High Density Sensor Network For Monitoring Grid Events

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***Abstract*— A customer installed residential-based monitoring system has been deployed in multiple areas to help address electrical hazards that cause house fires. Due to the high-density and high-resolution of the expanding distributed sensor network, additional benefits can be realized by utilities from higher visibility into power quality events and disturbances within their networks. This paper describes the technology and the benefits, contrasts other monitoring technologies, and provides a variety of case studies of this new approach to monitoring the grid.**

Keywords—Power quality, voltage, frequency, monitoring, data analytics, wildfires

I. Introduction

A number of risks exist on the current power system. These risks range from property damage to loss of life. The causes of these risks range from mis-operating equipment within a house to failing electrical equipment on the power transmission and distribution system itself. The utility delivery system is the primary focus of this paper. Certain technologies are available to sense and/or reduce grid component failures, but these systems are often expensive and usually provide limited visibility of assets on the system. The data monitoring and analytics system described within this paper addresses both of these failings of traditional grid monitoring and/or control systems.

A. Risks / Liabilities

Damage to and deterioration of the United States electric grid is increasing risk and liability for the grid's utility owners and their customers. For example, PG&E experienced over 2,400 grid-caused fires from 2014 through 2019[1]. These fires resulted in excess of $13B in liability and precipitated PGE filing for bankruptcy. A Texas Wildfire Mitigation Project found that 4,000 fires, most local and of little consequence, but also larger conflagrations, were caused by utility transmission or distribution system events taking place in a period of less than 4 years.

In addition to wildfires and damage to homes from the faults, increases in transformer fires and explosions and other catastrophic grid events are linked to deteriorating utility equipment. In one horrific example, in mid-July of 2019 firefighters were called to downtown Madison, Wisconsin, where a high-voltage transformer had exploded and caught fire[2]. Another recent event was the AEP Texas substation transformer explosion and fire at the end of July 2019[3]. In February of 2021, there was the tragic case of a woman dying in the Bronx, NY attempting to climb 17 flights of stairs during power outage caused by a blown transformer [4]. This failure was likely the result of a problem that had been nascent for some time, and might have been corrected long before its catastrophic failure, were that visible to utility operators.

B. Causes

In a residential setting, fires often begin in walls or other hidden cavities and gain significant heat and headway before they are detected by home occupants or smoke detectors, leading to significant damage. Electrical malfunctions are one of the leading causes of residential home fires. Because of the hidden nature of the ignition source, electrical fires are also a disproportionate cause of death. Electrical fires are estimated to cause 420 deaths, 1,370 injuries, and $1.4B in residential damages annually.

Still, as noted above, utility grid-caused fires have resulted in much larger economic damage, and often greater mortality, every year. Many power system components (e.g., switches, insulators, transformers) provide trouble-free service for decades, but transmission and distribution components eventually fail. Wildfires and other damage to property and life can be triggered[5] via a number of mechanisms including:

- downed lines,
- vegetation contact,
- conductor slap,

- arcing of damaged or deteriorating equipment,
- repetitive faults, and
- apparatus failures.

II. Existing Detection Systems

A number of approaches can be considered to help reduce the potential fire and explosion hazard of electrical infrastructure, the most common and traditional being tree trimming programs, routine system maintenance, and burying lines in particularly challenging environments. A UC Berkeley team formed a fire research group to address engineering solutions to reduce the likelihood of fires from transmission and distribution systems [6]. The following sections describe each of the technologies, however, Table 1, below, captures a summary of the benefits and costs associated with each technology.

TABLE I. MONITORING SOLUTIONS

Type	Detects	Density	Utility Cost
DFA	Incipient Faults on Lines	Low	High
DFR	Faults on Lines	Low	High
Pole Monitoring Solutions	Faults on Poles	High	High
Smart Line Reclosers	Faults on Lines	Medium	High
Smart Meters	Sags, Swells, Outages	High	High
Smart Relays	Faults on Lines, Substation Equipment	Low	High

A. Distribution Fault Anticipation (DFA)

DFA is a technology developed by Texas A&M Engineering in conjunction with EPRI. The technology automatically detects common equipment failures. While the technology has demonstrated value in predicting faults based on incipient characteristics, the technology is typically deployed in a substation and monitors lines coming in and out of a substation. Because the technology is deployed in a specific substation, it is typically purchased and deployed by the utility. In addition, this technology only captures issues associated with the lines and substation where it is installed. This results in a high cost of ownership for the utility.

B. Digital Fault Recorder (DFR)

A number of manufacturers produce digital fault recorders. This technology has proven effective at providing information about faults that have occurred on the power system. Properly configured systems can accurately identify fault locations and severity on monitored lines. Similar to DFA, this technology is purchased and deployed by utilities for implementation in utility substations. Additionally, this technology only captures issues associated with the lines, equipment, and substations where it is installed. Generally, this technology only reports on faults that have occurred. As such, they have minimal use for measuring and locating incipient fault conditions. The cost of ownership is relatively high for this type of monitoring solution.

C. Pole Monitoring Solutions

A number of recent solutions have been developed to monitor poles. Typically, a sensor is mounted to a utility pole or transmission structure. These sensors can identify a variety of issues like pole failure and vegetation ingress. The sensors are typically deployed by utility staff. These have benefits in measuring environmental conditions, and in some cases, arcing. Full coverage would require every pole to have a sensor deployed; as a result, deployment of this technology involves a significant investment by even a modest sized utility.

D. Smart Line Interrupters / Reclosers

Smart e reclosers are installed at strategic locations along a distribution feeder. When a fault occurs, the interrupter will disconnect the part of the line that has a fault and recloses other segments of the feeder to reconnect as many utility customers as quickly as possible. These devices are good at isolating faults, but not necessarily identifying incipient faults. These devices are expensive to install and therefore are only deployed in strategic locations.

E. Smart Meters

Many utilities have taken advantage of meter replacements to improve visibility on the grid. The smart meters are able to report back to a central database many times per hour. The status of each meter (or customer) is known. The meters are typically designed to report back utilization. Some may also report back status and voltage quality. In general, these meters are not designed to record or report information about fault activity. Additionally, since these devices are deployed for billing purposes, they are subject to more intense regulatory scrutiny. Some newer meters are being provided more flexible ‘edge’ computing capabilities, and applications will expand for using meter data but cannot enhance embedded sensor capabilities. Regardless of on-board computing capabilities, billing functions are typically given highest priority. Typically, these are installed at every customer location. The investment by the utility is high. This results in a high-density network, but at great cost.

F. Smart Relays

Many utilities have begun deploying smart relays to improve reliability on the grid. The smart relays can detect faults on each asset monitored. In addition, the relays activate protection functions to ensure that large investments like substation transformers are protected from fault conditions. These devices are expensive to install, but widely deployed in substations because of the relatively low cost compared to the assets being protected.

III. High Density Sensor Network

A. Origins

In the early 2000s, Earth Networks developed the technology to detect the build-up of electrical charge in the clouds through wireless sensors, or receivers. With the help of machine learning based “big-data” analytics, the company’s network of receivers, dispersed at intervals of as much as 50 to 100 miles, pinpoint the location of small, low energy cloud-to-cloud arcing before it becomes strong enough to form cloud-to-ground strikes.

Identify applicable funding agency here. If none, delete this text box.

B. Approach

It turns out, the same technologies also offer a means for much earlier detection of incipient hazards associated with much smaller-scale electrical events like residential home fires. The measurement device to detect activity at this scale is approximately the dimensions of a night-light and can be plugged into a wall outlet anywhere in a home. The instrument takes readings up to 30 million times a second using powerline carrier signal technology. Each device screens incoming signals using its edge computing capabilities, and then provides important data to the cloud where the data can be further analyzed using machine learning capabilities to identify troublesome micro-arcing and scintillations taking place in home wiring systems before they become a safety hazard.

Imagine a residential neighborhood with dozens of sensors. Each of the sensors are recording not only local phenomenon like arcing, but voltage, frequency, and other measurements which have a wider-area impact. This is a high-density network capable of high-resolution measurement of grid events. Figure 1, below, shows a small area where a number of devices have been installed.

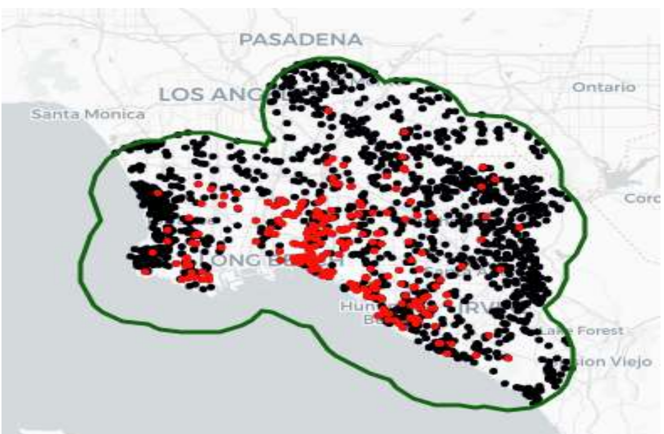

Figure 1 – Greater Los Angeles Device Locations

The result is a relatively dense network of sensors. The sensors are distributed across homes in the area. Since these have been installed by homeowners in homes, there is no upfront cost to the utility for installation. Maintenance is performed by the homeowner, who also provides power and wi-fi interconnection services.

IV. Case Studies

While the system was originally developed for detecting in-home electrical faults and incipient arcing events, the devices and the associated sensor network have proven useful for detecting grid events as well. The following sections show a variety of failures and events captured by the system.

A. In The Home

The sensor has identified 100's of incipient arcing events within the home that, if left undetected, could have resulted in electrical fires. These events include loose connections, damaged wires, failed pumps, and damage inside of wall outlets. Figures 2 and 3 below, show examples of failed components inside of homes.

Figure 2 - Damaged Wall Outlet

Figure 3 - Failing Radon Pump

For homeowners, the system is provided as a service. Once a hazard is identified, the operations team notifies the homeowner to the condition, and assigns a qualified, licensed electrician to locate and fix the problem, thus mitigating the hazard. In many cases, homeowners are provided a sensor at no cost by their home insurance carriers and may also receive a reduced home insurance premium.

B. On The Grid

The distributed nature of the devices allows for system events to be discriminated from local (in home) events. For example, voltage sags, interruptions, transients, voltage regulation, and frequency deviations are all visible to the sensor. In addition, since multiple devices record the event, calibration and measurement errors of any single device is mitigated.

1) Loose Neutrals

A common hazard is a loose neutral on the service transformer. The system has successfully identified more than 100 hazardous loose neutral, loose hot and failed transformer conditions. Homeowners were notified of these conditions and contacted their electrical utility. Utility technicians verified the hazard and fault conditions and took appropriate maintenance action to correct the problem. While these conditions are very clear in the data, these events often resulted in multiple truck rolls by utilities before the problem was identified and corrected. This is due to the transient nature of the faults. If utilities made use of this data, most all of these situations should be resolved in a single, efficient utility truck roll. Table 2, below, shows several cases where loose neutrals were positively identified by the measurement device.

TABLE II. LOOSE NEUTRAL CASES

WL Case No.	Location	Utility	Arc Event	ID Date	Repair Date
PQ2019-006	Atlanta, GA	Georgia Power	Loose Neutral	9/6/19	11/5/19
PQ2019-001	Nashville, TN	TVA	Loose Neutral	7/30/19	8/29/19
PQ2019-002	Knoxville, TN	KUB	Loose Neutral	8/11/19	2/24/20
PQ2019-003	Woodbridge, VA	NOVEC	Loose Neutral	9/24/19	10/1/19
PQ2019-004	Richardson, TX	TXU	Loose Neutral	10/3/19	10/28/19
PQ2019-008	Shaker Heights, OH	First Energy	Loose Neutral	6/11/19	12/13/19
PQ2020-001	Waterford, WI	We Energy	Loose Neutral	2/19/20	2/26/20
PQ2020-002	Ocala, FL	Duke	Loose Neutral	1/24/20	2/29/20

The graph below depicts a voltage time series dataset from the sensor network. As shown in figure 4, below, the voltage spikes routinely due to a loose neutral at the utility transformer. Data indicates the loose neutral condition prior to arrival of the utility technician, then a short power outage to the home during repairs, and then normal voltage data post the loose neutral correction.

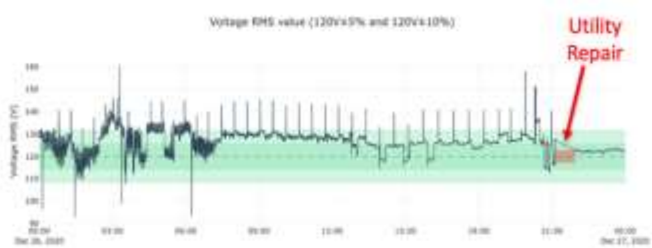

Figure 4 - Loose Neutral Voltage

2) Blown Transformer

Figure 5 shows arcing events from multiple sensors. The sensors started detected arcing nearly 30 minutes before a transformer fire was spotted. The event lasted about 5 minutes. Figure 6 shows the burned bus work above the failed transformer.

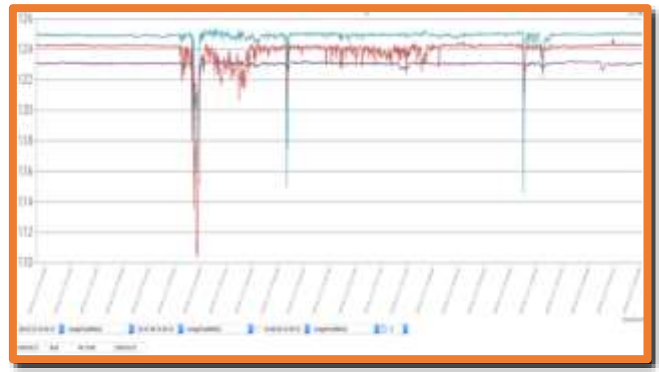

Figure 5 - Voltage Measurements

Figure 6 - Burned Bus work

3) Voltage Sags

Figure shows a voltage sag event as seen by a number of instruments in the same geographical area. Since multiple devices recorded the event, this was a system-based event.

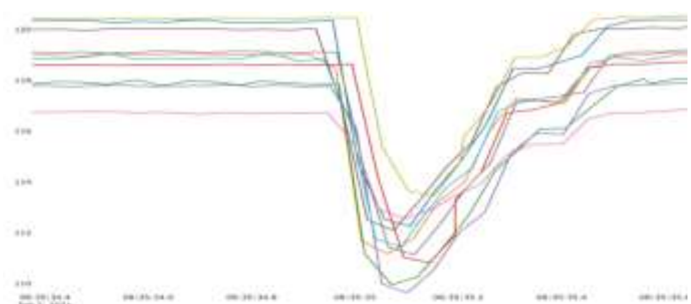

Figure 7 - Voltage Sag Event

4) Voltage Swells

Figure 8 shows a number of devices reporting a sudden increase in voltage. Because multiple devices see the event in the same area, this a grid-based event. The step change in voltage suggests some sort of device action took place. For example, a cleared fault on an adjacent feeder, a load-tap changer, or capacitor bank action may have been the root cause of the event below. Even for routine equipment operations, equipment may not be functioning properly.

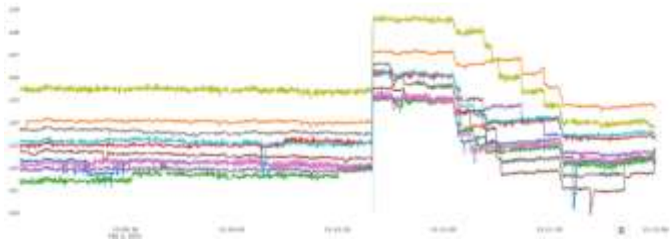

Figure 8 - Voltage Swell

5) Interruptions

On January 31, 2021 a number of devices reported an outage in Southern California. Since the data is time stamped, it can be readily calibrated with other phenomenon (like weather) to potentially identify root cause. Figure 9 shows a summary of the event along with a map of the devices that were impacted. Figure 10 shows the voltages and the outage. Outage duration can be derived from the voltage information. This information would be useful to protection engineers, operations staff, and compliance personnel within the utility to help measure efficacy of protection functions.

Figure 9 - Map of Interrupted Devices

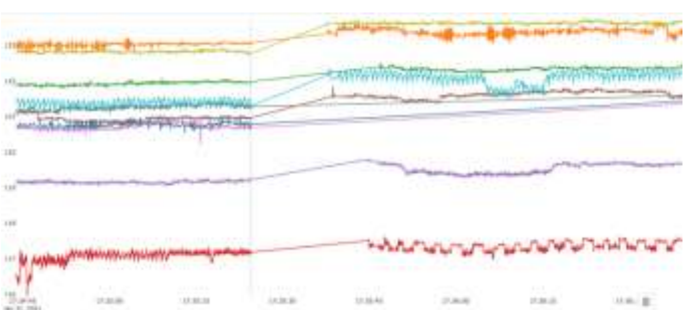

Figure 10 - Voltages Before/After Outage

At the same time, still other devices in the area indicated a voltage sag. This indicates that devices share an upstream common bus. Figure 11, below, shows the related instruments and figure 12 shows the corresponding voltage measurements. As sensor density increases, the system topology can be more accurately identified.

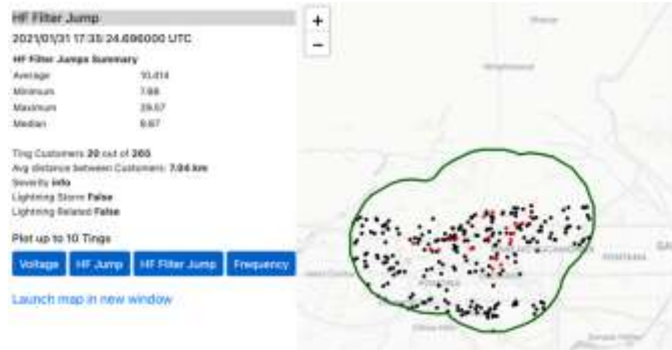

Figure 11 - Nearby sensors with voltage sag

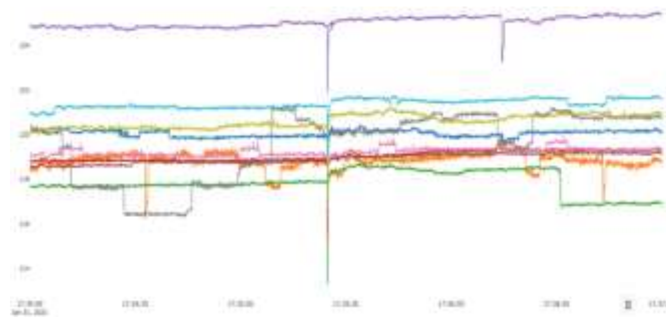

Figure 11 - Voltage Measurements

6) Transients

On January 31, 2021, a number of devices reported a transient event on the system. Figure 13, below, shows the devices that reported the events and Figure 14 shows the voltage measurements recorded.

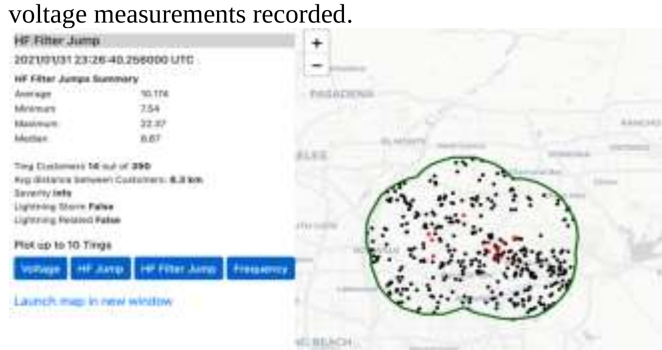

Figure 12 – Map of Devices With Transient Event

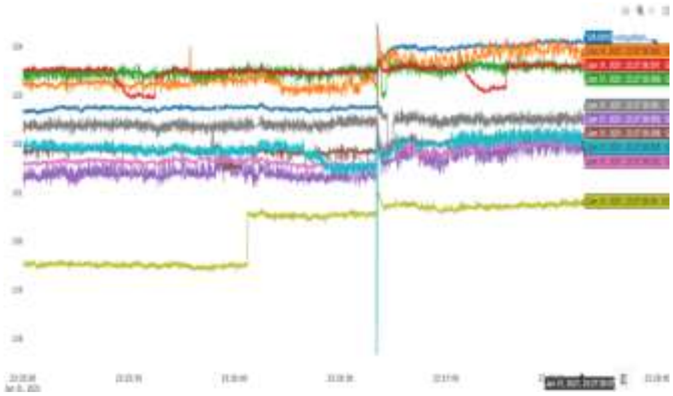

Figure 13 - Measured Voltages From Transient Event

V. CONCLUSIONS

In this paper, a variety of grid events were identified using a high-density, distributed sensor network. Over 40,000 sensors have been installed across several states already, and the network will grow significantly in 2021. The initial purpose for sensor deployments was to prevent home electrical fires. Insurance companies are enthusiastically deploying these sensors into the homes of their clients. Homes and lives are being saved. As the distributed network of sensors grows, these benefits come with growing benefits for the grid as well. This is a low-cost solution for high-resolution grid monitoring for utilities. Because the sensors are being deployed by homeowners, the cost for utilities to engage the platform can be considerably less than other approaches for monitoring the grid. And, of greatest import to utilities, because of the highly distributed nature of the sensors, their extreme sensitivity and the sophisticated nature of the machine learning analysis of the data, utilities will receive insights into the operational parameters of their grids that few other technologies can match.

REFERENCES

[1] CPUC, Pacific Gas and Electric Company - Fire Incident Data Collection Plan,2016.[Online].Available: https://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/Safety/PGE%20-%20Fire%20Incident%20Data%20Collection%20Plan%20-%20Report%20from%202014-2016.pdf. [Accessed: 03-Mar-2021].

[2] TM4J News, “Moment of explosion at Madison Gas & Electric substations,” WATCH: Moment of explosion at Madison Gas & Electric substations, 19-Jul-2019. [Online]. Available: https://www.youtube.com/watch?v=tWDsDbmxcsw. [Accessed: 03-Mar-2021].

[3] KIII News, Fire at AEP Texas substation causes large outage in Corpus Christi's southside, 31-Jul-2019. [Online]. Available: https://www.youtube.com/watch?v=vynlUuiqjyg. [Accessed: 03-Mar-2021].

[4] ABC7NY, “73-year-old woman attempting to go up stairs during Bronx power outage dies after oxygen tank runs out,” 27-Feb-2021. [Online]. Available: https://abc7ny.com/the-bronx-power-outage-co-op-city-transformer-fire/10374233/. [Accessed: 11-Mar-2021].

[5] T. A. M. University, “Texas Wildfire Mitigation Project,” 2014. [Online]. Available: https://wildfiremitigation.tees.tamus.edu/. [Accessed: 03-Mar-2021].

[6] Y. H. | S. Staff and Y. Huang, “UC Berkeley forms Fire Research Group to work on engineering solutions to wildfires,” The Daily Californian, 30-Nov-2018. [Online]. Available: http://www.dailycal.org/2018/11/28/uc-berkeley-forms-fire-research-group-to-work-on-engineering-solutions-to-wildfires/. [Accessed: 03-Mar-2021].