Measurements from an Electrical Distribution System Substation During Hurricane Zeta

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Abstract - *Hurricane Zeta made landfall on the United States mainland on October 29, 2020. The hurricane's impacts on electrical service within the storm path included millions of customers losing power. The eye of the hurricane crossed over Chattanooga, Tennessee, USA, where advanced sensors were monitoring the operational state of a utility substation. A report on the measurement capability and rudimentary results is presented here.*

1. SUBSTATION MEASUREMENT CAPABILITIES

Electricity generated at power plants moves through a complex network of electricity substations, power lines, and distribution transformers before it reaches customers. In the United States, the power system consists of more than 7,300 power generation facilities, nearly 160,000 miles of high-voltage powerlines, and millions of miles of low-voltage powerlines and distribution transformers connected to approximately 145 million customers [1]. Within this mix of devices, systems and facilities, closest to the customers is the distribution substation. As shown in Fig. 1, which depicts a generic electrical substation, the substation consists of devices used to switch generators, equipment, and circuits or lines in and out of the distribution system. It is also used to change alternating current (AC) voltages from one level to another, and/or change AC to direct current or direct current to AC. Measurement and monitoring of substation operational parameters is central to performance optimization.

The basis for these measurements comes from an envisioned broad deployment of sensing technologies made possible via sensors coupled with data analytics with goals including the following:

(1) Improved situational awareness of incipient failure and anomalous behavior regarding grid assets and the operational state of transmission and distribution systems,

(2) The ability to distinguish outages resulting from man-made events and naturally occurring faults and failure mechanisms, and

(3) Improvement of system restoration speed and efficiency, which may lead to better forecasting of future grid states with enough accuracy and lead time to avert deviations from normal operations.

The initial step to achieving these goals is the development and deployment of sensors capable of making measurements useful in the monitoring of substation operation and status.

The instrumented substation (aerial view shown in Fig. 2 below) has a 60 Hz, 46 kV AC three-phase incoming transmission line. The voltage and current of each phase of the 46 kV signal was measured. The substation building shown in the upper left-hand side of Fig. 2 contains the substation control system. Electrical power, nominally 120 V AC, 60 Hz, is available within the building. Measurement of this distribution power was performed within the building with timing provided via GPS.

The net result was a combination of voltage and current measurements of the substation input three-phase 46 kV power, as well as voltage and frequency measurements of the distribution-level 120 V AC power. All sets of measurements were logged either locally or within the cloud (Amazon Web Service).

Fig. 1: Traditional substation [2].

Fig. 2: Aerial view of the instrumented electrical substation.

2. HURRICANE ZETA

Hurricane Zeta formed in the Caribbean in late October 2020. After making landfall in the Yucatán Peninsula of Mexico, it proceeded through the Gulf of Mexico, making landfall in Louisiana, USA as a category 2 hurricane [3]. A track of Hurricane Zeta's path is provided in Fig. 3.

As shown in the satellite image presented in Fig. 4 below, the eye of Hurricane Zeta passed over Chattanooga, TN, USA. While no time stamp is provided on this image, the image was from early in the morning of October 29, 2020.

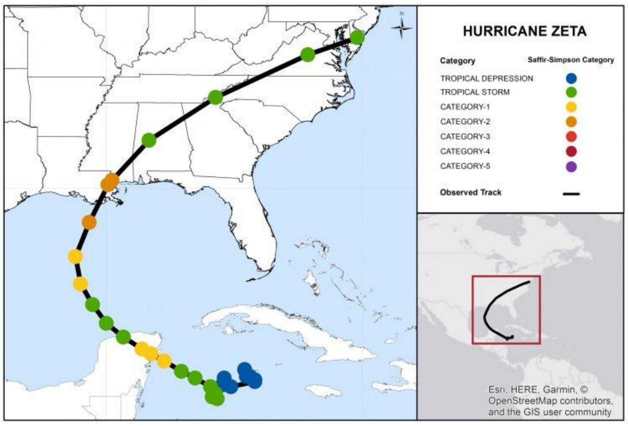


Fig. 3: Hurricane Zeta track [4].

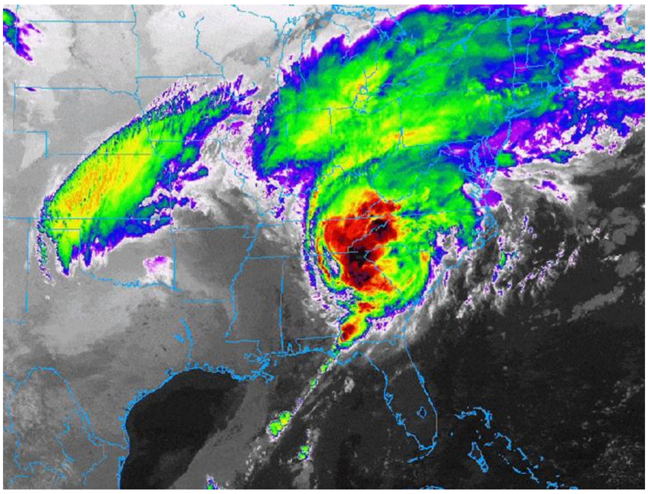


Fig. 4: Infrared satellite view of Hurricane Zeta with the eye over Chattanooga, Tennessee, USA [4].

Figure 5 presents three radar images (screenshots of Weather Channel reports) taken as the fast-moving (48 mph, 77 km/hr) storm tracking to the northeast. As is apparent in the 6:30 a.m. EDT radar image, Zeta transitioned into a post-tropical cyclone with an associated large storm shield [5].

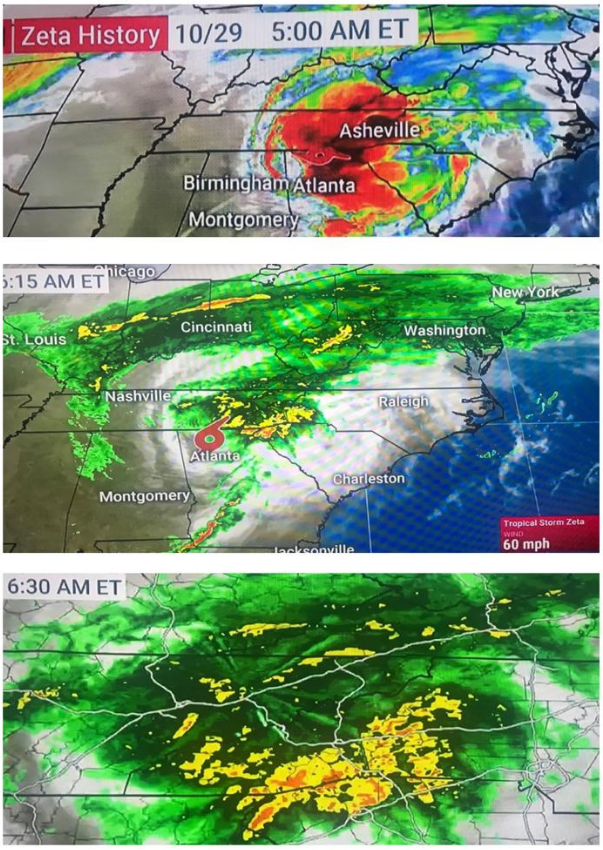


Fig. 5: Time sequence of radar imagery of Hurricane Zeta.

3. MEASUREMENTS

The measurements have two primary components: (1) voltage and frequency of the 120 V AC, 60 Hz power, and (2) voltage and current for each of the 46 kV, 60 Hz sub-transmission lines.[1] In each case, measurements were recorded at 5:00 a.m. EDT, 6:15 a.m. EDT, and 6:30 a.m. EDT, thereby in time synchronization with the radar imagery[2].

Figure 6 presents (a) a one-minute span of low voltage and (b) frequency measurements for each sampling interval (5:00 a.m., 6:15 a.m., 6:30 a.m.). While interpretation of the measurements is outside the scope of this paper—and left to power engineers for analysis and conjecture—it is readily apparent that with modest exceptions, the voltage and frequency of the low-voltage power signal showed minimal variations from the nominal 120 V AC, 60 Hz waveform as the hurricane passed through.

[1] Within the context of this paper, the 120 V AC power signal will be referred to as "low voltage." The 46 kV signal will be referred to as "high voltage."

[2] Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof.

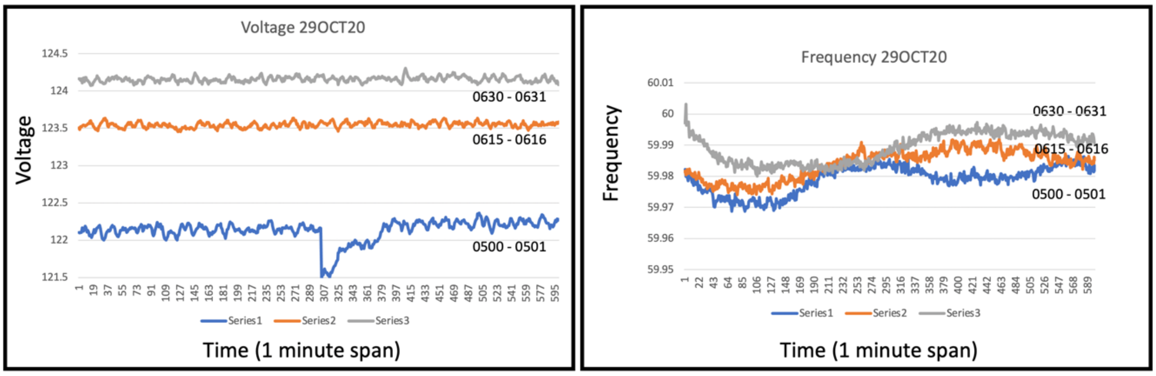
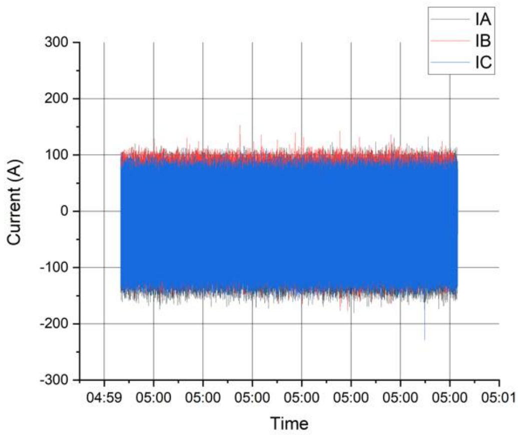
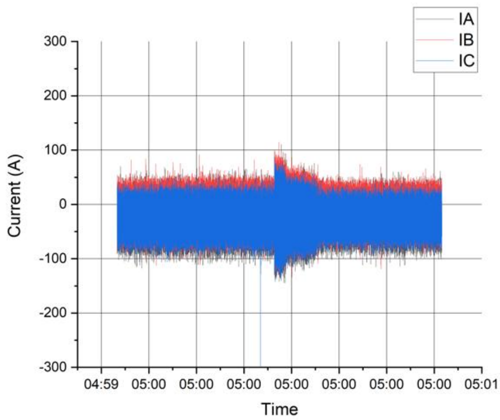


Fig. 6: Voltage measurements at distribution voltage (nominal 120 V AC).

Similarly, Fig. 7 presents the measured current of the three phases of the high-voltage AC power signal for the one-minute time span at the 5:00 a.m. sampling interval. Figure 7a shows the measured values for the day before (October 28, 2020), while Fig. 7b presents the measured values as the hurricane passed through the utility substation's service area.



(a)



(b)

Fig. 7: Current of each phase (overlaid). (a) The day before and (b) the day of (5:00 a.m., October 29, 2020) Hurricane Zeta. (Note: IA, IB and IC refer to the currents for each of the three phases of the 46kV power signal).

The voltage and current of each phase (A, B, C) of the three phase 46 kV, 60 Hz high-voltage power signal were measured at 5:00 a.m., 6:15 a.m., and 6:30 a.m. Twelve cycles of each high-voltage phase (at 5:00 a.m.) are presented in Fig. 8. Sampling of the sinusoid occurred hundreds of times per cycle.

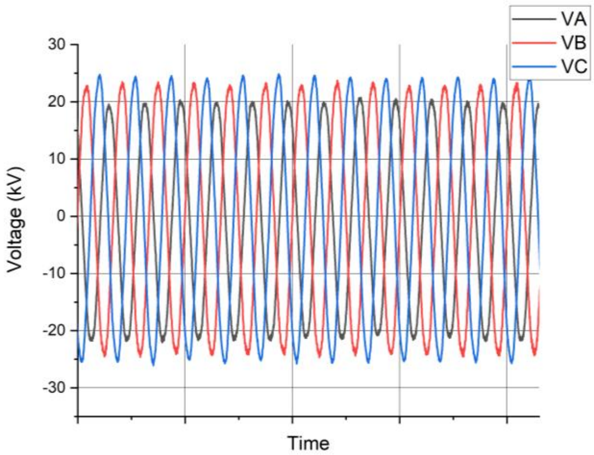
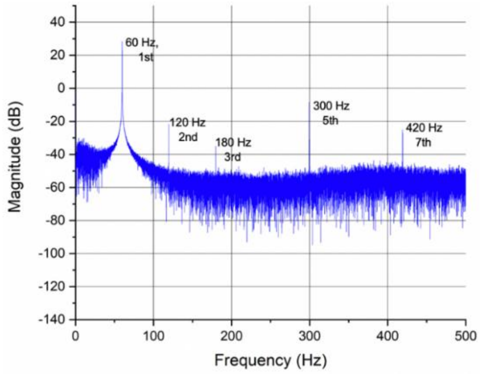


Fig. 8: Temporal strip chart recording of the three-phase voltages of the sinusoidal 46 kV power signal. (Note: VA refers to the voltage of the first phase, A, of the three phase power signal, similarly for VB and VC)

Fourier decomposition of the high-voltage signal was accomplished through the determination of the coefficients in the Fourier series expression (Eq. 1).

The measurements upon which the power signal's harmonic composition is based allow for a variety of characteristics to be determined. The level of harmonic distortion that may occur to the power signal is of particular interest. Figure 9 presents the frequency analysis of Phase A of the 6:15 a.m. October 29, 2020 high-voltage signal of Fig. 8.

$$P(t) = \frac{1}{2}a_0 + a_1 \cos \omega t + a_2 \cos 2\omega t + \ldots + b_1 \sin \omega t + b_2 \sin 2\omega t + \ldots \quad \text{(Eq.1)}$$



Frequency (Hz)	# Harmonic	Magnitude (dB)
60	1	26
120	2	-22
180	3	-33
240	4	-55
300	5	-12
360	6	-57
420	7	-26

Fig. 9: Frequency analysis of the high-voltage signal. The fundamental frequency, 60 Hz, along with the harmonics are identified with measured power levels shown.

Following the total harmonic distortion (THD) calculation per Eq. 2, the THD at 5:00 a.m. as the hurricane passed through was 74.4. Further analysis and conjecture is left to power engineers.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_{n\_rms}^2}}{V_{fund\_rms}} \quad \text{(Eq. 2)}$$

4. SUMMARY

As illustrated in Fig. 10, numerous hurricanes had landfalls within the continental United States in 2020. Significant power outages were associated with these hurricanes. For example, outages simply due to Hurricane Zeta exceeded 2 million [6]. Capabilities to measure substation status via specific voltage, current, and frequency measurements augment existing SCADA and operational systems. Linkage with ambient environmental data, such as radar imaging shown in this paper, will help utilities maintain operation with minimal outages.

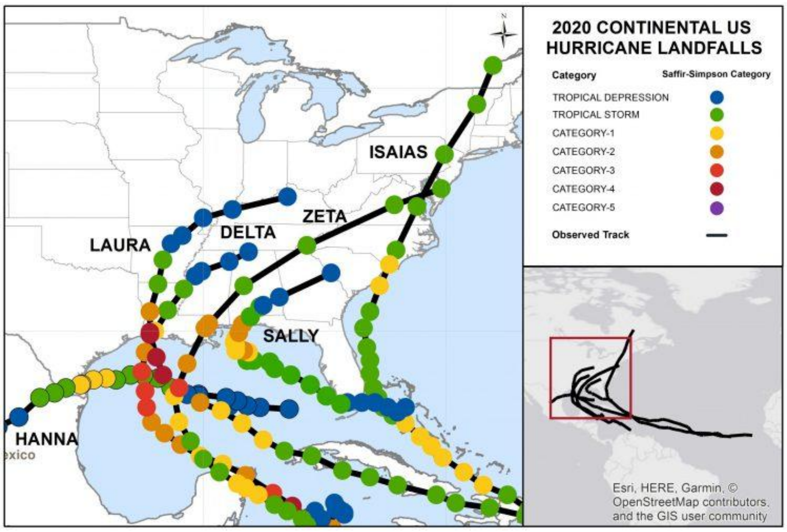


Fig. 10: Hurricanes that made landfall in the United States in 2020 (as of November 1, 2020).

5. REFERENCES

[1] "Electricity," US Energy Information Administration (EIA), accessed July 22, 2016, https://www.eia.gov/electricity/.

[2] "Illustrated Glossary: Substations," OSHA, US Department of Labor, accessed December 5, 2020, , https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/substation.html#Distribution.

[3] https://www.weather.gov/tae/zeta2020

[4] "CAT-i Bulletin: Hurricane Zeta," GC Capital Ideas, last modified October 30, 2020, https://www.gccapitalideas.com/2020/10/30/cat-i-bulletin-hurricane-zeta/.

[5] "Bulletin: Post-Tropical Cyclone Zeta," National Hurricane Center and Central Pacific Hurricane Center, National Oceanic and Atmospheric Administration, https://www.nhc.noaa.gov/archive/2020/al28/al282020.public_a.020.shtml?.

[6] B. Chapel, "Zeta Causes 2 Million Power Outages, Speeds Its Way Into Virginia," NPR, last modified October 29, 2020, https://www.npr.org/2020/10/29/929216223/zeta-causes-2-million-power-outages-speeds-its-way-into-virginia.