Frequencies



The sampling rate POW data, in this case 4.3kHz. The high sampling rate and the long time window together allow for high resolution spectrograms.

Data recorded during on-going U.S. Dept of Energy Project "GridSweep: Frequency Response of Low-Inertial Bulk Grids": 24 hours of GPS-time-stamped 4.3kHz point-on-wave sampling at 29-bit resolution, single-phase 120-volt nominal, recorded at Alex McEachern's residential kitchen in Alameda, California, USA on 2021/05/10 - 2021/05/11.

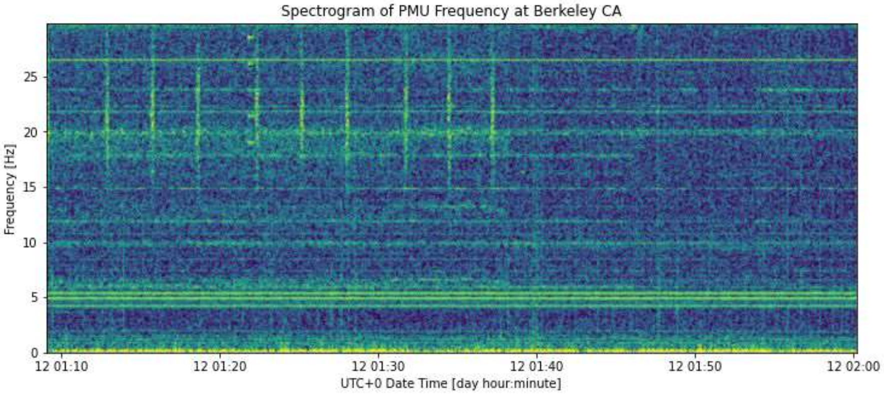
Comparing PMU and POW Data

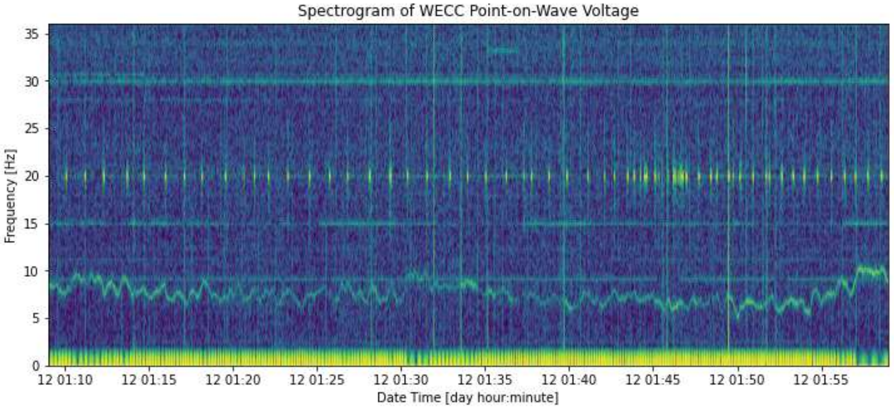

Spectrogram of PMU Voltage Magnitude at Berkeley CA

PMUs approximate phasors from POW data, often with a proprietary algorithm.

The POW and PMU spectrograms show different features.

The transparency of POW data is attractive for research purposes, while PMU data is less data intensive may be more suitable for specific real-world applications.


Spectrogram of PMU Frequency at Berkeley CA


Spectrogram of WECC Point-on-Wave Voltage