Observed Effects of Geomagnetic Disturbances from Wide Area Monitoring System

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SUMMARY

A distributed sensor network has been deployed in over 700000 homes so far. The sensor network identified several grid impacts during a May 10, 2024, solar storm. The storm produced geomagnetic disturbances (GMD) on many grid networks. This presentation will share measurements made by the sensor network and lessons learned from the event. Some of the lessons learned contradict traditional understanding of GMD events.

KEYWORDS

Geomagnetic Disturbance (GMD), Geomagnetically Induced Currents (GIC), Solar Storm, Wide Area Monitoring, Power Quality, Total Harmonic Distortion (THD), Harmonics

Background

Wide Area Monitoring System

To help prevent electrical fires within the home, several insurance companies have launched programs providing an Internet of Things (IoT) sensor to homeowners. The sensor has two sampling rates: 30kHz and 30MHz. The 30MHz channel detects electrical arcing and looks for faults in the home's electrical wiring. Meanwhile, the 30kHz channel assesses the electrical environment that the home is experiencing [1]: voltage, frequency, and total harmonic distortion (THD). The sensors send a continuous stream of data to the cloud-based data center.

Over the last four years, the sensor network has expanded to over 700,000 homes. The current rate of expansion is approximately 50,000 homes each month. As the sensor network expands, sensor data across homes is correlated by time and location to identify events on the grid. A current heatmap of the sensor locations is shown in the figure below.

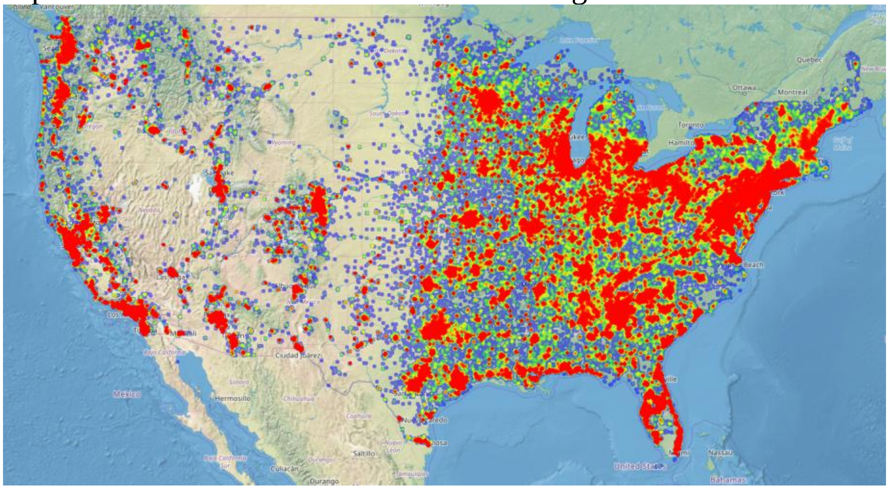

Figure 1 - Current Heatmap of Sensor Locations

The system discriminates between events sourced inside the home and outside the home. For example, the voltage from two different sensors is displayed in the graph below. While it is clear that these two sensors are electrically close by looking at the overall voltage profile throughout the day, it is also quite clear that some of the events are unique to the monitor. For example, the blue trace (home 1) has several small voltage sags related to a large load starting within the home. The green trace has similar sags associated with a large load starting within that home. The events do not occur simultaneously, so it is clear that these events are unrelated to grid operations.

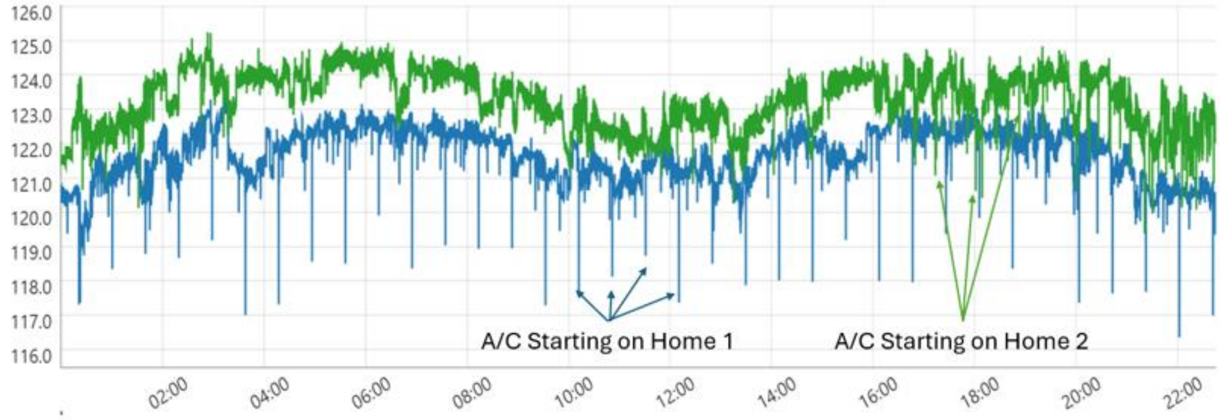

Figure 2 - Voltage Traces Showing Large Loads Starting Inside Home

Events are defined as grid events when multiple independent sensors record the same type of event within 200 ms of each other [2]. An example of a power outage is shown in the figure below [2]. Each trace represents the voltage from a sensor in different homes. The graph has a light blue vertical line at approximately 12:04, representing the outage's start time. Several traces have data gaps starting at this time, indicating that a power outage occurred at several homes simultaneously.

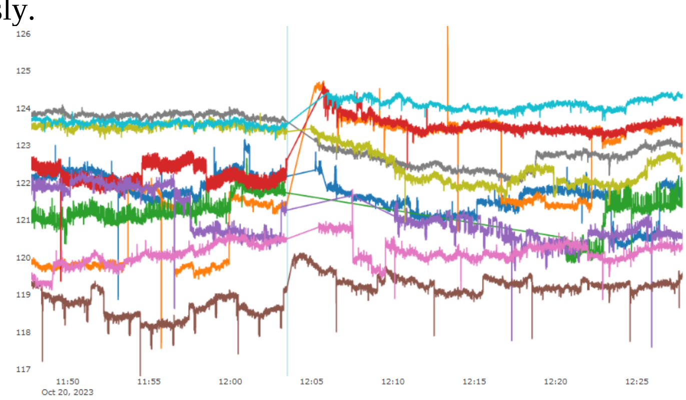

Figure 3 - Voltage Traces During Power Outage

In January 2024, the sensor network was upgraded to include THD measurements. The sensors continuously report the THD back to the data center. A map of the THD is shown in the figure below. Each dot represents the percent of THD recorded by each sensor. The colors indicate the severity of the THD at each location. Per IEEE 519, the limit for THD for locations below 1000 Volts is 8%. As can be seen in the map, there are a few hotspots around the country that routinely exceed this value.

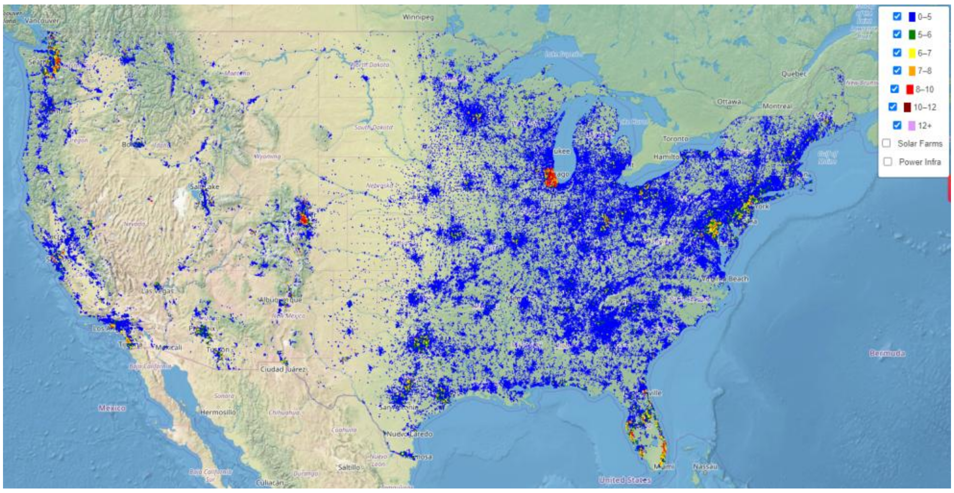

Figure 4 - THD Map

A trend plot of the THD is shown in the figure below. Each line in the graph below shows the THD recorded by a different sensor. Notice that several of the sensors all have a similar THD profile. The THD changes simultaneously, suggesting that the recorded THD is sourced on the grid. Notice that two sensors (blueish lines) do not follow the same pattern. Even though these sensors are geographically close to the sensors above, they are fed from a different circuit with a distinct THD profile.

Figure 5 - THD Trend

Geomagnetic Disturbances

A geomagnetic storm is a disturbance of the Earth's magnetosphere. One cause of these storms is solar coronal mass ejections (CMEs). The storms tend to last from hours to days. The storms can disrupt satellite communications, including those of the Global Positioning System (GPS) satellites. The storms can also produce Geomagnetically Induced Currents (GIC). The GIC, in turn, may negatively affect the power system [3].

The Sun's magnetic field flips roughly every eleven years in what is known as a solar cycle [4]. Near the maximum of the solar cycle, sunspot and CME activity increases. CMEs are large plasma and magnetic field expulsions from the Sun's corona. The figure below shows several CMEs from the Sun as captured by the National Oceanic and Atmosphere Administration (NOAA) [5].

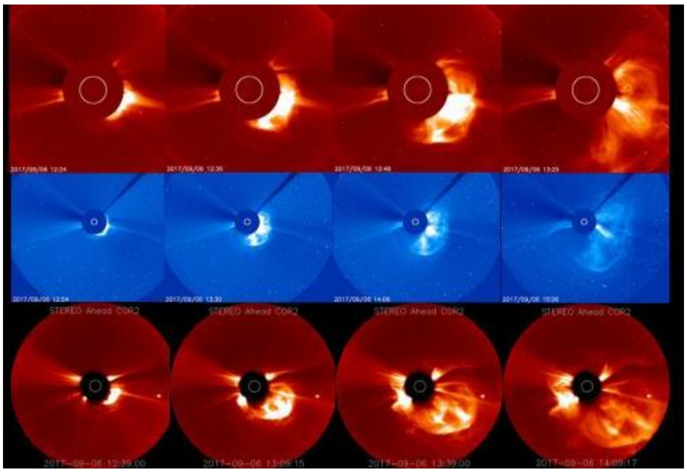

Figure 6 - CME

NOAA measures the influence of solar storms by recording values from several magnetometer stations spread across the globe. The measurements are converted to an index, which indicates the amount of geomagnetic activity. NOAA continuously monitors these indexes and issues alerts when thresholds are exceeded.

Historically, the impacts of these storms on the grid were thought to be primarily of concern to transmission. The relatively long transmission lines act as a parallel conductive path when transformers are grounded at both ends [6]. In addition to lines, the transmission transformers tend to be of concern as the GICs can present at quasi-DC currents on transformer neutrals, leading to saturation of the magnetic core [6].

GMD is of concern as there have been several historical outages related to this phenomenon. In 1989, the Hydro Quebec system collapsed because of space weather. Other storms have caused communication outages, such as those in November 1903 and March 1946. Still others have caused transportation issues, like the May 1921 event [7].

Measurements

On May 8, 2024, a recorded CME was directed toward the Earth. The travel time of the CME is generally a few days, and it began to interact with the Earth's magnetosphere on May 10, 2024. The figure below shows the Kp index during the two-day period [8].

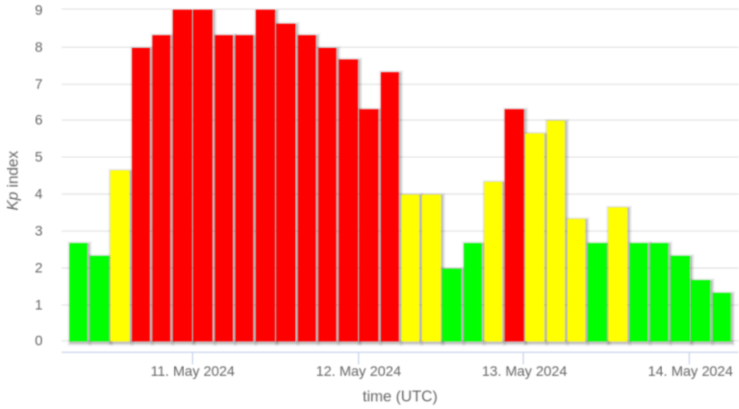

Figure 7 - Kp Index During May Solar Storm

At the same time, the sensor network detected elevated THD measurements across seven northern states: Arkansas, Maine, Minnesota, New York, and Washington. The figure below shows the THD trends for the sensors. Conspicuously, the THD measurements during the solar event were extremely elevated. The IEEE 519 limit for THD is 8% for systems with less than 1000V. During the storm, some locations experienced as high as 24% THD.

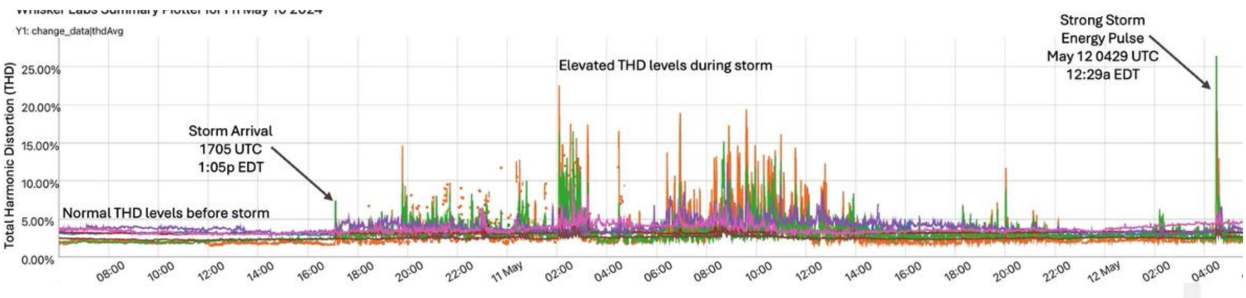

Figure 8 - THD Measurements During Solar Storm

Several sensors were enabled with waveform recording to better understand the harmonic data composition. The figure below shows the waveforms from several of the sensors overlapped. The dashed line represents a perfect 60Hz sine wave.

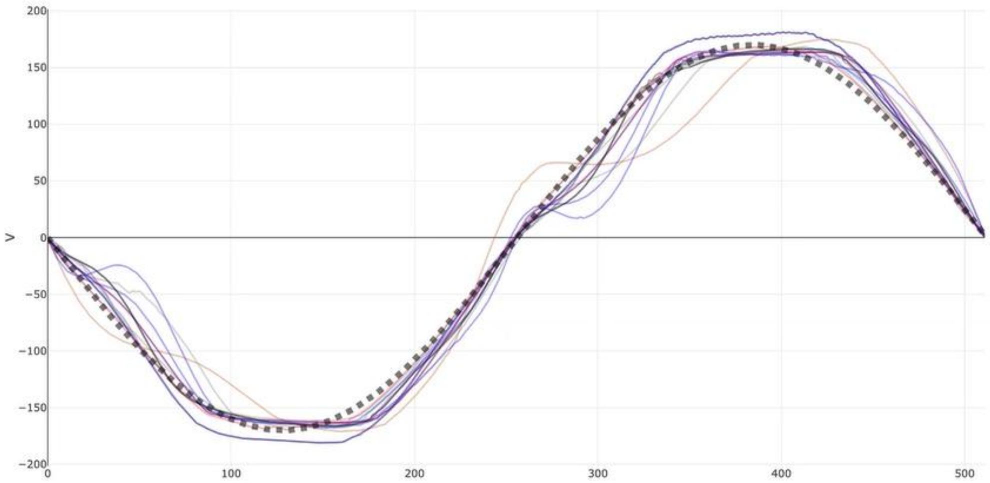

Figure 9 - Waveform Data

A Fast Fourier Transform (FFT) of the waveforms reviewed had elevated levels of harmonic spectra, particularly below the 13th harmonic. The figure below shows the FFT for one of the waveforms above. Most power systems have naturally occurring odd harmonics (3rd, 5th, and 7th). However, these values were elevated during the storm. In addition, most power systems do not typically have even harmonics. The 4th, 6th, and 8th harmonics were also elevated during the storm.

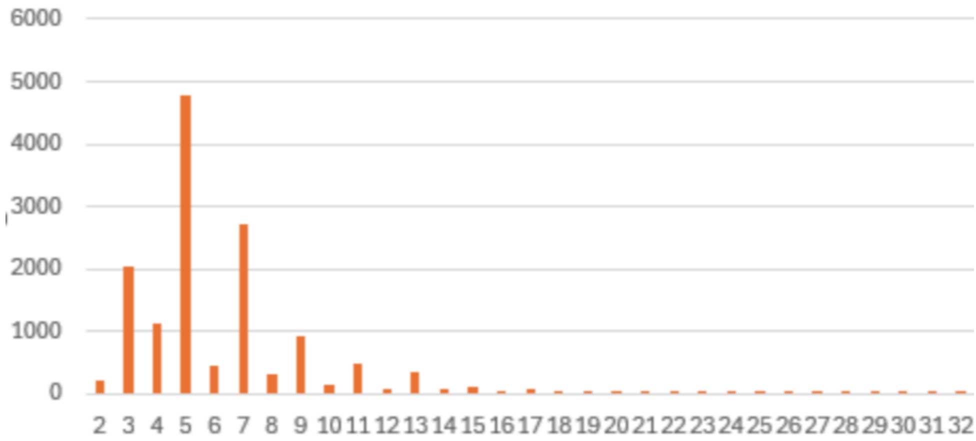

Figure 10 – Harmonic Components

The voltage was negatively impacted for several locations. The graph below shows the voltage trends for several sensors during one of the more severe GMD events. Though the voltage was influenced, it is unlikely the voltage variation caused any equipment misoperation.

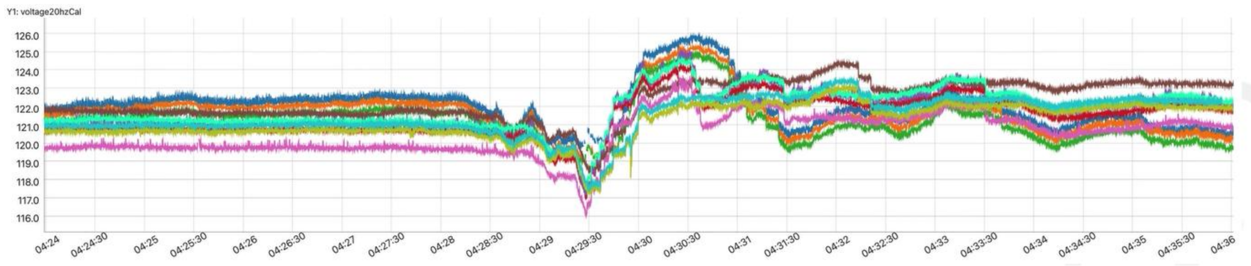

Figure 11 - Voltage Trend During Solar Storm

To better understand how widespread the event influenced the US grid, a heat map was produced to show where the THD increased. The map was normalized to reduce typical background THD values. Each dot in the figure below represents an individual sensor. The sensor's color shows the THD increase because of the solar storm. Each tile in the figure represents a different snapshot in time as the storm progressed.

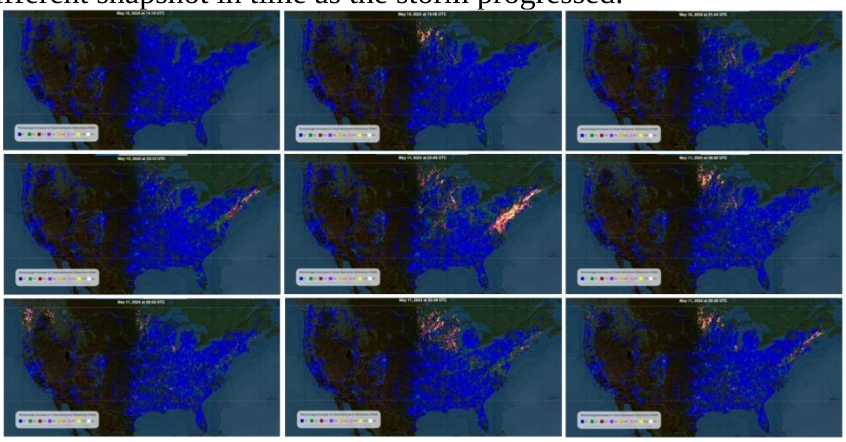

Figure 12 - Heatmap of THD Increase

Observations / Analysis
GIC is likely higher in areas where the Earth's resistivity is higher [7]. The figure below shows a map of the Earth's resistivity [9]. Indeed, there was a high correlation between the location of high earth resistivity and higher harmonic values, which suggests that the transformers were saturated and producing harmonic components, as previously stated [7].

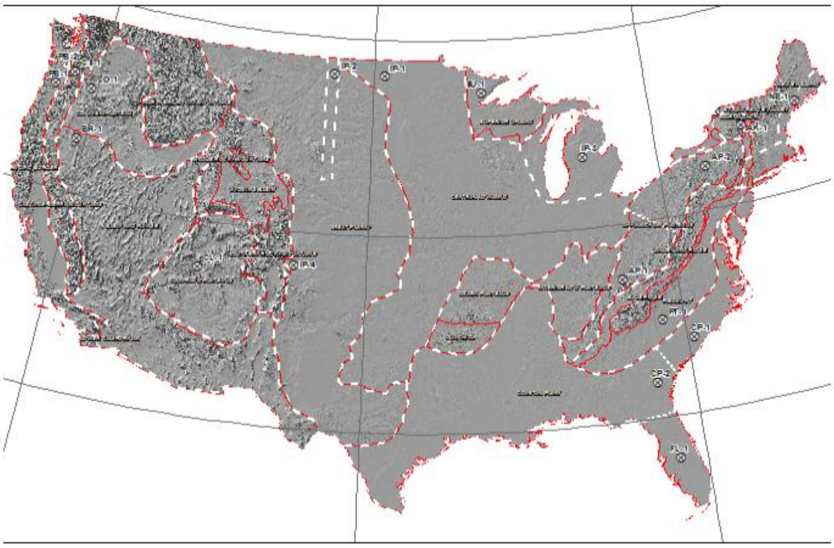

Figure 13 - Earth Resistivity

Findings / Conclusions
Historically, GIC was thought of as a transmission system-related issue [10].The wide area network has shown that the impacts can be relatively localized to the distribution system. Therefore, the following conclusions were drawn:

- Existing models appear to underestimate THD
- Existing models do not sufficiently predict the propagation of harmonics through the distribution network
- Improved data can help validate and refine existing models.

Fortunately, the wide area monitoring system captured data from the recent GMD event. Future studies could include much more granular data than in the past due to the availability of this resource.

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