A National Power Quality Index

Authors: (Whisker Labs) Bob Marshall, Joe McNulty, Chris Sloop

(Lifescale Analytics) Theo Laughner

Contact Author: Theo Laughner, tlaughner@lifescaleanalytics.com

Country: USA

Background

Electrical fires impact nearly 50,000 homes each year. These fires cause approximately $1.3B in property losses each year and result in thousands of injuries and deaths annually. A low-cost sensor network has been deployed with the primary goal of preventing electrical fires. To date, the service is active in 150,000 homes and has accumulated nearly 125,000 home-years of data, providing a statistically significant foundation for performance analysis data.

While the prevention of electrical fires was the primary focus of the sensor network, the data collected is also useful in describing the power quality performance of utilities where the sensors are deployed. By aggregating data from individual homes, the performance of areas within a utility can be described and more broadly the overall performance of each utility. The system records voltage sags, voltage swells, voltage interruptions.

Previous studies (EPRI, 2022) namely DPQI, DPQII, and DPQ/TPQIII have been previously conducted by EPRI. While those studies were limited by the few utilities involved. Interestingly, the data has good correlation to the distributed sensor network described herein. In the report, the estimated impacts due to power quality disturbances was estimated between $145B and $240B USD. Naturally, knowing where these events occur, and fixing them in a timely fashion is important.

The Technology

(Babrauskas, et al., 2022)Electricity travels over conductors on the grid, inside the home, up to and inside connected devices and appliances. Electrical fires can occur when a conductor fails to conduct, or an insulator fails to insulate.

Conductors fail to conduct because a joint fractures, the last strand of a cable breaks, or an outlet, 'push-in' or other connection or junction on a conductor becomes loose. These conditions often leave conductors with too small a surface area to provide a safe and reliable connection. Consequently, the lack of a quality connection can result in a high resistance connection that produces heat and leads to physical and chemical processes that oxidize the connection, further increasing resistance and heat. Electrical arcing often occurs across these poor connections depending on many factors, including but not limited to physical changes in the connection (temperature), the energy load drawn across the connection, and the changing quality (or lack of quality) of the connection.

Insulators fail where a flexible cord or rigid insulator fractures or pollutants or water infiltrates an intended insulation opening. Fractures may arise from defects in manufacturing, hammer blows during construction, or repeated stress in use. Each time a small electrical failure occurs across one of these fractures, a bit more of the insulator is damaged, (usually) extinguishing the immediate failure but (usually) facilitating future failures. Most organic insulators "char," slowly transforming them into more conductive simpler organic materials through a process known as "carbonization of insulation" . In other words, the function of the insulator is slowly compromised.

In turn, arcing along these carbonized paths produces "scintillations," dim flashes of red, orange, yellow, or white light. Scintillations and the fault currents associated with them are sporadic and highly intermittent. As scintillations and fault currents evolve and become more active, they generate pulses with high-frequency content. These pulses propagate through the home's electrical network. This process, arc tracking, is a slow process that can take from a few weeks up to many years. These electrical discharges may eventually become continuous arc faults, resulting in a large flow of current and large energy releases (with correspondingly high temperatures) that can ignite a fire.

The sensor is designed to detect electrical arcing and power quality problems. Electrical arcing produces impulsive signals at ignition and extinction many times in each 60 Hz electrical cycle. Impulsive signals produce broadband electrical noise, including high-frequency energy that propagates freely through home wiring, which behaves as a communications network at high frequencies. The sensor samples voltage at 30 MHz, providing high-resolution, high-frequency monitoring of the entire home. The sensor consists of custom-built hardware and digital signal processing capable of digitizing, detecting, and interpreting the medium to high-frequency content in these pulses. The overall system design considers the signal characteristics, channel transfer characteristics, and the noise environment of the home.

For simplicity, this paper refers to electrical conditions identified by the sensor that have the potential to cause a fire as 'hazards'; generally, such hazards present as series arcing (conductor failing to conduct) or parallel arcing (insulator failing to insulate), and/or power quality problems. The system's "signal library" includes proprietary high-frequency fingerprints corroborated from sensor-identified electrical hazards. This library is reinforced and grows with each hazard, forming a crucial component of its learning system. The system's signal library and learning system details fall outside the scope of this paper.

Power Quality Analysis

Over 1000 cases or hazard detection and mitigation events - have been documented at the time of this paper. Each case is an event where the system detected, localized, identified, and mitigated a hazard prior to the potential ignition of an electrical fire. In general, events are classified potential fire hazards and categorized as one of the following: an Electrical Fire Hazard (EFH, those generally found in the home), a Utility Fire Hazard (UFH, those related to electric utility infrastructure), or a power quality (PQ) event which is always related to utility infrastructure. For the purposes of this paper, we will focus most of our discussion to the power quality events.

PQ Criteria

A PQ event is a classified as a sag, swell, or interruption. A sag event is when the voltage drops below 90% of nominal. A swell event is when the voltage is above 110% of nominal. An interruption is when the voltage drops to below 70% of nominal. These numbers broadly align with the ITIC Curve (Stymiest, 2022) shown in figure 1, below.

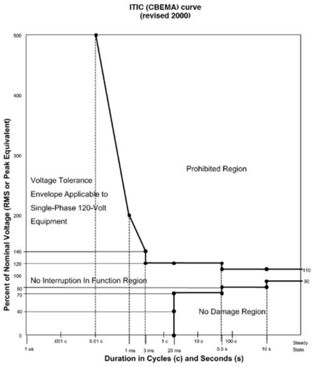

Figure 1 - ITIC Curve

There are several reasons that lead to poor utility PQ performance. Equipment issues, lightning, and vegetation ingress can all cause PQ issues on the grid. When a single sensor the network detects and event, it is generally classified as an EFH or UFH. However, when at least two sensors detect an event within a .5 second window and the sensors are more than 30 meters apart, then the event is classified as a PQ event. This criterion eliminates single-home events. Moreover, if multiple events are detected by multiple sensors in the same home, then a home is only counted one time.

Aggregation

Individual meter data is not shown. This is to protect the privacy of the individual homeowner. The data is aggregated either by utility boundary or by grid. The utility boundaries were identified by the Homeland Infrastructure Foundation-Level Data (December 2021). For this reason, the exact utility boundaries may be in error as shown in the index. In addition to aggregation by utility, the data is also aggregated using a 50 km^2 grid. To improve the statistical significance, utilities must have more than 250 sensors to be displayed. In addition, grids must have at least 25 sensors to be displayed.

Data can be displayed for a specific month or averaged over the last 12 months. The heat map scale changes based on the event type. This is due in part because sags/outages occur about 5 times more often than surges. In addition to seeing the individual event types, a summary of all the event types is also available. The following sections show examples of the various maps available in the system.

Interruptions

Figure 2, below, shows the interruptions for July, 2022 aggregated using grids. While figure 3, shows the same data aggregated by utility.

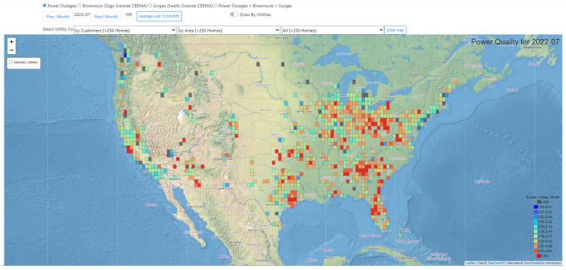

Figure 2 - July, 2022, Interruptions by grid.

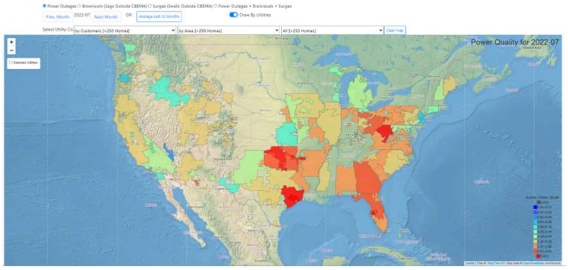

Figure 3 - July, 2022, Interruptions by utility.

Looking at the same data for March of 2022 in figures 4 and 5 below, there are significantly more outages in the summer months. This is likely due to summer storm activity. There are fewer squares in the maps below. This is not due to a change in sensor coverage, but a change in the number of events. Though additional sensors have been deployed between March and July.

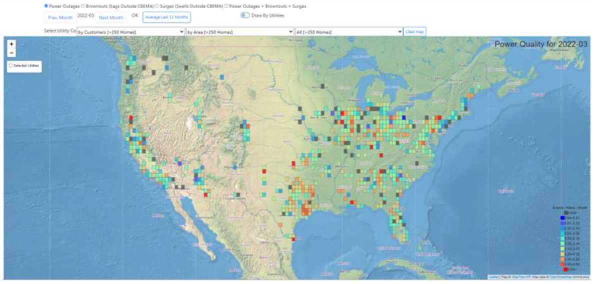

Figure 4 - March, 2022, interruptions by grid.

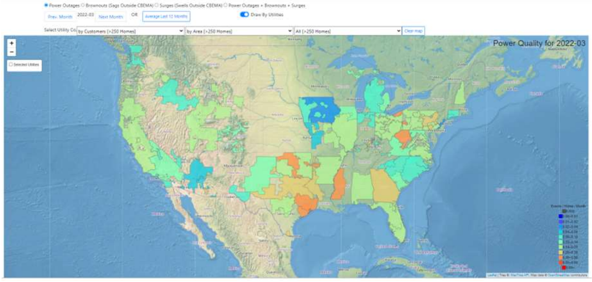

Figure 5 - March, 2022, interruptions by utility.

In addition to a map of the data, a table is provided to compare the exact numbers by utility. Table 1, below, shows the top 5 worst performing utilities for power outages. As can be seen in the map, not all utilities have monitors in place. Consequently, these would be the worst performing utilities where there are monitors.

Table 1 - 5 Worst performing utilities for interruptions in March 2022

Utility	Power Outage Index	Brownout Index	Surges Index	Power Outage + Brownout + Surge Index
CENTERPOINT ENERGY	0.438	0.302	0.003	0.77
PPL ELECTRIC UTILITIES CORP	0.26	0.083	0	0.377
GEORGIA POWER CO	0.258	0.193	0.014	0.526
ONCOR ELECTRIC DELIVERY COMPANY LLC	0.233	0.132	0.035	0.427
OHIO EDISON CO	0.191	0.062	0.003	0.285

According to the TPQ/DPQIII data (EPRI, 2022) the number of outages (SARFI-10) per site per year was roughly 0.9 events for DPQII and 3.4 events for DPQ-TPQ III. This translates to roughly .075 event per month for DPQII and .28 events for DPQ/TPSIII for month. This is lower than the worst utility (Centerpoint Energy) at .438 events per site in the month of July, but this suggests that the scale and the data is within reason, based on the sparse data that the EPRI study was based on.

Sags

Selecting brownouts shows the utilities where the voltage sags have occurred in a particular month. The brownouts for the month of July, 2022, are shown both as grids (figure 6) and by utility (figure 7).

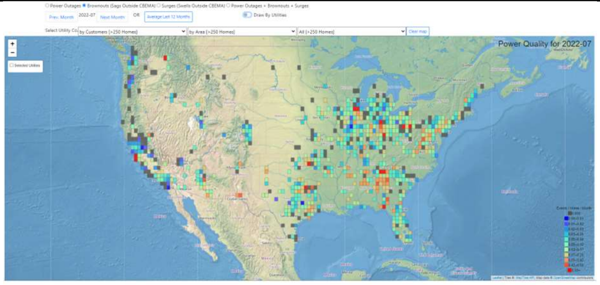

Figure 6 – July, 2022, sags by grid.

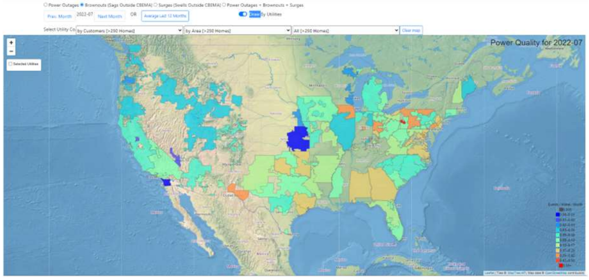

Figure 7 – July, 2022, sags by utility.

Table 2 shows the worst performing utilities for sags in the month of July, 2022.

Table 2 – 5 Worst performing utilities for voltage sags in July 2022

Utility	Power Outage Index	Brownout Index	Surges Index	Power Outage + Brownout + Surge Index
COMMONWEALTH EDISON CO	0.271	0.352	0.176	0.855
PECO ENERGY CO	0.16	0.254	0.008	0.473
GEORGIA POWER CO	0.581	0.241	0.009	0.912
CENTERPOINT ENERGY	0.696	0.238	0.009	0.988
PUBLIC SERVICE ELEC & GAS CO	0.059	0.205	0.008	0.34

According to the TPQ/DPQIII data (EPRI, 2022) the number of sags for SARFI-ITIC per site per year was roughly 13.9 events for DPQII and 17 events for DPQ-TPQ III. This translates to roughly 1 event per month for DPQII and 1.5 events for DPQ/TPSIII for month. This is higher than the worst utility (Commonwealth Edition) at .352 events per site in the month of July, but this suggests that the scale and the data is within reason, based on the sparse data that the EPRI study was based on.

Swells

Selecting Surges shows the utilities where the voltage swells outside CBEMA/ITIC have occurred in a particular month. The surges for the month of July, 2022, are shown both as grids (figure 8) and by utility (figure 9).

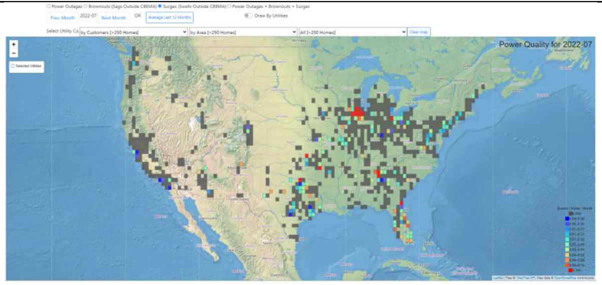

Figure 8 – July, 2022, swells by grid.

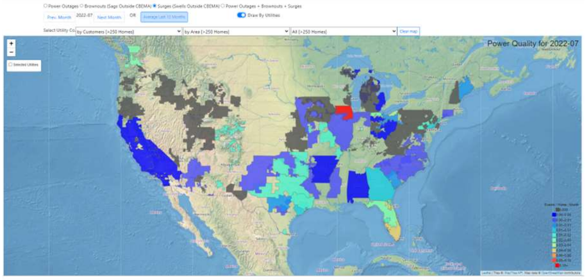

Figure 9 - July, 2022, swells by utility.

Table 3 shows the worst performing utilities for surges in July, 2022.

Table 3 - 5 Worst performing utilities for swells in July 2022

Utility	Power Outage Index	Brownout Index	Surges Index	Power Outage + Brownout + Surge Index
COMMONWEALTH EDISON CO	0.271	0.352	0.176	0.855
FLORIDA POWER & LIGHT CO	0.352	0.111	0.044	0.591
DUKE ENERGY FLORIDA, LLC	0.503	0.132	0.024	0.771
PUGET SOUND ENERGY INC	0.105	0.044	0.02	0.186
PUBLIC SERVICE CO OF COLORADO	0.242	0.083	0.017	0.366

According to the TPQ/DPQIII data (EPRI, 2022) the number of swells per site per 30 days was roughly .34 events. This is higher than the worst utility (Commonwealth Edition) at .176 events per site in the month of July, but this suggests that the scale and the data is within reason, based on the sparse data that the EPRI study was based on.

Composite score

The composite score is the sum of the outage, sags, and swells. Figure 10 shows the composite score by grid and figure 11 shows the composite score by utility.

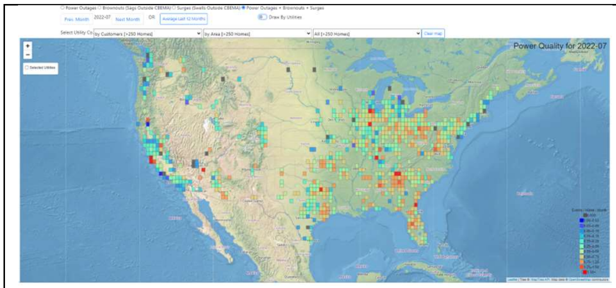

Figure 10 - July, 2022, Composite score by grid.

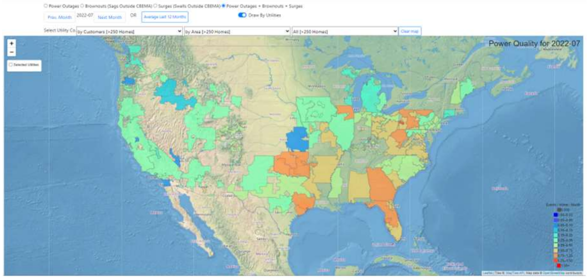

Figure 11 - July, 2022, Composite score by utility.

Table 4 shows the overall worst performing utilities by composite score in July, 2022.

Table 4 - 5 Worst performing utilities by composite score in July 2022

Utility	Power Outage Index	Brownout Index	Surges Index	Power Outage + Brownout + Surge Index
CENTERPOINT ENERGY	0.696	0.238	0.009	0.988
GEORGIA POWER CO	0.581	0.241	0.009	0.912
COMMONWEALTH EDISON CO	0.271	0.352	0.176	0.855
DUKE ENERGY FLORIDA, LLC	0.503	0.132	0.024	0.771
ALABAMA POWER CO	0.428	0.203	0.002	0.727

Future Work

Currently, the indexes are exclusively based on voltage data. However, future enhancements include harmonic analysis and frequency analysis. Since the locations of the events are known demographic data could be used to help identify areas that need additional support based on socioeconomic impact.

Conclusions

A low-cost sensor network has been deployed into about 150,000 homes in the USA (Robert King, 2021). The system was originally deployed to capture EFHs within the home. This data is the first of its kind regarding the fact that there is now an independent, continuous, real-time monitoring system that can perform like-kind comparison of power quality performance across utilities. This data will enable utilities to identify which part of their systems need additional work. While only voltage data is being used to compare utilities (Sags, Swells, Interruptions) future work will enable harmonic and frequency analysis. Finally, the data will allow anyone to compare the performance of utilities to one another.

Bibliography

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