

In Situ Continuous Synchronized Waveform Recording and Sub-Synchronous Probing of Coupled 120 V and 480 V Grid Circuits

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Abstract—This paper presents a field demonstration of two emerging power system monitoring technologies in a coupled 120 V and 480 V circuit: *continuous synchronized waveform recording* and *sub-synchronous low-amplitude probing*. Challenges are addressed, including cross-device measurement alignment, the impact of transformers on synchronized data, and the signal processing required to detect low-amplitude perturbations. Experiments confirmed that low-amplitude sub-synchronous perturbations injected at a standard 120 V outlet are detectable not only by nearby 120 V waveform measurement units (WMUs) but also by a utility-grade 480 V WMU on the far side of a wye-delta transformer. This detection was made possible by precise GPS-based time synchronization and advanced signal processing techniques, including amplitude demodulation, Fourier analysis, and vector time averaging, which effectively extracted subtle probe signatures from noisy real-world data. These findings establish low-amplitude modulated probing as a practical tool for feeder-wide assessments and pave the way for low-cost active monitoring, with potential applications in stability margin assessment, inverter model validation, and network diagnostics.

Index Terms—Field demonstration, continuous synchronized voltage waveform recording, sub-synchronous probing, synchro-waveforms, low-amplitude probing, 120 V circuits, 480 V circuits.

I. INTRODUCTION

A. Background and Purpose

Time-synchronized waveform measurement units (WMUs) have recently emerged as a new class of sensors for enhanced grid visibility [1]–[3]. By capturing raw point-on-wave voltage data continuously and with GPS timestamps, these *synchro-waveform* measurements enable analysis of sub-cycle dynamics that traditional phasor measurement units (PMUs) cannot resolve [4]. One critical application is to monitor sub-synchronous oscillations in distribution systems, which can arise with high inverter-based resource penetration and are difficult to detect using conventional trigger-based monitors.

While WMUs (and PMUs) are inherently *passive* sensors, their ability to monitor the power system is significantly enhanced when they are paired with technologies that can enable *active* probing. By injecting small perturbation signals and observing the response, active probing creates new opportunities to learn about the power system, such as identifying the parameters of the power grid [5], [6]. Probing offers a complementary approach to power systems identification and power system stability assessment; see [7, Chapter 6].

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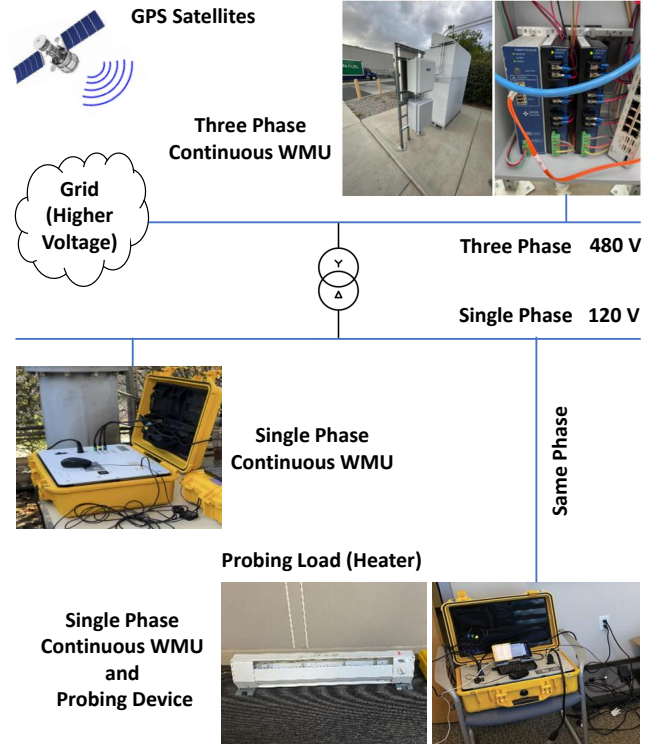


Fig. 1. In Situ experimental setup for the field tests presented in this paper. Waveform measurements are continuously recorded on the 480 V, three-phase circuit using SEL Axion, and on the 120 V, single-phase circuit using McEachern GridSweep. The two circuits are connected by a wye-delta transformer. Sub-synchronous, low-amplitude probing is performed on the 120 V circuit, and its impact is analyzed at different voltage levels.

Prior studies have demonstrated probing at transmission and medium-voltage levels, but probing at the 120 V (low-voltage) circuits remains largely unexplored. Low-voltage probes could provide granular insight into feeder stability at the grid edge.

Field experiments are essential to validate continuous waveform monitoring and active probing techniques under real-world conditions. Laboratory tests alone cannot capture practical challenges such as instrument noise, load variability, and network complexity. In this work, we conduct a field demonstration using state-of-the-art WMUs, simultaneously at both 120 V and 480 V, as shown in Fig. 1. This setup allows us to address open problems including cross-device measurement alignment (between different vendors and with different sampling rates), the impact of distribution transformers on synchronized waveform data, and the detectability of low-magnitude perturbations across a live low-voltage feeder.

B. Summary of Experiments and Contributions

We developed a real-world experimental platform to implement *continuous* (i.e., *gapless*) voltage waveform monitoring and current waveform modulated probing in the field. Our setup deployed specialized hardware at both 120 V and 480 V circuits. Over the course of the study, we collected several terabytes of synchronized waveform data, including raw voltage waveforms at multiple voltage levels, processed metrics, active probe logs, and related operational data.

Using this rich dataset, we analyzed the time-synchronized waveform measurements across different voltage levels, sensor types, and sampling rates. We compared high-resolution recordings from a utility-grade 480 V WMU and a prototype 120 V WMU, quantifying how distribution transformers affect the voltage waveforms. We also characterized the system to establish baseline compatibility between the different sensors.

We also conducted *sub-synchronous* probing experiments (i.e., at probing frequencies below 60 Hz) on in-service circuits. We demonstrate that a small modulated perturbation that is injected at a 120 V outlet is observable not only by another nearby 120 V WMU, but also by a 480 V WMU located on the far side of a distribution transformer.

To the best of our knowledge, this is the first experimental confirmation that a low-magnitude sub-synchronous perturbation injected at 120 V can be detected at a 480 V bus. We visualize these probing results using *time-frequency heatmaps*, confirming the propagation of the probe throughout the feeder.

C. Literature Review

Recent works have explored technologies and infrastructure for time-synchronized waveform measurements in power systems [8]. Rather than relying on event-triggered records, it has recently been proposed to continuously record synchro-waveforms to enhance situational awareness. Continuous recording can reveal low-magnitude oscillations and disturbances that might be otherwise missed [9]. New data compression and analysis techniques have been proposed to utilize continuous synchro-waveforms in grid applications [10], [11].

Active probing and perturbation-based techniques have been studied at different voltage levels. One of the early experiences with active probing at the Western Electricity Coordinating Council (WECC) was done on the transmission grid to identify small-signal stability modes [5]. More recently, active perturbations have also been applied to distribution feeders using dedicated devices, such as to estimate feeder impedance and topology [6]. However, most prior efforts focus on substation or medium-voltage injection. In contrast, we inject the probe at 120 V at a live (in-service) network, using GridSweep, which is a low-voltage continuous WMU and a probing signal generator [12], as well as Axion, which is a utility-grade three-phase continuous WMU [13], [14]. We demonstrate low-voltage probing and its detection across multiple voltage tiers.

Preliminary field tests of the GridSweep WMU have been reported on a limited scale in [15], but without looking at other voltage levels, and without probing. Both of these limitations are addressed in this paper. Likewise, the Axion WMU may have been used by utilities in their power transmission and distribution monitoring systems. Building on these developments,

our work is the first to integrate GridSweep and Axion in a joint field experiment, leveraging their continuous recording and time synchronization capabilities to perform cross-voltage analysis and active probing in a unified framework.

II. DETAILS OF THE EXPERIMENTAL SETUP

In this section, we describe the key elements of the experimental setup that were previously shown in Fig. 1.

A. Continuous Waveform Measurements at 480 V

The SEL 2240 Axion is a modular sensor configured to capture three-phase voltage and current waveforms at a 480 V bus, i.e., ~ 277 V per phase. The Axion sampled all channels at 50 samples per cycle (3 kHz at 60 Hz) with GPS-synchronized time-stamping to align with the GridSweep devices. The Axion continuously streams synchro-waveform measurements via Ethernet to a local server for recording, storage and analysis.

B. Continuous Waveform Measurements at 120 V

GridSweep is a briefcase-sized, plug-in WMU designed for standard 120 V outlets. It combines two capabilities: (a) *continuous synchro-waveform recording*: GPS-timestamped continuous, high-resolution voltage monitoring; and (b) *sub-synchronous probing*: the ability to inject small, controlled perturbations into the outlet by modulating the current draw by an attached load at frequencies from 1 Hz up to 40 Hz.

Each GridSweep unit employs a 32-bit A/D converter and careful analog filtering and shielding to achieve a measurement noise floor below 10 parts-per-billion in the 1–40 Hz band. Its waveform sampling rate is roughly 4 kHz per phase, with each sample GPS time-stamped. Data are stored locally in one-minute files and periodically offloaded manually for analysis.

C. Sub-Synchronous Low-Amplitude Probing at 120 V

GridSweep is also capable of amplitude-modulating an external 120 V load (a 1 kW resistive heater) at frequencies from 1 Hz to 40 Hz. A control loop drives the desired perturbation current, typically only a few percent of the 15 A circuit rating.

When one GridSweep injects a probing signal at a given location and frequency, other GridSweep devices at other locations on the same system can detect the resulting voltage fluctuation at parts-per-billion resolution. Other WMUs, including at higher voltage levels, may also *potentially* detect the perturbations; as we will explore in Section IV.

III. INITIAL (PRE-PROBING) ANALYSIS OF SYNCHRO-WAVEFORMS AT DIFFERENT VOLTAGE LEVELS

In this section, we analyze the synchronized voltage waveform measurements at 120 V and 480 V prior to any active probing, to establish baseline consistency across sensors.

A. Analysis of Per-Cycle RMS of Waveform Measurements

As a baseline comparison between the single-phase GridSweep measurements at 120 V and the three-phase Axion measurements, we converted each 60 Hz cycle of the raw waveform data to a single Root-Mean-Square (rms) voltage value. This allowed us to directly compare the voltage trends

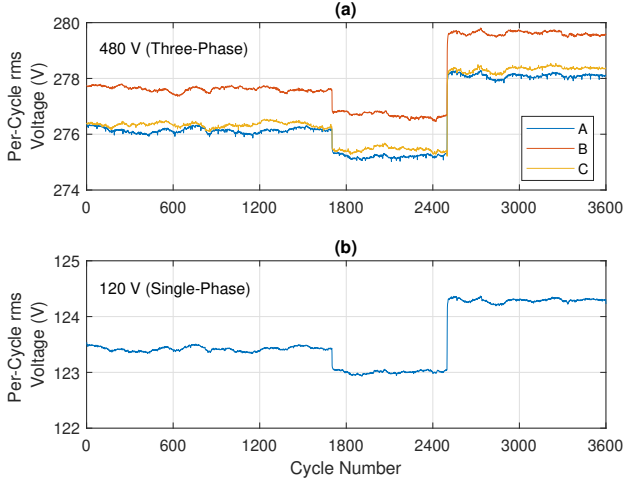


Fig. 2. Per-cycle RMS values at different voltage levels: (a) Three-phase 480 V Axion measurements; (b) Single-phase 120 V GridSweep measurements.

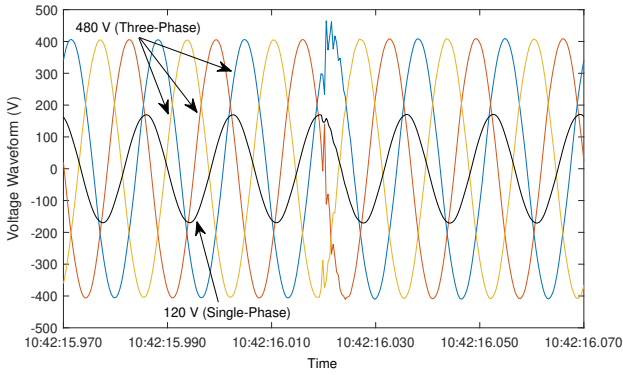


Fig. 3. Time-synchronized voltage waveform measurements at 480 V and 120 V over a 100 ms window. A transient event is visible at around 10:42:16.020. The inherent phase offset is due to the wye-delta transformer.

from both types of sensors on a common time axis. The results are shown in Fig. 2, over 3600 cycles (1 minute). The per-cycle rms trends clearly match between the two instruments.

B. Analysis of Raw Synchronized Waveform Measurements

Next, we compare the raw waveform measurements from the instruments. To confirm precise alignment, we examine a *transient event* that was simultaneously captured by both types of instruments at different voltage levels. The results are shown in Fig. 3. Both instruments registered the disturbance at exactly the same instant, at 10:42:16.020. The cause of this event is a capacitor bank switching at a nearby substation.

Notice that, in Fig. 3, there is a 30° phase offset between the 120 V (black) and 480 V (red) voltage waveforms. This is caused by the wye-delta transformer. Nevertheless, the moment at which the event starts is aligned across all waveforms, further confirming the timing fidelity of the measurements.

IV. ANALYSIS OF SUB-SYNCHRONOUS PROBING RESULTS AT DIFFERENT VOLTAGE LEVELS

A. Generating Low-Amplitude Probing Signals

Recall from Section II.C that GridSweep devices can generate probing signals by modulating the current draw of a

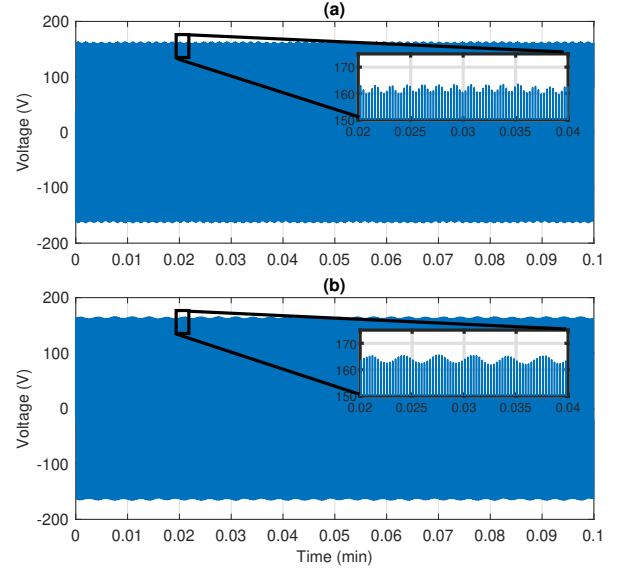


Fig. 4. GridSweep's 120 V voltage waveform measurements during active probing at two frequencies at the same location where probing is done: (a) 11 Hz; and (b) 5 Hz. The zoomed inset highlights the injected sub-synchronous oscillation at the specified probing frequency, demonstrating that GridSweep can both inject and detect controlled perturbations on a low-voltage outlet.

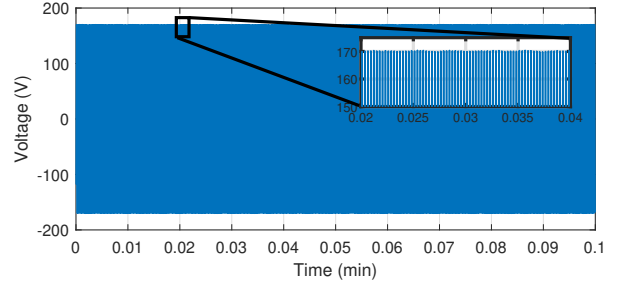


Fig. 5. Voltage waveform measurements by a *second* GridSweep at another location, while the first GridSweep was probing at 5 Hz. Even on the same 120 V circuit, the probe's effect is *not* visibly apparent at this location; yet it can be extracted using proper signal processing, as we will see in Fig. 7.

120 V 1 kW heater, at a specified sub-synchronous frequency. Fig. 4 illustrates the effect of such probing at two example frequencies. When GridSweep injects an 11 Hz or 5 Hz modulating current, a corresponding low-amplitude oscillation is superimposed on the local 120 V waveform (visible in the zoomed inset). These traces confirm that the probing GridSweep device can both drive a controlled sub-synchronous signal and detect its presence in its own voltage measurements.

At other locations, however, the injected perturbation is *not* readily visible in the raw voltage waveforms. For instance, in Fig. 5, when one GridSweep was injecting a 5 Hz probe, another GridSweep at another location but on the same 120 V network recorded no obvious oscillation in its voltage. Thus, dedicated signal processing is necessary to reliably detect the probe's signature, as we will see in Section IV.B next.

For the remainder of the probing experiment, the injection frequency was varied over a full day. The schedule of probe frequencies is shown in Fig. 6. At midnight, the probe was set to 10 Hz. At 2:00 AM, it stepped to 28 Hz for 15 minutes. Thereafter, the frequency increased in 0.2 Hz increments every 15 minutes (28.2 Hz, 28.4 Hz, ..., 29.4 Hz), then at 4:00 AM

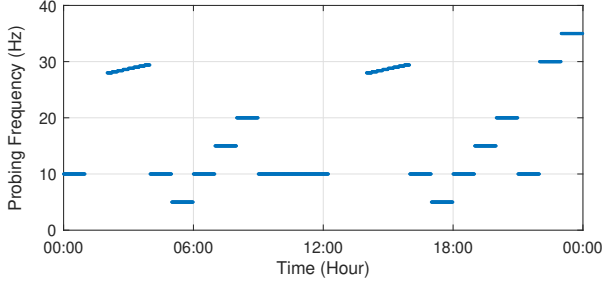


Fig. 6. The frequencies of the probing during a 24-hour probing experiment.

dropped back to 10 Hz. Similar changes continued throughout the day, ending at 35 Hz just before midnight.

B. Signal Processing to Detect Probing Signals

Initial raw data consisted of continuous waveform voltage samples, organized into 1-minute GPS-synchronized blocks.

1) *Addressing Transformer's Impact*: While the 120 V waveform measurements from the second GridSweep can be used as-is, the 480 V Axion waveforms must be adjusted for the presence of the wye-delta transformer between the 120 V and 480 V circuits. The Axion provides three phase-to-neutral voltages $v_a(t)$, $v_b(t)$, and $v_c(t)$. Therefore, we converted these to line-to-line waveforms to make them comparable with the 120 V waveforms (where the probe is injected): $v_{ab}(t) = v_a(t) - v_b(t)$, $v_{bc}(t) = v_b(t) - v_c(t)$, and $v_{ca}(t) = v_c(t) - v_a(t)$. These transformed 480 V signals were then used in all subsequent data-cleaning and processing steps.

2) *Signal Scrubbing*: We scanned the raw data for integrity, confirming that (i) each 1-minute block contained the expected number of samples, (ii) all sample values were within reasonable voltage bounds, and (iii) the point-to-point value changes were nominal (allowing for perturbations) with no prolonged flat-lining or excessive noise bursts. We interpolated any minor gaps to ensure that each 30-second half-block had exactly $2F + 2^N$ samples, where F is the number of taps in the low-pass filter (Step 3) and N is the number of points for the FFT (Step 3). In our experiment, $F = 64$ and $N = 17$.

3) *Amplitude Demodulation and Fourier Analysis*: Next, we scanned through each scrubbed 30-second window and extracted the amplitude modulation of the 60 Hz carrier: (i) We created an amplitude-demodulated series using a conventional in-quadrature demodulator at 60 Hz, multiplying the waveform by sine and cosine reference signals using double-precision arithmetic. (ii) To further suppress the 60 Hz carrier, we applied a 64-tap low-pass filter (triangular weighted) to the demodulated samples. It was applied forward and backward to avoid phase shift. We discarded the first and last 64 samples, leaving 2^N demodulated samples. We then performed a 2^N -point FFT on the demodulated segment, converting it to magnitude and phase spectra. We discarded all frequency components outside the band of interest [1.0 Hz, 40.0 Hz].

4) *Vector Time Averaging and McEachern Filtering*: To extract the small amplitude-modulation signal from noisy spectra: (i) We chose a time-averaging interval $T_{\text{avg}} = 15$ minutes and an averaging scheme, using a sliding window with

1-minute step. (ii) For each frequency bin in [1 Hz, 40 Hz], we compute the vector-averaged magnitude over T_{avg} . We apply the ‘‘McEachern filter’’ by rotating the phasors from the second half of each GPS minute by 180° before accumulating, effectively canceling any interfering signal with constant phase.

5) *Time-Frequency Heatmap Visualization*: The results form a three-dimensional data set, indexed by time, frequency, and signal magnitude, are used to generate heatmaps with time on the x-axis, frequency on the y-axis, and color indicating the averaged modulation magnitude. Each heatmap includes: (i) the recording location and UTC time range, (ii) a subtitle indicating T_{avg} , averaging type, frequency range, and the full-scale color value, and (iii) labeled axes (frequency in Hz, magnitude in parts-per-million of 120 V). In our analysis, we used a linear magnitude scale (in micro-Volt or ppm) since it correlates directly with grid impedance at each frequency.

C. Detection of Probing Signals at 120 V Circuit

Consider the synchro-waveform measurements from the second GridSweep device that was *not* injecting, but rather observing the circuit for the presence of probe signals. Fig. 7 provides the corresponding time-frequency heatmap, generated by using the signal processing pipeline of Section IV-B. It shows how the injected sub-synchronous probe propagates through the 120 V circuit. Each pixel represents the vector-averaged modulation magnitude at a given time and frequency.

Compare the heatmap in Fig. 7 with the probing frequencies in Fig. 6. Theoretically, they should be identical in the *absence* of any form of *background* sub-synchronous amplitude modulation in the power system. However, in practice, the heatmap in Fig. 7 looks noisy; because *background* sub-synchronous modulations *do* exist in the power system; and they can make low-amplitude probing signals more difficult to observe.

Nevertheless, the heatmap in Fig. 7 closely follows the probing frequencies shown in Fig. 6. Therefore, although a visual inspection cannot reveal the presence of probing signals in the second GridSweep (as it was shown in Fig. 5), signal processing can still clearly reveal the probing actions.

D. Detection of Probing Signals at 480 V Circuit

Fig. 8 similarly shows the results of applying the same analysis to the three-phase Axion data on the 480 V side. The probe-induced bands are again visible (though at a lower amplitude and with modest background noise). Their presence on the high-voltage side is pivotal: the 120 V perturbation survives passage through a wye-delta transformer and is observable by a substation-grade WMU. This is, to our knowledge, the first in situ demonstration that a hand-held 120 V device can inject a sub-synchronous signal that is simultaneously detected at a 480 V bus without any intermediate amplification.

Together, the two heatmaps in Figs. 7 and Fig. 8 confirm the core thesis of our multi-voltage probing experiments across 120 V and 480 V circuits: sub-synchronous probing signals injected at 120 V are simultaneously observable on both the low-side (secondary) and high-side (primary) voltages of the network. These results establish GridSweep-based probing as a practical tool for feeder-wide small-signal stability assessment.

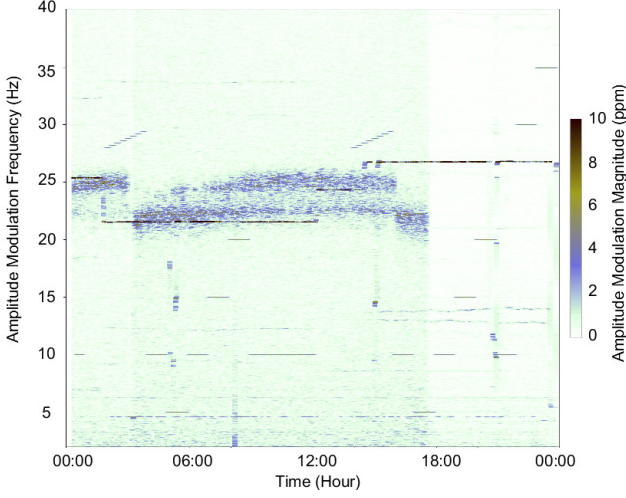


Fig. 7. Time-frequency heatmap of amplitude-modulated voltage measured over one day by the *second* GridSweep, further away from the probing injection point, but still on the same 120 V circuit. The presence of the probe is clearly visible at the same frequencies and timings as in Fig. 6.

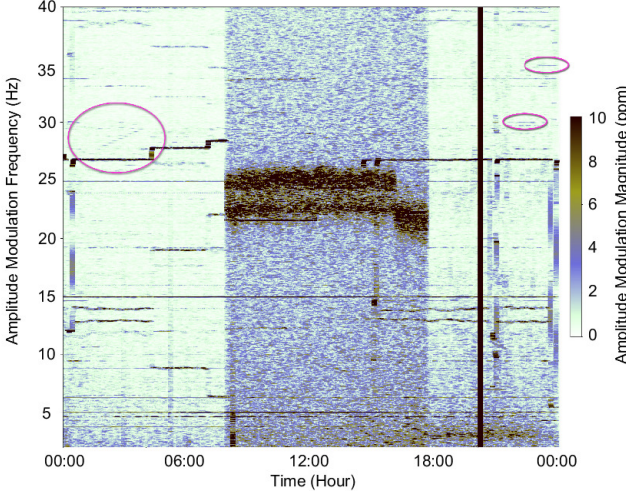


Fig. 8. Time-frequency heatmap of amplitude-modulated voltage measured over one day by Axion at 480 V. Despite the transformer coupling and lower signal amplitude, the same probe frequencies (circled) are visible, confirming that sub-synchronous oscillations injected at 120 V propagate through the wye-delta transformer and are detectable by standard utility sensors.

V. CONCLUSIONS AND FUTURE APPLICATIONS

This study successfully conducted the first field demonstration of continuous synchronized waveform recording and sub-synchronous low-amplitude probing across 120 V and 480 V circuits. A pivotal finding is the experimental confirmation that low-magnitude sub-synchronous perturbations injected at a standard 120 V outlet are detectable not only by nearby 120 V sensors but also by a utility-grade 480 V sensors located on the far side (primary) of a wye-delta distribution transformer. This detection was made possible through GPS-based time-synchronization of measurements across different sensor types and sampling rates, coupled with advanced signal processing techniques, including amplitude demodulation, Fourier analysis, and vector time averaging. These methods effectively extract subtle probe signatures from noisy real-world data.

The experimental results in this paper pave the way for

various potential applications in power distribution systems.

1) *Applications of Low-Voltage Probing*: The ability to detect a low-voltage probing signal at a 480 V bus opens up new possibilities for low-cost active monitoring. For example, a utility may inject a mild sub-synchronous perturbation on a feeder and observe the damping before and after adding a large solar inverter; providing a real-world stability margin. Similarly, control engineers can validate inverter dynamic models by checking whether resonant peaks predicted around certain frequencies actually manifest in field data during probing.

2) *Applications of Low-Voltage Synchro-Waveforms*: Beyond the detection of *intentional* probing, waveform measurements also reveal numerous *incidental* micro-disturbances. By correlating which devices observe each micro-event, and with what amplitude, one can infer phase connectivity, shared neutrals, or localized equipment issues. This passive use of continuous waveform measurements can be combined with active probing to further enhance inference and diagnostics.

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