Using Secondary Voltage Data to Detect Struggling Distribution Transformers

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***Abstract*-- A high density, smart home power quality monitor network records high-resolution voltage data. An in-depth examination of this voltage data has led to the identification, localization, and resolution of countless residential power quality problems across the U.S. These problems range from loose neutral connections to out-of-range base voltage. A more rigorous analysis of this same voltage data reveals distinctive characteristic patterns that help identify overloaded or degrading transformers before their ultimate failure.**

***Index Terms*-- Distribution Transformer, Smart Grid, Power Quality**

I. Introduction

The sensor is a passive electrical safety monitoring device that plugs into a standard three-pronged outlet in a residential home. It monitors electricity in the home with two independent channels. The first, high speed channel samples the voltage 27 million times every second (27 MHz), 24x7x365. This channel focused exclusively on high frequency (HF) signals that are optimized to detect electrical arcing signals. The second is focused on lower frequency voltage signals and samples at 30 thousand samples per second, or 30 KHz. This channel is used for all Vrms measurements and power quality measurements. The sensor measures voltage in a range from 20 - 160 volts with an accuracy of one percent (1.0%) and a resolution of 0.1047 volts. A third, independent channel is optimized to measure voltage surges up to 3 KV. Therefore, the sensor can analyze the quality of power delivered at a very high resolution.

As of the published date of this paper, the network is actively monitoring 100,000 homes across the United States. While the main purpose of the system is early detection of the precursors of electrical fires within the home, the system also monitors the voltage supplied to the home to detect fire hazards that can originate with the servicing utility outside the home.

An accurate estimate of the number of distribution transformers in the United States was not available; suffice to say, there are several million in existence today. For Exelon, the number of failures per year was indicated on the order of 2,000, representing 0.5% percent of their fleet each year. [1]

Based on analysis of the sensor voltage data over the past 18 months, we hypothesized that sensor network could detect a potentially failing transformer by sampling household voltage over several days. As of 1 October 2021, the sensor network had identified nearly 350 suspected struggling distribution transformers, with each diagnosis confirmed by the responding servicing utility crew.

II. Discussion

Typically, a household's air conditioning uses more power than any single appliance in a house. Installed in nearly 90% [2] of all U.S. houses, air-conditioning units on average account for 48% of a home's energy consumption. [3] Consequently, contending with summer heat is responsible for the greatest electrical consumption in the U.S. and represents the largest load on a distribution transformer. In turn, daily household power consumption can be - and is often - directly related to the outside temperature.

During Power Quality reviews in the summer of 2020, a significant number of sensors reported unusual and meandering voltage patterns, similar to a sinusoid. A more rigorous review of this sinusoidal behavior indicated a correlation between air temperature in the region and the amplitude of the sinusoidal voltage pattern (see Figure 1).

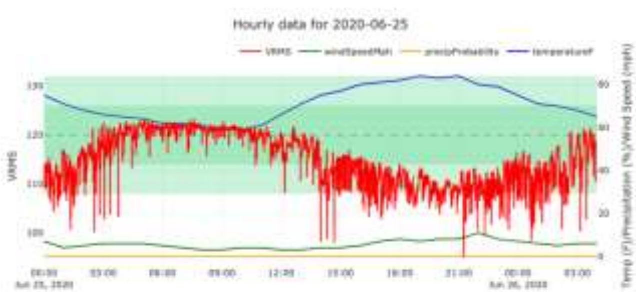

Fig. 1. Plot of root-mean-square (rms) Voltage vs. Time. The red line indicates the voltage, the green line indicates wind speed, the yellow line indicates the chance of precipitation, and the blue line indicates temperature. The voltage values are on the left axis, the weather values are on the right axis. The meandering, "sinusoid" voltage pattern can be seen - along with its peak during the coldest time of day - and its trough during the hottest time of day.

An invaluable discovery arose in June 2020, when one case allowed us to look at a home's voltage both before and after a distribution transformer was replaced. Before replacement, sensor data exhibited the sinusoidal pattern. After replacement, the sinusoidal voltage pattern ceased (see Figure 2).

Based on this observation, we hypothesized that increased air temperatures correlate to increased demand from air-conditioning systems, which increases electrical current demand on a given transformer. This increased load, in turn, manifests itself as large daily voltage swings only for transformers that are in a state of degradation. As expected, these large voltage swings correlated well with temperature over the day.

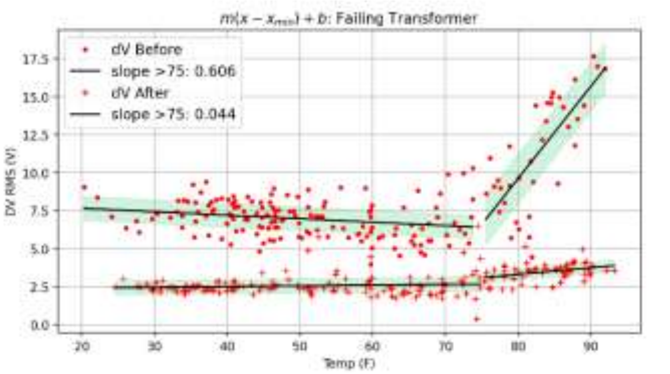

Fig. 2. This scatter plot illustrates the difference in the changing voltage before and after replacing the distribution transformer serving the home. The daily change in Vrms is plotted on the y-axis, with the daily high temperature on the x-axis. The circular points illustrate the change in voltage for a given daily high temperature before transformer replacement, while the "+" points indicate the same data after replacement. This plot shows a correlation between the maximum daytime temperature and the voltage change for an overloaded transformer.

As of 1 October 2021, the system had identified nearly 350 homes across the United States exhibiting this unique voltage behavior. In response, a tool was developed to identify these sites based on two simple criteria: the maximum air temperature observed near the home and the difference between the highest and lowest voltage (minus outliers to exclude transient events) observed by a home's sensor during the day.

Where everyday data over a period (typically several weeks) has an adequate temperature variation - and is plotted as a scatter plot of change in the voltage (delta-V) versus maximum air temperature for the day - positive slope for homes that exhibit sinusoidal voltage behavior is observed. Furthermore, when a least-squares fit is applied, the positive slope can be quantified (See Figure 3).

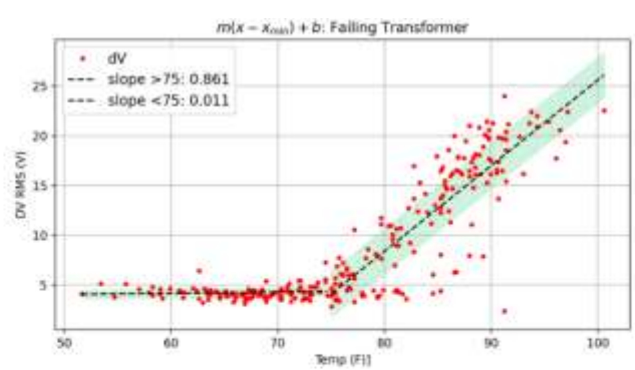

Fig. 3. Scatter plot showing the relationship between the daily change in voltage and the maximum temperature during the day. The daily change in voltage is plotted on the y-axis, while the temperature is represented on the x-axis. The plot illustrates that once reaching a certain daily high temperature, the voltage begins to vary significantly over the course of the day. Furthermore, this variation becomes more extreme as the maximum temperature increases.

When comparing this data to similar data from a transformer known to be new and operating under similar conditions, the difference is immediately identifiable (See Figure 4).

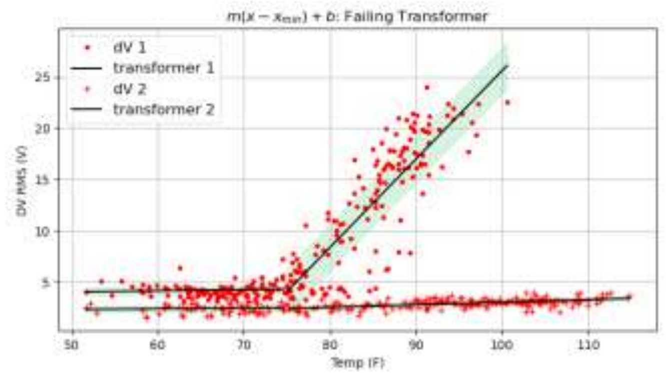

Fig. 4. A scatter plot of change in voltage vs. maximum daytime temperature. This plot illustrates the difference between a transformer believed to be struggling (transformer 1) and a normal operating transformer (transformer 2).

Subsequently, the use of Fourier Transforms (FT) and a cosine best fit identify potential faulty/overloaded transformer sites using data from just two and a half consecutive hot days. In this case, the FT algorithm of best fit processes the characteristic sinusoidal pattern, and frequency and amplitude are defined (see Figure 5). The units are such that the frequency component of one equates to 1 cycle/day.

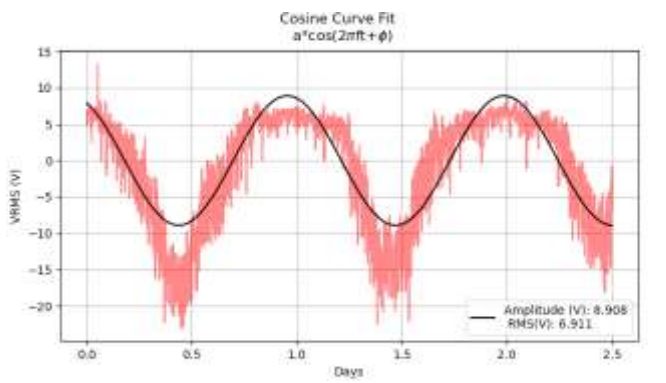

Fig. 5. Two and a half days of voltage data, centered around zero, and its best-fit cosine curve. The plot shows the sinusoidal nature of a transformer dependent on the outside temperature. At t=0 the voltage data started at approximately 5 am for the homeowner's local time, therefore having the highest likelihood for cool temperatures and least load. In turn, this corresponds with a max voltage at t = 0, or a cosine curve with little phase shift.

Using the amplitude calculated from a least squares curve fitting with

$$V(t) = A * \cos(2\pi f t + \varphi) \qquad (1)$$

where V(t) is voltage with respect to time, A is amplitude, f is frequency, φ is phase shift, and t is time. Using this equation, a measure of the transformer's condition can be defined (see Figure 6). Each sinusoid is centered around its respective mean.

The difference is readily observable when a suspected struggling transformer is plotted alongside a normal transformer (see Figure 6).

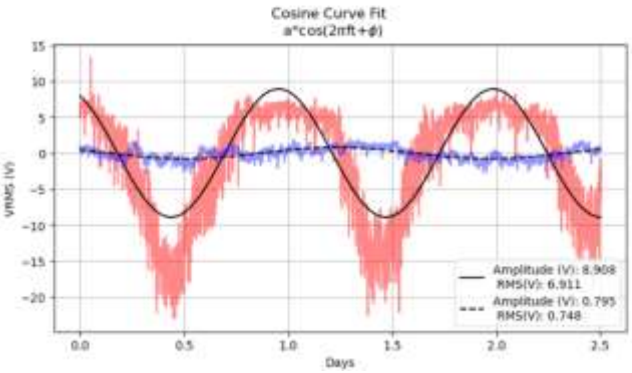

Fig. 6. Voltage data from Figure 6 compared to a normal operating transformer's voltage, plotted in blue. The voltage in blue is from the same sensor as the linear comparison presented in Figure 5. Both voltages are taken from the hottest two and one-half consecutive days in August, with temperatures above or near 100 degrees. A well-behaved transformer may still show some daily sinusoidal patterns. However, when comparing the blue (normal) voltage to the red voltage of the failing transformer, the blue cosine fit possesses an amplitude value that is smaller than an order of magnitude than the red voltage's amplitude.

It can be computationally exhaustive to fit thousands of data points with a best-fit cosine function. It is also time-consuming to wait weeks or months for a transformer's delta voltage vs. temperature relationship to reveal itself. Fortuitously, a Fourier analysis can reveal a struggling transformer using a single day's output voltage. In order to accomplish this, the frequency unit is set to one cycle per day. The voltage data for the day is then analyzed using a Fourier analysis that calculates the different sinusoidal characteristics of the data ranging from one up to 10 cycles per day.

In Figure 7, a Fourier analysis was conducted on two transformers (one suspected of struggling, and the other thought to be good) from 0 frequency to 10 cycles per day. This plot reveals a significant response around 1 Hz (cycle/day), as the voltage output inversely follows the outside temperature and has a large one cycle/day component in the data. The control transformer's voltage output dependency is so low on the daily load that the expected noise in the voltage data greatly outweighs any frequency component.

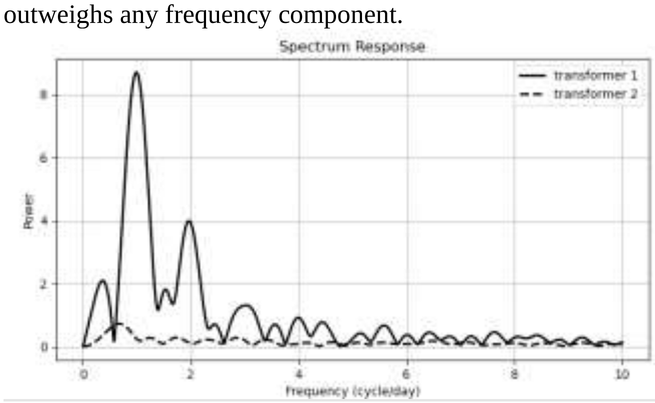

Fig. 7. This plot illustrates the results of the Fourier analysis. The graph for the struggling transformer has a strong response around 1 Hz, indicating that a struggling transformer will produce a voltage graph that cycles like a sine wave over the course of a day. The same response is not present for a transformer that is operating properly. This approach is consistent with the methods of identifying struggling transformers.

Fourier analysis demands less data and is computationally easier; the results are consistent with the earlier analyses.

III. Conclusion

Voltage data collected inside tens of thousands of homes across the country reveal a characteristic sinusoidal pattern that has shown to be associated with degrading or failing distribution transformers. This behavior manifests itself when the transformer is under heavy load, typically associated with significant air-conditioning demand on high heat days.

The data was subjected to several analytical methods to define key parameters that indicate the presence of an overloaded or degrading transformer. One of these methods requires just a single day of data with the transformer under load to identify if it is behaving normally or not.

If the voltage patterns detected by the sensor network can be validated using inspections of transformers in the field, this would define a method to identify overloaded or degrading transformers that utilize remotely detected secondary voltage.

At scale, this method of detection of failing distribution transformers can: 1) enable predictive versus reactive maintenance of distribution transformers, 2) lower the costs of distribution transformer ownership and maintenance, 3) improve customer power quality, 4) improve customer satisfaction with fewer truck rolls and definitive, actionable data on arrival, and 5) help prevent wildfire ignitions.

IV. Future Work

As of 1 October 2021, the sensor network had identified nearly 350 suspected struggling distribution transformers. The sensor data needs to be corroborated with utilities to proactively correlate potentially failing transformers identified using the sensor data with physical evidence (also known as 'ground truth') before repair/replacement. This will allow us to validate our data and methodology further.

V. References

[1] https://www.tdworld.com/grid-innovations/asset-management-service/article/20971387/predicting-distribution-transformer-failures
[2] https://www.eia.gov/todayinenergy/detail.php?id=42915
[3] https://www.energy.gov/articles/history-air-conditioning

VI. Biographies

Theo Laughner (SM' 1998) was born in Warsaw, IN, USA. He attended Tennessee Technological University and graduated from the University of Tennessee at Chattanooga.

He is presently the Director of Engineering for Lifescale Analytics, Inc., which is based in Roseville, MN, USA. Previously, he spent 21 years at the Tennessee Valley Authority where he served as the Senior Program Manager of Power Quality.

Mr. Laughner received the 2017 NSPE Top 10 Federal Engineers of the Year award. He serves as the US National Committee Representative to CIGRE Study Committee C4. In addition, he has served in leadership roles to a variety of technical committees within the IEEE Power and Energy Society.

Robert Price was born in Mineola, NY, USA. He graduated from the State University of New York at Buffalo. He has been a Fire Operations Engineer at Whisker Labs since 2019. Previously, he had over 35 years of military, government, international, and private sector experience in program management, complemented by a master's degree in Engineering Management from The George Washington University..

Matthew Wilkin was born in Oxford, MS, USA. He graduated from the University of Maryland, College Park with a B.S. in Astronomy and a B.S. in Physics. He has been a Fire Operations Engineer at Whisker Labs since the summer of 2020. He previously participated in research in the astronomy department at Maryland, receiving honors for his project. Matthew also participated in a team research project in the honors college at Maryland to design a heads-up display system for astronauts, and received an honors citation upon completion.