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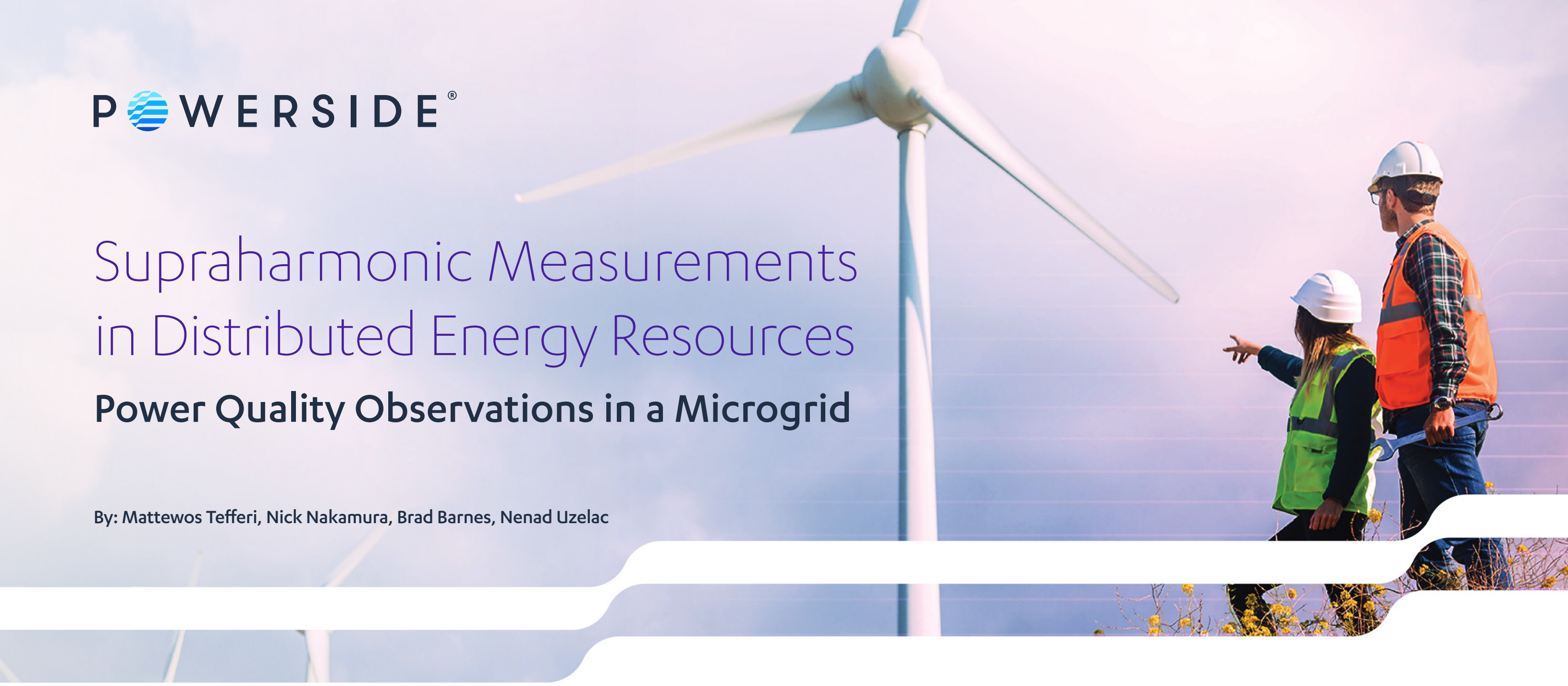


Supraharmonic Measurements in Distributed Energy Resources

Power Quality Observations in a Microgrid

By: Mattewos Tefferi, Nick Nakamura, Brad Barnes, Nenad Uzelac

Power systems are experiencing a significant transformation with the implementation of emerging technologies to face the 21st century challenges such as decarbonization, digitization, and decentralization. **The penetration of renewable energy is increasing worldwide and initiatives such as distributed energy resources (DERs) based microgrids play a vital role in generating electrical power with less environmental impacts.**

The operation of a microgrid depends on successful integration of DERs, relying on several factors such as hosting capacity, anti-islanding, synchronization and power quality. Modern renewable energy sources use power electronic systems such as rectifiers, DC/DC converters, and DC/AC inverters that are susceptible to emitting power quality phenomena into the network such as voltage instability, harmonics, frequency instability, and flicker. The continuous increase in switching frequencies resulting from these power electronics technologies has led to the emergence of conducted emissions in the range of 2 to 150 kHz (supraharmonic frequency), outside the traditional frequency range for power quality. **Supraharmonics have the potential to disrupt network operations by damaging capacitors, disrupting communications, degrading dielectric insulation, and mis-operating relays/controls.** These symptoms can negatively affect the operation of street lighting controls, household dimmers, semiconductor manufacturing equipment, medical scanners, security systems, and transportation controls. Traditional technologies used on the grid today may not have the capability to properly measure and detect this new, emerging supraharmonic threat to the electric power system reliability.

This paper presents measurement observations of DER impact to voltage and frequency stability, utilizing state-of-art technologies available today. In the first part of the paper, seven test scenarios were performed in a microgrid test bed to intentionally introduce disturbances and measure the resulting impact. In the second part, an unintentional event occurred in the microgrid, and the resulting measurements were recorded and evaluated.

The study was performed in a medium voltage (MV) microgrid with natural gas generators, battery storage, voltage regulators, solar panels, and a wind turbine. The measurement instrumentation in the microgrid includes a set of capacitive voltage divider sensors (0.5 class) certified to IEC 60044-7 and a Powerside PQube® 3 power quality analyzer certified to IEC 61000-4-30 Class A for data collection and analysis of the measurement data.

High Accuracy Low Power Voltage Transformer (LPVT) Technology

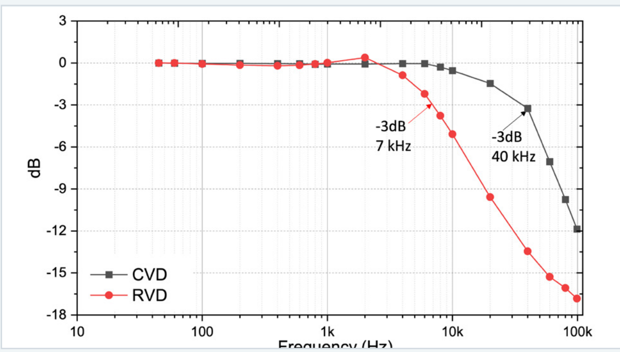
Instrument transformers (ITs) are key technologies that enable applications for metering, protection, and control of modern power grids. Initiatives such as DERs and optimizing energy efficiency and resiliency are driving a need for high precision sensing technologies that can effectively monitor the state of the modern grid.

Low Power Voltage Transformers (LPVTs) are typically based on either capacitive voltage dividers (CVDs) or resistive voltage dividers (RVDs) and are used to step down the primary MV to an appropriate low voltage signal measured by an intelligent electronic device (IED) such as a meter or controller.

A CVD sensor consists of a series of two capacitive arms: a primary arm with low capacitance value, in the order of few pF, and a secondary arm with high capacitance value, typically hundreds of nF. On the other hand, a RVD comprises high primary resistor, in the order of 10~100 MΩ and low secondary resistor, typically 10~100kΩ. **Both technologies involve connections to the primary voltage and secondary voltage is then measured across the secondary arm.**

A key characteristic of CVD sensor technology used in DER applications is the dynamic measurement range and ability to measure and detect supraharmonics (2kHz~150kHz) phenomenon. LPVTs must maintain accuracy class over a wide band of frequency range. **The frequency characteristics of CVD and RVD via the frequency sweeping method is shown in FIGURE 1.** A constant voltage was applied, and the output voltage was monitored for both technologies. The cut-off frequencies were 7 kHz and 40 kHz for RVD and CVD respectively. The high cut-off frequency of CVDs makes it suitable for detecting high frequency, supraharmonic phenomenon up to 40kHz.

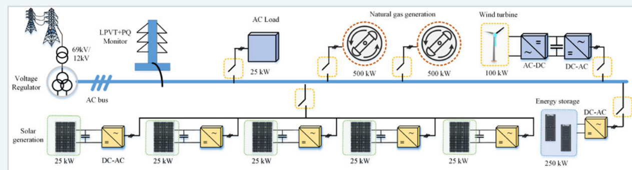
FIGURE 1 | Frequency response of CVD and RVD sensors



Microgrid Test Bed Under Study

FIGURE 2 represents a simplified scheme of the microgrid test bed under study. The DERs in the microgrid include natural gas generators, battery storage, solar panels, and a wind turbine. The microgrid services either the on-site research facility and an electric vehicle station or a small distribution feeder serving approximately 200 residential and small commercial customers. The battery energy storage system (BESS) and natural gas generators both have grid forming capability. When islanding only the on-site research center and vehicle charging station, the BESS is used as the grid forming asset. When islanding the distribution feeder, the natural gas generators act as the grid forming asset. In either islanding scenario, the renewable assets are allowed to produce with their output level managed by the microgrid control system. **All assets are available for use when the system is grid tied.**

FIGURE 2 | Simplified scheme of the microgrid test bed network and location of measuring devices



Analysis of Power Quality Measurements During Test Scenarios

Seven test scenarios were performed with the various DER sources in the microgrid. These experiments were performed to intentionally introduce disturbances and measure the resulting impact with two different measurement instruments including low power G&W Accusense CVD sensors and a PQube® 3 power quality analyzer.

A view of the voltage magnitude, frequency, conducted emissions (supraharmonic frequencies), total harmonic distortion (THD), and flicker were monitored over this time-period. **Based on the data observed, the analysis in this data evaluation will focus on test scenarios 4, 6 and 7 shown in the table below.**

TABLE 1 | Testing Scenarios in Microgrid

TEST SCENARIO	DER SOURCE	TEST SEQUENCE	TIME
1	**Grid Tied Generator**	1. Turn on generators 2. Ramp up generators 3. Turn off generators	8:00 - 8:09 AM
2	**Grid Tied Battery**	1. Charge battery 2. Discharge battery 3. Idle battery	8:10 - 8:29 AM
3	**Voltage Regulator**	1. Step-up voltage regulator 2. Step down voltage regulators	8:30 - 9:09 AM
4	**Islanding all DERs**	1. Transition into Island 2. Transition out of Island	9:10 - 10:07 AM
5	**Solar Inverters, Grid-tied & Isolated**	1. Isolate each of the 3 solar inverters 2. Run the 3 inverters independently	10:08 - 10:39 AM
6	**Solar Inverters, Islanded & Isolated**	1. Isolate each of the 3 solar inverters 2. Run the 3 inverters independently 3. Run all inverters simultaneously	10:40 - 11:40 AM
7	**Wind Turbine, Islanded & Isolated**	1. Turn wind turbine on 2. Turn wind turbine off 3. Turn wind turbine on 4. Turn wind turbine off	11:41 - 11:59 AM

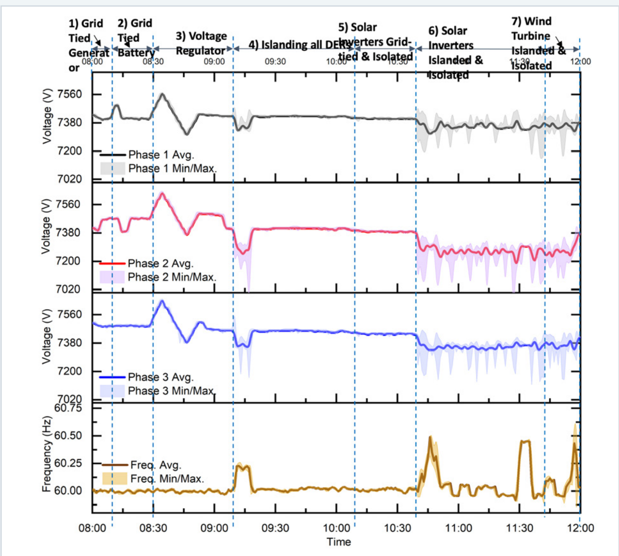
Voltage and Frequency Fluctuations

Voltage fluctuations are systemic variations of the voltage envelope or random voltage changes. Industry standard IEC 61000-4-30 indicates voltage dip (sag) thresholds are typically in the range of 85%-90% of the nominal voltage while voltage swell thresholds are typically greater than 110% of nominal voltage.

While no voltage deviations exceeded 10% of the nominal 7.2kV line-to-ground system voltage, voltage instability was observed with minimum values of 6.9kV observed during islanding all DERs and 6.84kV observed during islanded and isolated solar scenarios. The voltage magnitude behavior exhibited fluctuations and less stability when islanded and stabilized when tying back into the grid on all phases.

Frequency deviations of +0.2Hz were observed for 10 minutes during islanding all DERS and +0.5Hz during periods with solar inverters islanded and isolated. The highest frequency deviations of +0.6Hz occurred during periods with the wind turbine islanded and isolated.

FIGURE 3 | Voltage and frequency fluctuations observed during test scenarios 1 to 7



Supraharmonics

Supraharmonics are harmonic distortions in voltage and current waveforms in the frequency range of 2kHz-150kHz. The continuous increase in DERs has resulted in a proliferation of inverter-based power electronics that are subject to switching frequencies in the supraharmonic frequency range. Additionally, these distortions are found in non-linear loads associated with variable frequency drives (VFDs), electric vehicle chargers, LED controllers, and uninterruptible power supplies (UPS). These sources are subject to exhibiting symptoms such as thermal stress on connected equipment, insulation stress on cables, premature power supply failure, IED mis-operation, and lighting control malfunction.

Industry standard IEC 61000-4-30:2015 Ed3 (informative) provides guidance on how to measure these supraharmonic distortions (conducted emissions) in the 2-150kHz range.

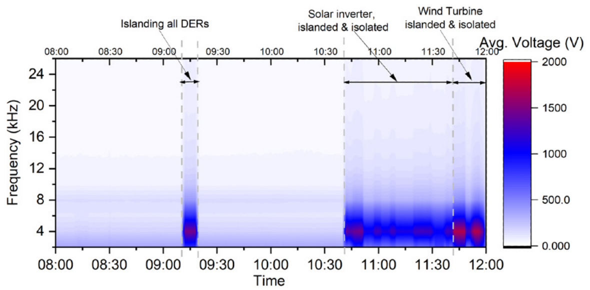
The PQube® 3 power quality analyzer referenced in this study measures conducted emissions in 2kHz segments with minimum, average and maximum magnitudes of the rms voltage in each segment. Other standards that reference conducted emissions include IEC 61000-2-2:2002, with focus on compatibility levels for voltage distortion and emissions and CISPR-16, with focus on providing methods for measuring high frequency radio disturbances and immunity greater than 9 kHz.

> **Supraharmonics** are harmonic distortions in voltage and current waveforms in the frequency range of 2kHz-150kHz.

While the potential for supraharmonic phenomena exists in a DER impacted grid, there are limited references documented in industry standards or guides for measuring supraharmonics in medium voltage, or as a complete measurement system including sensors, cables, and the intelligent electronic devices (IED). The measurement results published herein are subject to uncertainty in the measurement system used in the test bed demonstration. The measurement instruments used in the test have been tested independently at voltage supraharmonic levels with the PQube® 3 power quality analyzer compliant to IEC 61000-4-30:2015 guidance and the Accusense CVD sensors tested to frequency cutoff as identified in **FIGURE 1**.

FIGURE 4 presents the supraharmonics during the test scenarios. Supraharmonic measurements were observed throughout the islanding transition and islanded isolated solar and wind experiments. The graph on the top represents the average conducted emissions voltage measurements observed and the table on the bottom represents the maximum voltages observed at four (4) frequencies in the supraharmonic range, ranging from 4 to 16kHz. The maximum values were observed when the solar inverters and wind turbines were islanded, suggesting they are the main sources of MV supraharmonic distortion.

FIGURE 4 | **Supraharmonics observed during the testing scenarios**



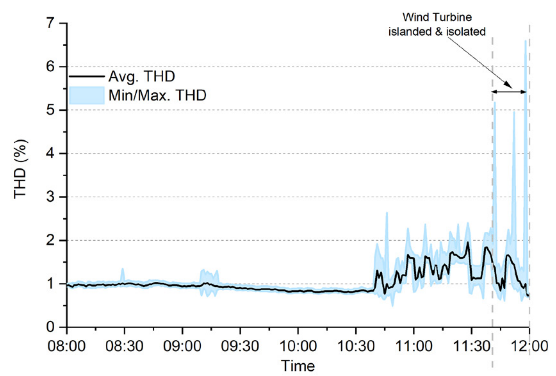
Freq.	Max. Voltage and time occurrence
4 kHz	4469.3 V @ 11:48 AM
8 kHz	1450.6 V @ 11:56 AM
12 kHz	746.7 V @ 11:45 AM
16 kHz	505.5 V @11:47 AM

Total Harmonic Distortion (THD)

Harmonic distortion in DERs is caused by nonlinear devices (non-linear loads), when the current is not proportional to the applied voltage. As the integration of DERs into the grid advances, various harmonic distortion limit criteria are implemented to ensure that the voltage and current waveform are compatible with the grid. IEEE 519, IEEE 1547-2018, and IEC 61000-3-2 standards impose the voltage THD must not exceed 5% at medium voltage levels.

FIGURE 5 represents the total harmonic distortion observed during isolated and islanded solar and isolated and islanded wind turbine. The THD is observed up to 6.6%, exceeding the limits identified in the standards.

FIGURE 5 | **THD values observed during the testing scenarios**

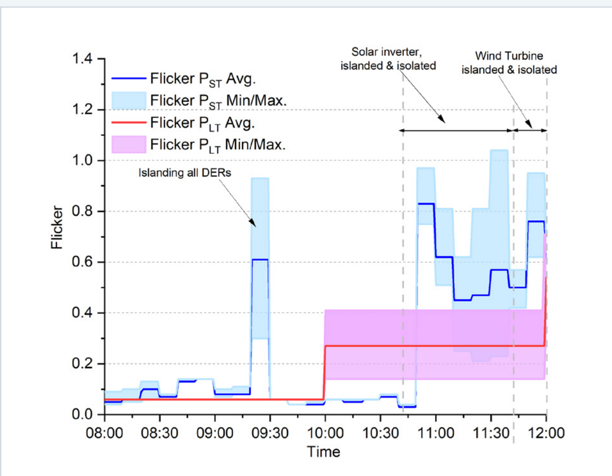


Voltage Flicker

Flicker is defined in the IEC 61000-4-30 standard as an impression of visual discontinuity induced by a light stimulus whose luminance or spectral distribution fluctuates with time. Light flicker phenomena appears when there is a fluctuation of voltage. The IEC 61000-4-15 standard establishes a voltage signal as the input, and the measurement procedure reproduces the response of the human vision system by precisely characterizing real flicker perception. Instantaneous flicker perception (P_{INST}) is given in perceptibility units, where a unit value defines the reference human flicker perceptibility threshold, which means that such level of flicker would be perceived by 50% of the population. However, this perception does not mean irritation and, therefore, cannot be directly related to customers complaints. In order to represent the irritation, the flicker meter integrates the flicker perception P_{INST} over two types of flicker. The short-term flicker (P_{ST}) is a statistical analysis of P_{INST} after 10 minutes and long-term flicker (P_{LT}) is the mean value of P_{INST} over the previous 2 hours, both synchronized to a real-time clock. The value of P_{ST} shall not exceed 1.0 and the value of P_{LT} shall not exceed 0.65.

FIGURE 6 represents the flicker values measured during island transition and the islanded and isolated wind and solar experiments.

FIGURE 6 | **Flicker voltage fluctuations observed during test scenarios**



Analysis of Power Quality Measurements During Island Event

During the test bed demonstration, an island event was observed that lasted for a duration of approximately 45 minutes and resulted in several power quality observations.

The battery energy storage system (BESS) is the grid forming asset with an imposed maximum state of charge. The microgrid control system is designed to temporarily curtail solar and wind DERs when in island mode if the energy production exceeds demand and the BESS is at its imposed maximum state of charge. Once the BESS state of charge drops below a prescribed threshold, the DER curtailment will be released. If communication to the DER source fails and the curtailment signal is not acknowledged, the microgrid control system will open the DER interconnection switch to isolate the asset from the microgrid.

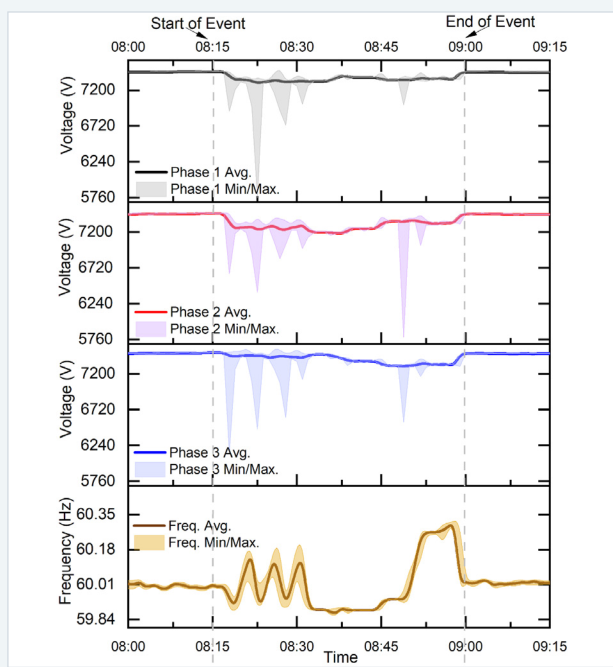
During an islanding event, the microgrid control system was unable to communicate with one of the five inverters that make up the solar DER. This resulted in a looping sequence that involved isolating the entire solar DER due to loss of communication, the BESS discharging to a state below its threshold, and closing the solar DER back into the island. Based on the sequence of events, the most likely cause of the voltage and frequency instability observed is likely due to the switching operation and resulting transformer inrush current, an over-power production issue that drove the BESS inverter into an unstable region, or a combination of both.

> **Flicker** is defined in the IEC 61000-4-30 standard as an impression of visual discontinuity induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Voltage & Frequency Fluctuations

Voltage and frequency fluctuations were observed for approximately 45 minutes before stabilizing as observed in Figures 7. Voltage dips (sags) were observed below the typical 10-15% threshold at 5.76kV on a nominal 7.2kV system.

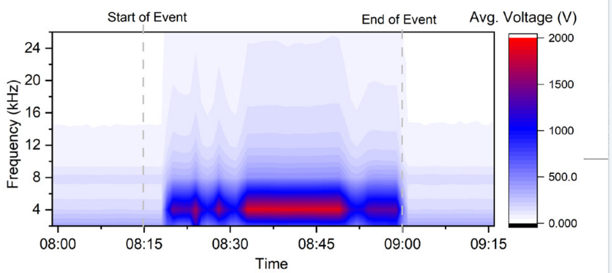
FIGURE 7 | **Voltage and frequency fluctuation during island event**



Supraharmonics

FIGURE 8 represents the supraharmonics measured throughout the duration of the islanding event. The graph on the top represents the average conducted emissions voltage measurements observed and the table on the bottom represents the maximum voltages observed at four (4) frequencies in the supraharmonic range, ranging from 8kHz to 24kHz. **These observations demonstrate the emission behavior during the event showed maximum values that are significantly higher (approximately 3 to 4 times) than what was observed in the test scenarios during islanding.**

FIGURE 8 | **Supraharmonics observed during island event**

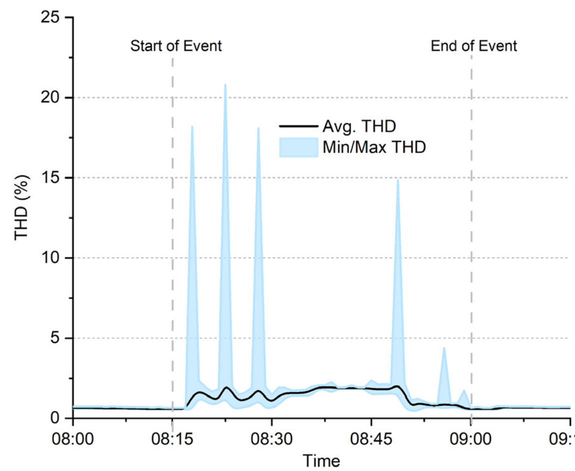


Freq.	Max. Voltage and time occurrence
8 kHz	3930.8 V @ 8:24 AM
16 kHz	1993.9 V @ 8:24 AM
20 kHz	1611.8 V @ 8:24 AM
24 kHz	1263.7 V @ 8:24 AM

Total Harmonic Distortion (THD)

FIGURE 9 represents total harmonic distortion observed during the islanding event. Maximum values were observed up to 20.85%, exceeding the 5% limits identified in the standards.

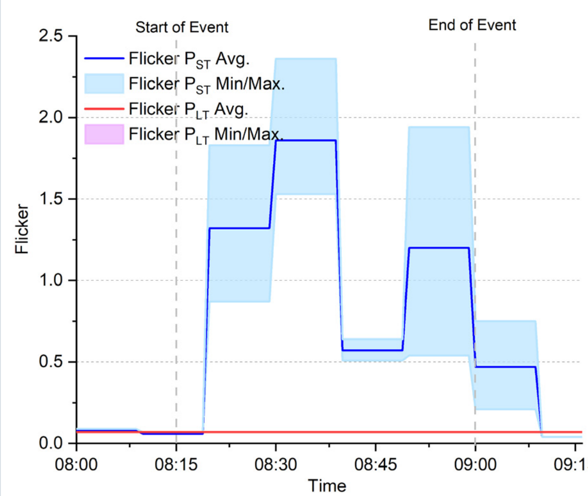
FIGURE 9 | **Total harmonic distortion observed during island event**



Flicker

FIGURE 10 represents the flicker values measured during the islanding event. The P_{ST} values were observed >1.0, above the thresholds published in standards. During the event, it was reported that flickering lights were observed.

FIGURE 10 | **Flicker observed during island event**



Conclusions

The microgrid test bed demonstration with the PQube® 3 power quality analyzer paired with Accusense CVD sensors proved that **DERs are susceptible to generating power quality phenomena** such as supraharmonics, voltage instability, total harmonic distortion, and flicker.

The test scenarios performed yielded power quality related observations in three of the seven experiments. Islanded conditions demonstrated instability with voltage fluctuations, THD, and evidence of supraharmonic frequencies in the 4 to 16kHz range.

In addition to the test scenarios, an unintentional event was measured and recorded with the Accusense CVD sensors and PQube® 3 power quality analyzer. This event involved an islanded condition with a sequence of switching DERs that resulted in approximately 45 minutes of power quality issues. During this event, observations were recorded including voltage sags at 5.76kV, frequency of 60.3Hz, flicker P_{ST} >1.0, THD up to 20.8%, and supraharmonic frequencies up to 24kHz.

TABLE 2 below summarizes the power quality issues observed during the three test scenarios and the microgrid islanding event.

TABLE 2 | Test Scenarios and Event Observations Summary

TEST SCENARIO #/EVENT	DER SOURCE & EXPERIMENT	TEST SEQUENCE	OBSERVATIONS
4	**Islanding, all DERs**	1. Transition into Island 2. Transition out of Island	• Voltage dropped to 6.9kV (7.2kV L-G nominal) • Supraharmonic frequencies (conducted emissions) observed up to 12kHz • Flicker present
6	**Solar Inverters, Islanded & Isolated**	1. Isolate each of the 3 solar inverters 2. Run the 3 inverters independently 3. Run all inverters simultaneously	• Variation/instability observed in voltage magnitude • Voltage dropped to 6.84kV (7.2kV L-G nominal) • Supraharmonic frequencies (conducted emissions) observed up to 14kHz • 2 frequency observations up to 60.5Hz
7	**Wind Turbine, Islanded & Isolated**	1. Turn wind turbine on 2. Turn wind turbine off 3. Turn wind turbine on 4. Turn wind turbine off	• Voltage dropped to 7.01kV (7.2kV L-G nominal) • Supraharmonic frequencies (conducted emissions) observed up to 16kHz • 1 frequency observation up to 60.6Hz
ISLAND EVENT	—	—	• Voltage sags at 5.76kV and frequency observations up to 60.3Hz • THD up to 20.8% and flicker P_{ST} >1.0 • Supraharmonic frequencies (conducted emissions) observed up to 24kHz

These measurement observations demonstrate that **DERs do have an impact on grid power quality** and that **supraharmonic frequencies are present** beyond what traditional technologies can measure at the medium voltage level.

Traditional instrument transformer technologies may have frequency cut-off measurement limitations that inhibit their ability to measure supraharmonic frequencies. Traditional IEDs may have frequency measurement limitations if they are designed to measure up to typical industry guidelines at the 50^{th} harmonic (3kHz). **While the impact of supraharmonic activity to medium voltage grid reliability is not thoroughly understood, this study demonstrates DERs do generate them, and that they can be measured with capable sensors and power quality analyzers.** The Powerside PQube® 3 power quality analyzer and G&W Accusense CVD system applied in this microgrid test bed have demonstrated supraharmonic frequency measurement of 4kHz-24kHz that may be limited or undetectable with traditional measurement systems.

For Further Reading

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