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Power Quality Assessment in Distributed Energy Resources

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SUMMARY

The penetration of renewable energy is increasing worldwide and initiatives such as distributed energy resources (DERs) and microgrids play a vital role in generating electrical power with less environmental impacts. The inherent nature of these inverter based DERs creates significant technical challenges to power industry. As the grid continues to evolve towards renewable power generation, grid stability and power quality monitoring will become more prominent to maintain a reliable grid.

This paper presents a data driven based understanding of how DERs impact the power quality of the grid. Several test scenarios were performed at a Utility microgrid test site, consisting of various DER sources and measurement instrumentation. These tests were performed to intentionally introduce disturbances and measure the resulting impact with measurement instruments including low power capacitive voltage dividers (CVDs) sensors and a power quality analyzer. In addition to these tests, the microgrid was monitored for 10 months (Aug 2020-June 2021) and subjected to all 4 seasons. Throughout this monitoring period, an event was observed that exhibited significant power quality disturbances. The voltage magnitude, frequency, conducted emissions (supraharmonic frequencies), total harmonic distortion (THD), and flicker were recorded to observe behavior and its impact to the system.

The 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 intelligent electronic devices (IEDs) may have frequency measurement limitations if they are designed to measure up to typical industry guidelines at the 50th 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 CVD sensor and power quality analyzer system applied in this microgrid test bed have demonstrated frequency measurement of 4kHz-24kHz that may be limited or undetectable with traditional measurement systems.

KEYWORDS

Power quality, Microgrid, Supraharmonic, Distributed Energy Resources, Capacitive Voltage Dividers

1. Introduction

Power systems are experiencing a significant transformation with the implementation of emerging technologies that address 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 [1].

The operation of a microgrid depends on successful integration of DERs and requires consideration of several factors such as anti- islanding, synchronization and power quality. Modern renewable energy sources use power electronic systems such as 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 from these inverters 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 supraharmonic threat to the electric power system reliability [2-3].

This paper presents measurement observations of DER impact to voltage & 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, a unintentional event occurred in the microgrid was captured and the resulting measurements were 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) tested to IEC 60044-7 and a power quality analyzer tested to IEC 61000-4-30 Class A for data collection and analysis of the measurement data.

2. 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 & 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 divide the primary MV down 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 ~100s 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 are connected 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 40 kHz and 7 kHz for CVD and RVD respectively. The high cut-off frequency of CVDs makes it suitable for detecting high frequency, supraharmonic phenomenon up to 40kHz.

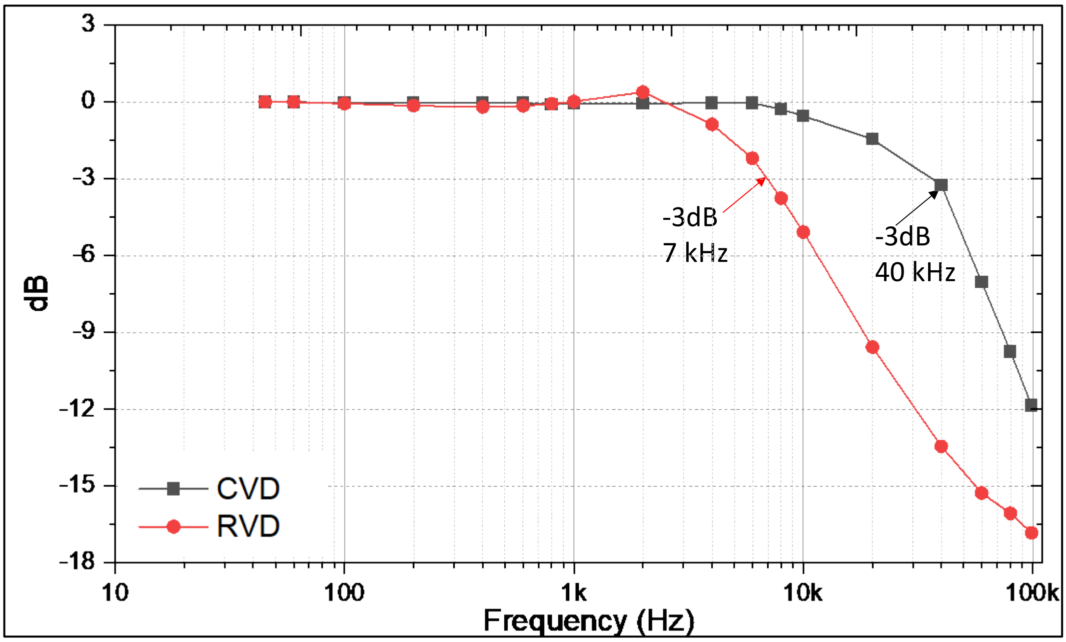


Figure 1: Frequency response of CVD and RVD sensors

3. The Microgrid Architecture Under Study

Figure 2 represents a simplified scheme of the microgrid test bed under study. The main components of the microgrid are:

- a voltage regulator
- 2 × 500 kW natural gas generators
- a 250 kW battery storage
- a 100 kW wind turbine
- 4 photovoltaic plant with a rated power of about 25 kW
- a 25-kW load.

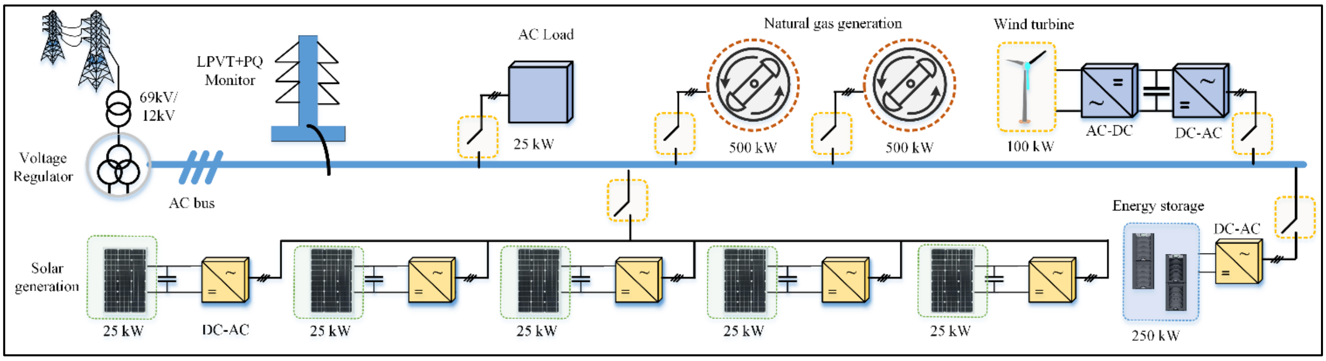


Figure 2: Simplified scheme of the microgrid test bed network and location of measuring devices.

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 3 shows the renewable energy sources and field installation of the CVDs at the microgrid.

Figure 3: Renewable energy sources at the microgrid and field installation of voltage sensors

4. Analysis of Power Quality Measurements During Testing Scenarios

Seven simulated experiments were performed with the various DERs in the microgrid as shown in table 1. These experiments were performed to intentionally introduce disturbances and measure the resulting impact with two different measurement instruments including low power CVD sensors and a power quality analyzer. A view of the conducted emissions (supraharmonic frequencies), voltage magnitude, frequency, total harmonic distortion (THD), and flicker were monitored over this time-period.

Table 1: Testing scenarios in the microgrid

Exp.	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

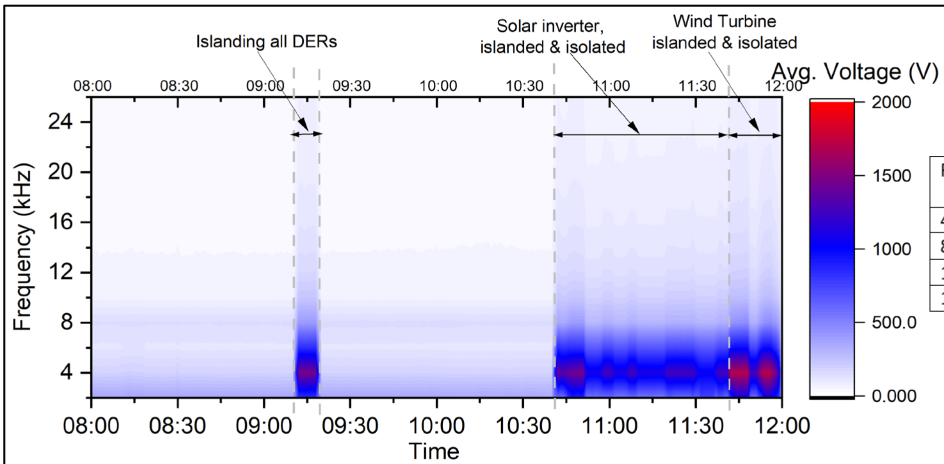
4.1 Supraharmonics

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 [4] Ed3 (informative) provides guidance on how to measure these supraharmonic distortions (conducted emissions) in the 2-150kHz range. The 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 & immunity greater than 9 kHz.

While the potential for supraharmonic phenomena exists in the DER impacted grid, there is little documented in industry standards or guides for measuring supraharmonics in medium voltage or as a complete measurement system, including sensors, cables, and the IED. The measurement results published herein are subject to error and 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 power quality analyzer compliant to IEC 61000-4-30:2015 guidance and the CVD sensors tested to frequency cutoff as identified in section 2.

As shown in Figure 4 supraharmonic measurements were observed throughout the islanding transition and islanded isolated solar and wind experiments. The graph on the left represents the average conducted emissions voltage measurements observed and the table on the right represents the maximum voltages observed at four frequencies in the supraharmonic range, ranging from 4-16kHz. The maximum values were observed when the solar inverters and wind turbines were islanded, suggesting they are the main sources of MV supraharmonic distortion.



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

Figure 4: Supraharmonics observed during the testing scenarios

4.2 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 behavior exceeded 10% of the nominal 7.2kV line-to-ground system voltage, voltage instability was observed throughout the experiments with 6.9kV observed during islanding all DERs and 6.84kV observed during islanded and isolated solar. The voltage magnitude behavior exhibited fluctuations & less stability when islanded and stabilized when tying back into the grid on all phases.

Frequency deviations of +0.2Hz was observed for 10 min during islanding all DERS and +0.5Hz during solar inverters islanded and isolated. The highest frequency deviations of +0.6Hz occur during the wind turbine islanded and isolated as shown in Figure 5b.

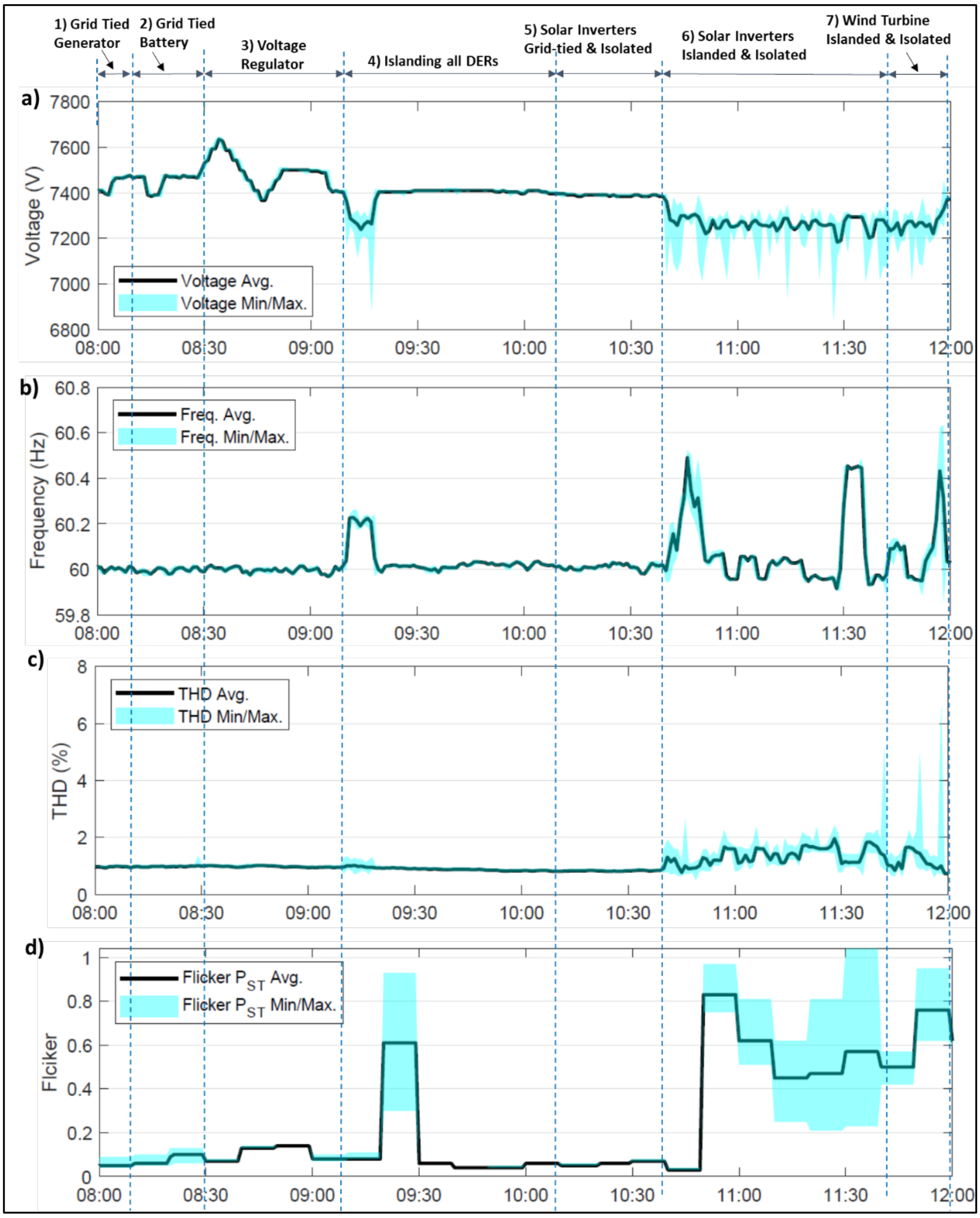


Figure 5: a) Voltage fluctuations b) Frequency fluctuations c) THD and d) Flicker observed during the test scenarios

4.3 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 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. The THD is observed up to 6.6% as shown in Figure 5c, exceeding the limits identified in the standards [4-6].

4.4 Voltage Flicker

Flicker is defined in the IEC 61000-4-30 [3] standard as an impression of visual discontinuity induced by a light stimulus whose luminance or spectral distribution fluctuates with time. Light flicker phenomena appear when there is a fluctuation of voltage. The IEC 61000-4-15 [7] 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 5d represents the flicker values measured during island transition and the islanded and isolated wind and solar experiments.

5. Analysis of Power Quality Measurements During Island Event

During the 10 month test bed demonstration, an island event was observed that lasted for a duration of approximately 45 minutes (8:15-9:00 AM, May 10th 2021) and resulted in several power quality observations. Voltage sags were observed below the typical 15% threshold at 5.76kV on a nominal 7.2kV system. Supraharmonics 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. Maximum values of THD were observed up to 20.85%, exceeding the 5% limits identified in the standards. During the event, it was flickering lights were observed (Pst values were observed >1.0).

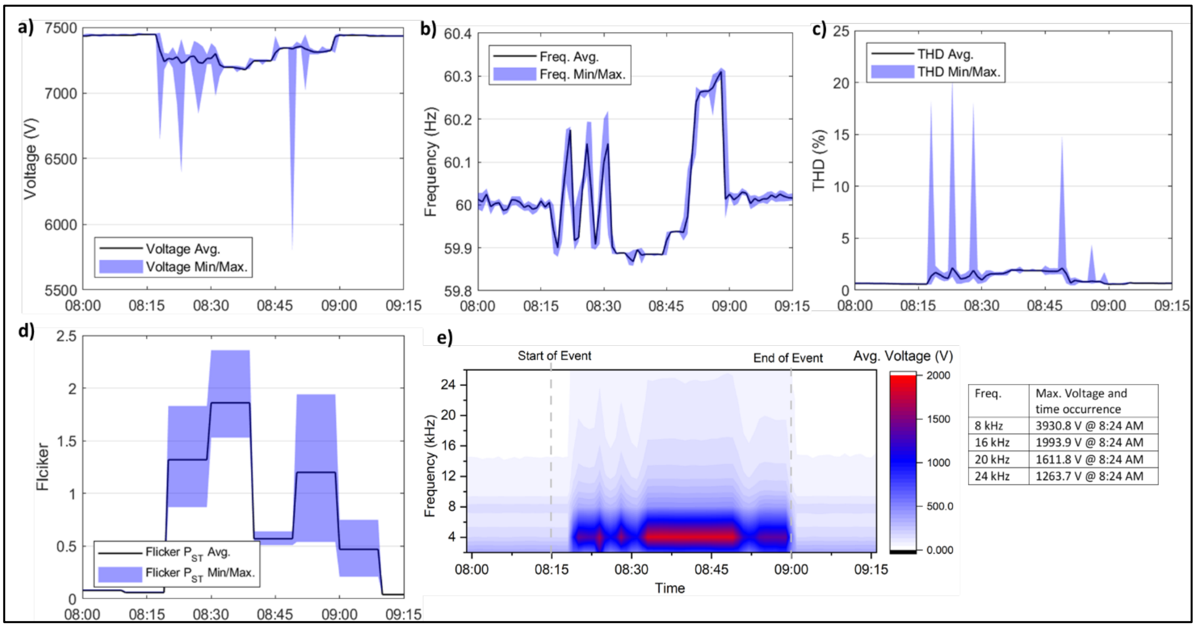


Figure 6: a) Voltage fluctuations b) Frequency fluctuations c) THD d) Flickers e) Supraharmonics observed during Island event

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.

6. Summary

The microgrid test bed demonstration with the power quality analyzer paired with high performance 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 3 of the 7 experiments and the islanded event, summarized in Table 2 below.

Table 2: Test Scenarios and Event Observations Summary

Exp.	DER Source	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 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 up to 14kHz - 2 frequency observations at 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 frequency up to 16kHz - 1 frequency observation at 60.6Hz
Island Event	-	-	- Voltage sags at 5.76kV - THD up to 20.8% and flicker Pst >1.0 - Supraharmonic frequencies 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 50th 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 CVD sensor and power quality analyzer system applied in this microgrid test bed have demonstrated frequency measurement of 4kHz-24kHz that may be limited or undetectable with traditional measurement systems.

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