Final Scientific/Technical Report

Sensing Electrical Networks Securely & Economically (SENSE)

WORK PERFORMED UNDER AGREEMENT

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U. S. Department of Energy

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

GAMMA – Global Asset Monitoring, Management, & Analytics platform
GSM – Global System for Mobile
4G/LTE – 4th Generation/Long Term Evolution
MCU – Micro Controller Unit
JSON – JavaScript Object Notation
A/D or ADC – Analog to digital converter
AFE – Analog front end
ODR – On Demand Radio
BLE – Bluetooth Low Energy
CUSUM – Cumulative Sum
LDO – Low Drop Out Linear Regulator
DC – Direct current
ARM – Advanced Risc Machines
SMPS – Switch Mode Power Supply
IC – Integrated Circuit
CT – Current Transformer
HV – High Voltage
UART – Universal Asynchronous Receiver Transmitter
LiPo – Lithium Polymer Battery
I2C – Inter Integrated Circuit Communication Protocol
I/O – Input/Output (pins)
PCB – Printed Circuit Board
MVP – Minimum Viable Product
AMI – Automated Metering Infrastructure
PV – Photo Voltaic
EV – Electric Vehicle
KNN – K-Nearest Neighbors
FEA – Finite Element Analysis
FFT – Fast Fourier Transform
WT – Wavelet Transform

STFT	– Short time Fourier Transform
SVM	– Support Vector Machines
NN	– Neural Network
ANN	– Artificial Neural Network
PCA	– Principle Component Analysis
AES	– Advanced Encryption Standard
RSA	– Rivset-Shamir-Adleman cryptographic algorithm
E2EE	– End to End Encryption
UI	– User Interface
API	– Application Programming Interface

I. Executive Summary

The growing adoption of distributed energy resources (DERs) like battery energy storage systems and roof top solar/PV and the rapid penetration of electric vehicles (EVs), the electric grid is undergoing a major transformation with elevated stress on legacy grid assets. Despite a lot of expenditure to address these challenges, both in dollars and manpower, utilities have not been able to receive the value that was promised. The gains have been most visible at the transmission and substation level, especially where the main objective was improving operational and economic efficiency for the utility. Improving visibility and control at a few select points enhances the existing and established paradigm of centralized command and control.

With changing load patterns, load types and the overall transition to an "active grid", the centralized control and coordination paradigm gets challenged. To address the challenges, a new architecture and mechanism is needed, one that supports decentralized control and decision making, extracting value streams at the grid edge, particularly as the changes are fueled by transitions occurring in the distribution system. To address this, a communications and data processing platform, "GAMMA" was developed and demonstrated through the project. At the heart of the platform, are distributed, intelligent edge nodes with sensing and compute capabilities, that can record and analyze information locally. They are embedded in sensors and actuators specific to different distribution system applications.

Phase 1 of the project focused on developing novel sensor technology that can be used for monitoring utility pole top distribution transformers. The sensors were designed with the objective of being low-cost, communicating with the GAMMA cloud using novel "delay-tolerant" networking using Bluetooth and a secure mobile application. They were non-intrusive in nature so that they can be installed quickly in the field, resulting in overall low cost of deployment and operations.

Following the successful completion of Phase 1, the team manufactured 100 units for a field demonstration in Phase 2. The field demonstration was carried out on two real feeder systems with the local utility partner. In total, 100 sensors were installed and operated over a period of 6 months in the state of Georgia. The platform is operational end to end, with the cloud infrastructure deployed on a distributed, serverless environment that can serve multiple data streams, an analytics engine and a portal to securely view the data from multiple assets. The data collected through the GAMMA Mobile Phone app showcased the viability of the novel delay tolerant networking architecture, and the data processing algorithms developed through the course of the project, were successful in extracting important information about the overall network, improving the utility's visibility and situational awareness in the distribution feeder.

II. Objectives

The objective of this project was to develop and harden a novel distribution system sensing and awareness solution, that can be deployed at scale. The solution comprised of edge-intelligent sensor agents that get installed in the field, a novel, "zero-cost-communication" platform, called GAMMA platform, and the cloud infrastructure to support the data generated by the sensors, along with the computational engine that can derive value and insights from a fleet of sensors operating in the distribution network.

The communication platform relies on Georgia Tech's GAMMA – Global Asset Monitoring, Management and Analytics platform that uses a novel, decentralized architecture for processing data [1]. Edge nodes (called GAMMA Kernel) can analyze local events and extract meaningful information to be reported to the cloud. The communication channel is through an end-to-end encrypted Bluetooth Low Energy link that communicates with a proprietary smart phone application called GAMMA Data Mule that can store and forward data packets both ways between the end nodes and the cloud. The cloud platform is a serverless, scalable, service-oriented architecture that can ingest, decrypt, store the time series data and can call specific algorithms for data analysis and deriving further insights from the gathered data set.

For developing a low-cost, scalable, distribution system monitoring solution, a customized sensing solution that can target the pole top distribution transformer was developed by the team. Pole-top distribution transformers are the most commonly found utility assets in the distribution network and are presently, largely unmonitored. The sensor was developed with the aim of being installed on the transformer in a matter of minutes, with a non-intrusive mode of sensing so that the overall cost of deployment is low. The platform can activate the sensors through the mobile phone application, and record GPS positions of the units so that the locational information is recorded in the backend.

The prototype went through rigorous validation and testing at the High Voltage Test cell at Georgia Tech's Center for Distributed Energy, with all parameters being validated within design specifications. An in-field demonstration was conducted at utility partner Southern Company's Klondike Distribution Testing Facility at Atlanta, GA to showcase the functionality of the sensor, and to familiarize the field crew with the handling and installation process. Following a successful review, a "go decision" was made to initiate the mass manufacturing process.

The sensors were designed and developed in house with the aim of being able to mass-manufacture them at scale with a US-based manufacturing partner. The designs were developed with the objective of being able to withstand the harsh environment, with dust moisture and weather-proof enclosures, ability to withstand wide temperature cycles while simultaneously being low-cost and easy to operate and install in the field. The sensors were fabricated in partnership with Endeavour Energy and Jabil Circuits, with the aim of installing and operating 100 units in the field with the utility partner – Southern Company and their subsidiary, Georgia Power.

To showcase the viability of the solution, two independent distribution feeders were chosen in Georgia Power's service territory and 50 units were installed on each of the feeders. This validated the performance of the overall system, end to end, in a real-world scenario. Approximately 6 months of data were collected and analyzed to validate the capability of the sensors in the field.

Finally, to demonstrate a viable business model with the sensors and their value proposition, an industry partner has been engaged in commercializing the technology stack and is working with several utilities to deploy the solution at scale.

III. Technical Approach

In order to support the development of edge-intelligent sensors that can support the transformer monitoring application, GAMMA platform played a central role in the overall architecture of the system – enabling the end-to-end secure communication channels between the devices the cloud backend through mobile phones that act as data mules. The platform architecture is shown below –

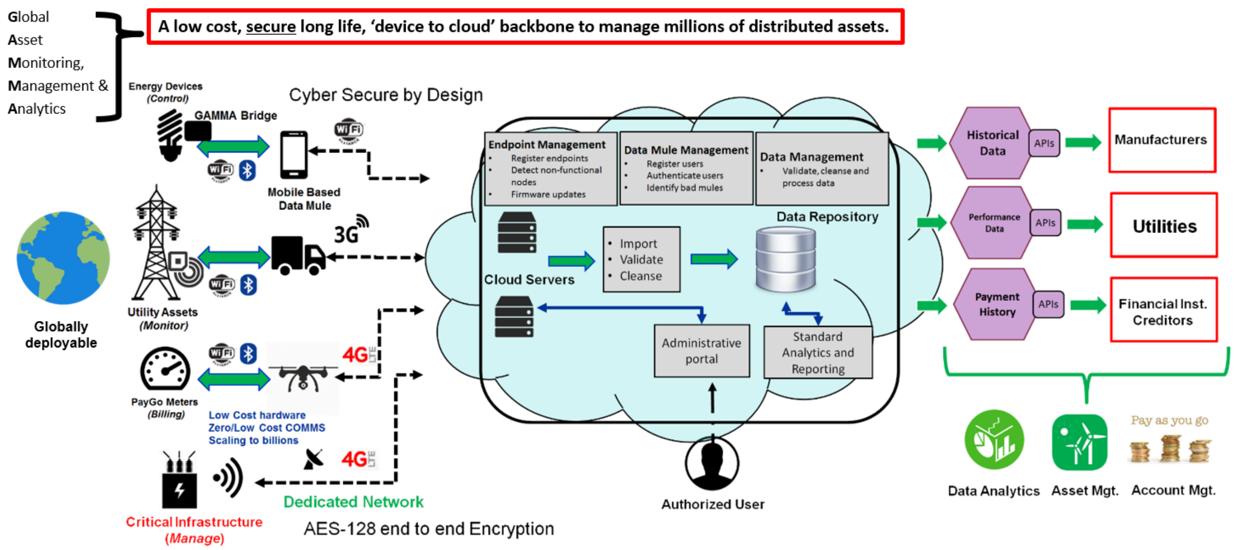

Figure 1 GAMMA Platform Architecture

The platform has the following features –

1. Timestamped data generation, local storage (6+ months) and analysis
2. Long Range Bluetooth communication
3. End to end encryption using AES-128 bit keys unique to each device
4. Duplex communication from device to cloud
5. Mobile phone acts as data mule pass through device
6. Secure, scalable, flexible, server-less architecture
7. API driven interface with Web UI portal, PI-Historian and utility systems

Based on the features of the platform, a novel sensing solution was developed specifically for the distribution transformers.

The sensors have the following capability –

Measurement Ranges/Sensor Performance Metrics –

Voltage: 50 – 300 Vac, 50/60 Hz

Current: 50 mA to 500 Amps nominal, upto 10 kA faults

Transformer case temperature: –30 to +80*C

Ambient temperature: –30 to +80*C

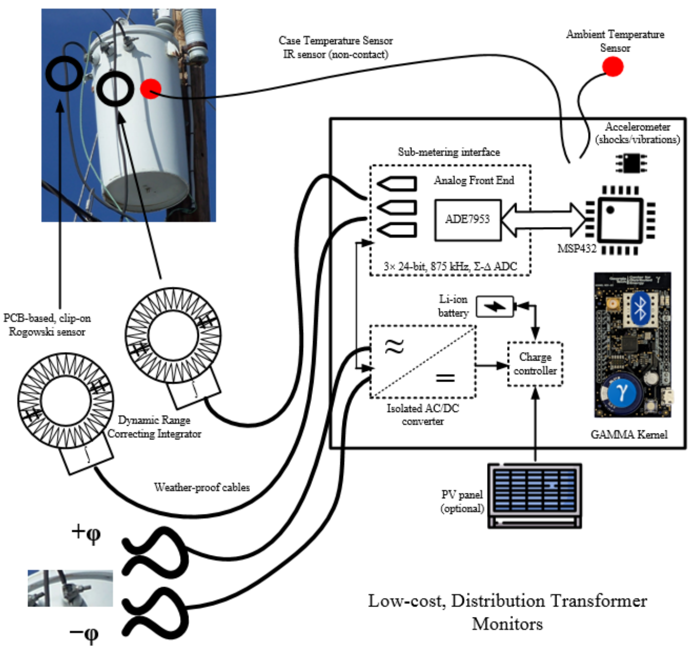

Figure 2 Architecture of the transformer monitor

Faults and overloads are one of the leading causes of transformer failures in the grid. In order to successfully capture fault current waveforms, specialized sensors are needed, which are typically more expensive than sensors that can record nominal current levels. To capture nominal as well as fault current waveforms, a novel current sensor and signal conditioning module was developed as shown below.

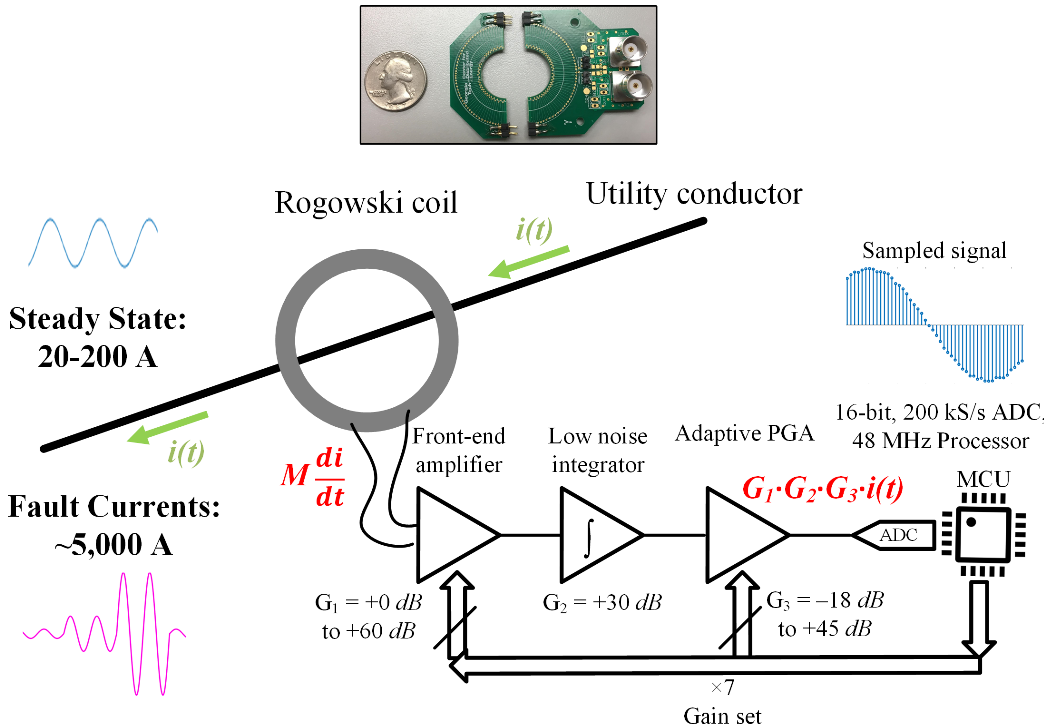

Figure 3 Current sensing and signal conditioning stage

The details behind the current sensor design and validation can be found in [2] and [3]. The clip-on Rogowski sensors form the basis for monitoring the phase currents in the transformer monitoring unit and allow for dynamic range correction and the ability for the same sensors to be used across multiple transformer sizes without the need for customizations, ultimately saving valuable field engineering time and leveraging the manufacturing scale for lowering costs. The sensors record instantaneous values for the above quantities at every 1 min interval. After 15 such measurements are recorded, the sensor averages the 15 measurements to generate one averaged quantity for each parameter being measured, thus generating 1 data point every 15 min. Thus, in one day, the sensor will generate approximately 96 data points. It must be noted, that by design, the sensors cover a wide operating range and can determine normal (nominal) operating conditions from electrical disturbances/power quality events. When power quality events like voltage sags, surges, fault currents occur, the sensor enters an “events mode” and records these disturbances and reports them to the cloud along with nominal data. The specifications and ranges for measurements are included in the next section. Each data point is constructed into a JSON structure following GAMMA protocol.

The size of each of the data packets is approximately 95 – 110 bytes. This JSON structure is serialized and encrypted with a unique AES-128 bit key, creating a randomized byte stream that is uplinked via Bluetooth to the GAMMA Console App that the team has developed. The data collection process is automatic as long as the mobile phone app is in the range of the sensors (field tested range is several hundred meters). The only user interaction needed is the initial secure login for the user profile and activating appropriate Android permissions for the application to function. As long as the utility crew members activate the app following the appropriate steps, the application runs in the background and pulls data from the surrounding GAMMA sensors.

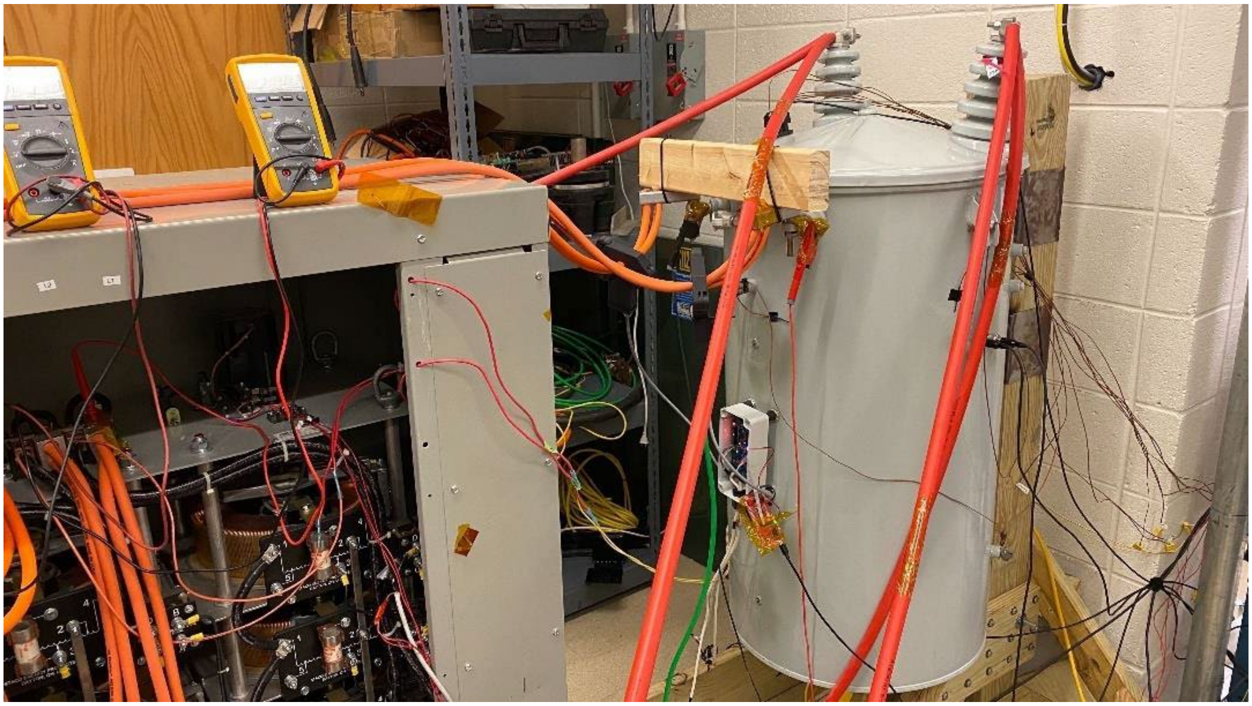

Figure 4 Snapshot of the sensor under test with a 50 kVA transformer

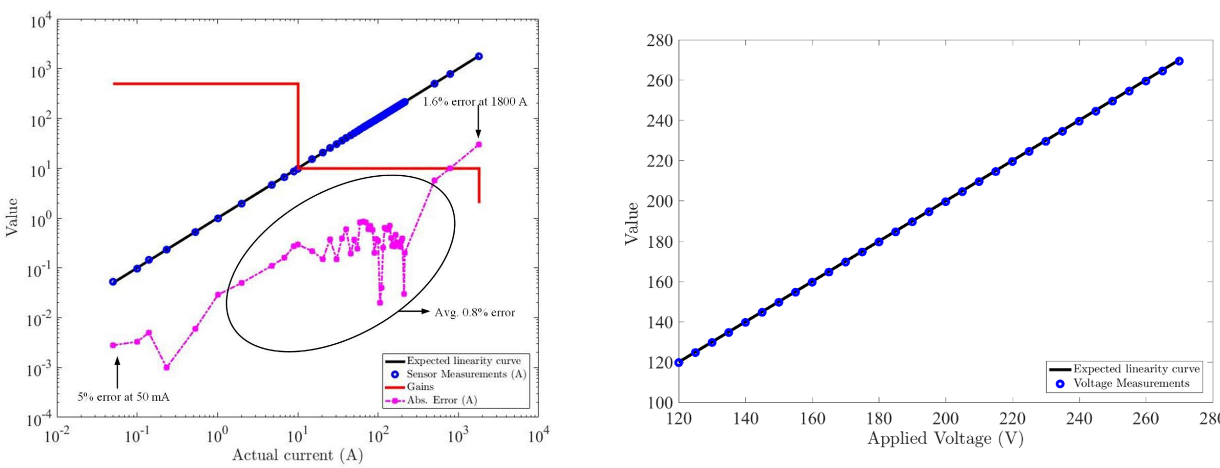

Figure 5 Current and voltage sensing characterization

Figure 6 Utility lineman handling and installing the sensor in the field

Figure 7 Sensor installation

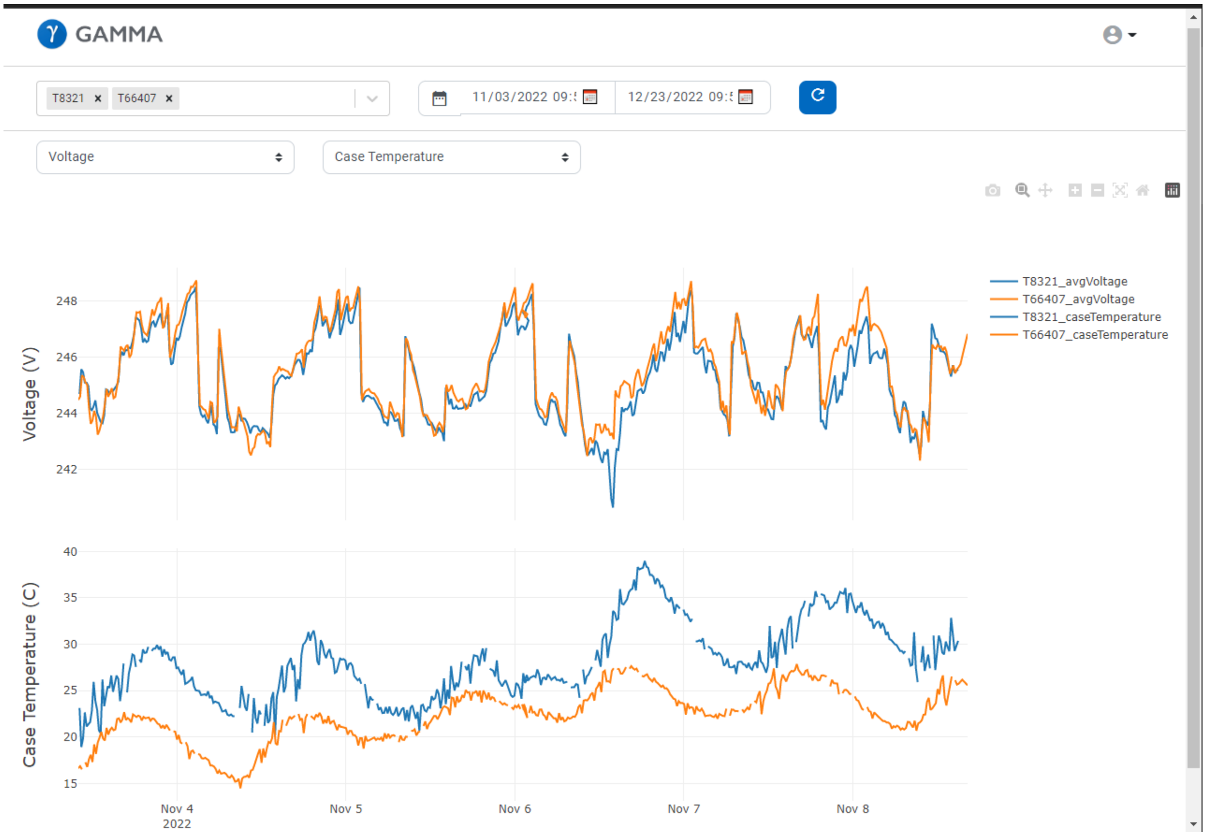

Figure 8 Data collection and visualization on GAMMA Platform Web portal

IV. Accomplishments and Conclusions

In summary, the project as showcased promising outcomes and met the overall objectives of demonstrating a low-cost asset monitoring platform that can be scalable and viable in a commercial setting. The team has developed a solution for monitoring the health and performance of pole-top distribution transformers through non-invasive sensors that can be installed in a matter of minutes and activated with a smart phone. The high-fidelity sensors are able to measure key parameters of the transformer and record, in-depth, time-stamped data that can be analyzed locally and through the cloud.

The project established a successful data processing and communications architecture for GAMMA Platform that can support such large-scale fleet deployment and operations. This was the first such field demonstration of a decentralized, delay-tolerant, edge-computing platform for supporting power grid applications. This successful demonstration paves the way for other applications in the grid monitoring and control space that can be supported by GAMMA platform.

The project developed and demonstrated a novel clamp on current sensor that can automatically scale itself for measuring nominal as well as fault state currents. This has major implications in power grid metrology across a wide dynamic range and the technology was demonstrated for the application of transformer monitoring.

The team also developed and demonstrated several data analytics algorithms that can derive valuable insights from the data that the sensors record. The algorithms provide advanced visibility into the state of the distribution network and can infer key parameters and relations between the sensors and the assets being monitored.

The entire technology stack has been licensed by Endeavour Energy LLC for scaling and commercialization with ongoing efforts to engage with the broader utility base in the US.

APPENDIX A: Product or Technology Production

Information Dissemination –

1) Conference Presentations & Proceedings –

   a) "Evaluating time varying connectivities and system throughput in opportunistic networks for smart grid applications", in *Proc. IEEE 5th World Forum on Internet of Things, Limerick, Ireland, 2019.*

   b) "Asset monitoring using smart sensing and advanced analytics for the distribution network", in *Proc. North American Power Symposium, Wichita, USA, 2019*

   c) "Sensing Service Transformer Secondary Currents using Planar Magnetic Pick-up Coils", in Proc. IEEE PES Innovative Smart Grid Technologies Conference, Washington, D.C., USA, 2020.

   d) "Distribution transformer health monitoring using smart meter data", in Proc. IEEE PES Innovative Smart Grid Technologies Conference, Washington, D.C., USA, 2020.

2) Journal Publications –

   a) "Enabling a Decentralized Smart Grid using Autonomous Edge Control Devices", in IEEE Internet of Things Journal, vol. 6, no. 5, pp. 7406-7419, Oct. 2019.

   b) "An Edge-Intelligent, Clip-on Rogowski Current Sensor With Wide Dynamic Range" in IEEE Sensors Journal, vol. 21, no. 2, pp. 1059-1071, 15 Jan.15, 2021.

   c) "Online detection of inter-turn winding faults in single-phase distribution transformers using smart meter data", in in IEEE Transactions on Smart Grid, vol. 12, no. 6, pp. 5073-5083, Nov. 2021.

3) Thesis Dissertations –

   a) S. Kulkarni, "Distributed, Intelligent Edge-Sensing for a Smarter Grid", Georgia Institute of Technology, 2021 – Available Online – https://smartech.gatech.edu/handle/1853/66413

b) K. Ashok, “Distribution Transformer Asset Monitoring On The Grid Edge Using Smart Sensor Data”, Georgia Institute of Technology, 2021 – Available Online – https://smartech.gatech.edu/handle/1853/66415

Product and Technology Transfers –

1) Patent Applications –

   a. “Current Sensors Employing Rogowski Coils and Methods of using Same”, US Patent Application, Publication No. US 2022/0252642 A1, 2019.

2) Technology Licenses –

   a. GAMMA Platform Intellectual Property – The core IP behind GAMMA Platform and related applications has been licensed by Endeavour Energy LLC.

APPENDIX B: Demonstration Summary Report

Demo Sites and Installation

To demonstrate the technology in the field, a search was initiated by Southern Co. to locate feeders within their service territory to deploy the prototype units on a feeder that each has characteristics of common feeders across the United States, or across a distribution substation with more than two distribution feeders. The location was narrowed down to Georgia Power service territory with one feeder preferably located close to metro-Atlanta area. Each feeder would host 50 sensors developed by GT-CDE team. Hence the total count across the two feeders is 100 sensors.

Final feeders selected –

According to the above requirements, Southern Co. performed a search within the internal database and selected the following two feeders for the field demonstration –

1) Paces Ferry (Located North Atlanta):

    i) Address – 3316 Northside Parkway NW Atlanta GA 30327

    ii) GPS Coordinates – 33.846833, -84.429281

    iii) Feeder #– F2192

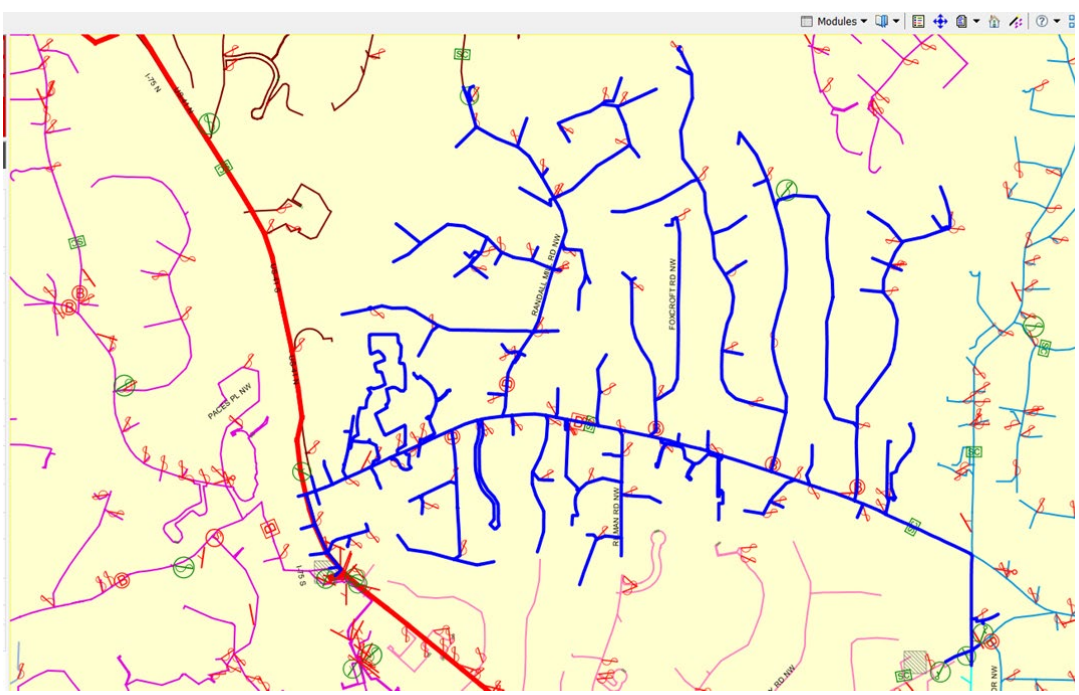

Figure 1: Paces Ferry Road Feeder# F2192

2. Donalsonville (Located South Georgia):

    (a) Address – 3256 S Knox Ave Donalsonville, GA 39845

    (b) GPS Coordinates - 31.042966, -84.883831

    (c) Feeder #-C0382

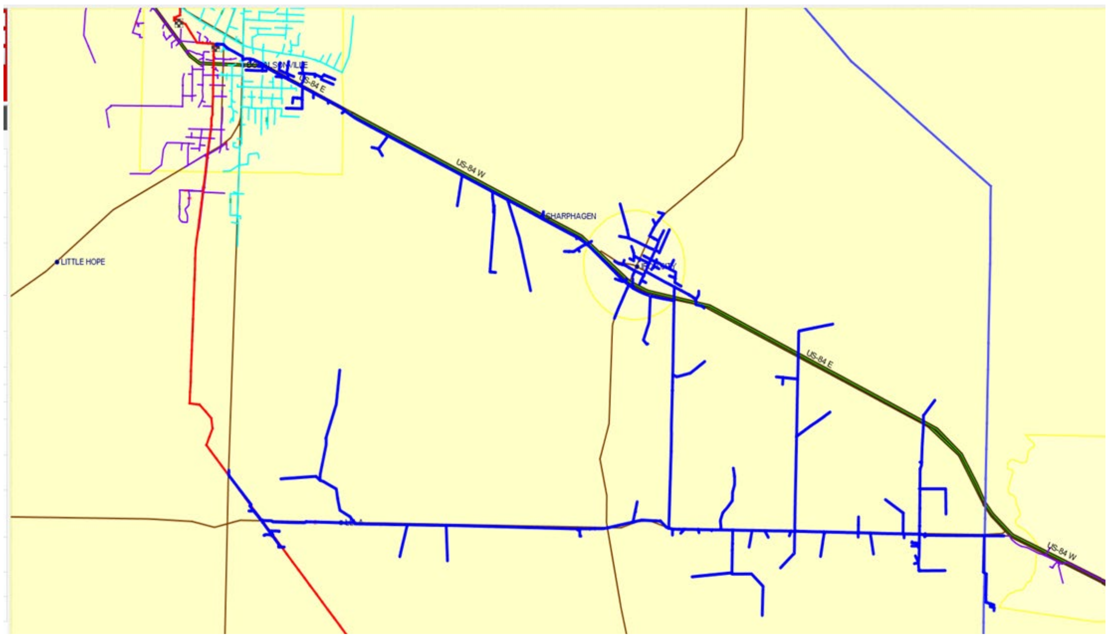

Figure 2: Donalsonville Feeder# C0382

Evaluation at Klondike Distribution Test and Training Facility –

The team visited Southern Company distribution test facility at Klondike, Atlanta, GA to perform an in-person demonstration of 2 test units of the transformer sensor. The team interacted with the field engineers, the line technicians and the senior distribution engineering staff to discuss and understand the nuances of installing the sensors in the field.

Following the review, the 2 sample sensors were installed as shown in Fig. 3 below.

Figure 3: Sample #1 being installed on a “live” transformer

Finally, the team began the installation of sensors in the two feeders and completed the same with the help of Southern Co/Georgia Power's field crew. A total of 100 units were installed, commissioned, and operated in the two distribution feeder locations mentioned above.

Figure 4: A transformer monitor being installed in the field

Figure 5: Transformer monitors in the field

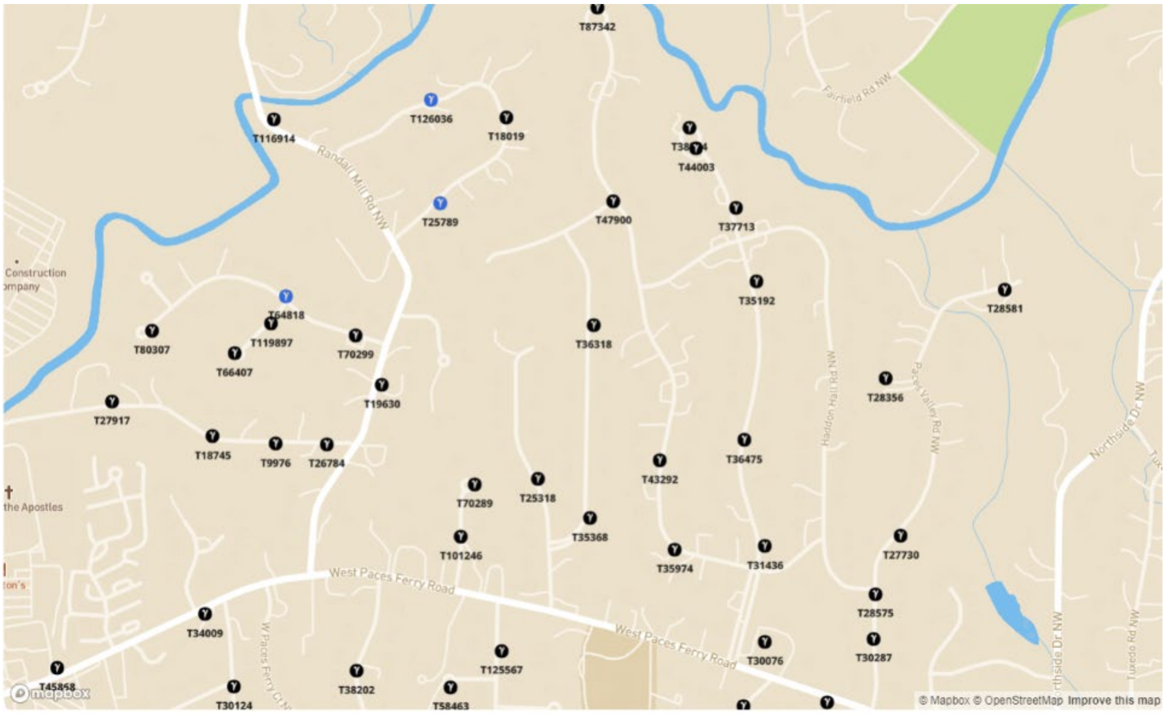

Figure 6: Map location of all 50 units in Paces Ferry neighborhood in Atlanta, GA

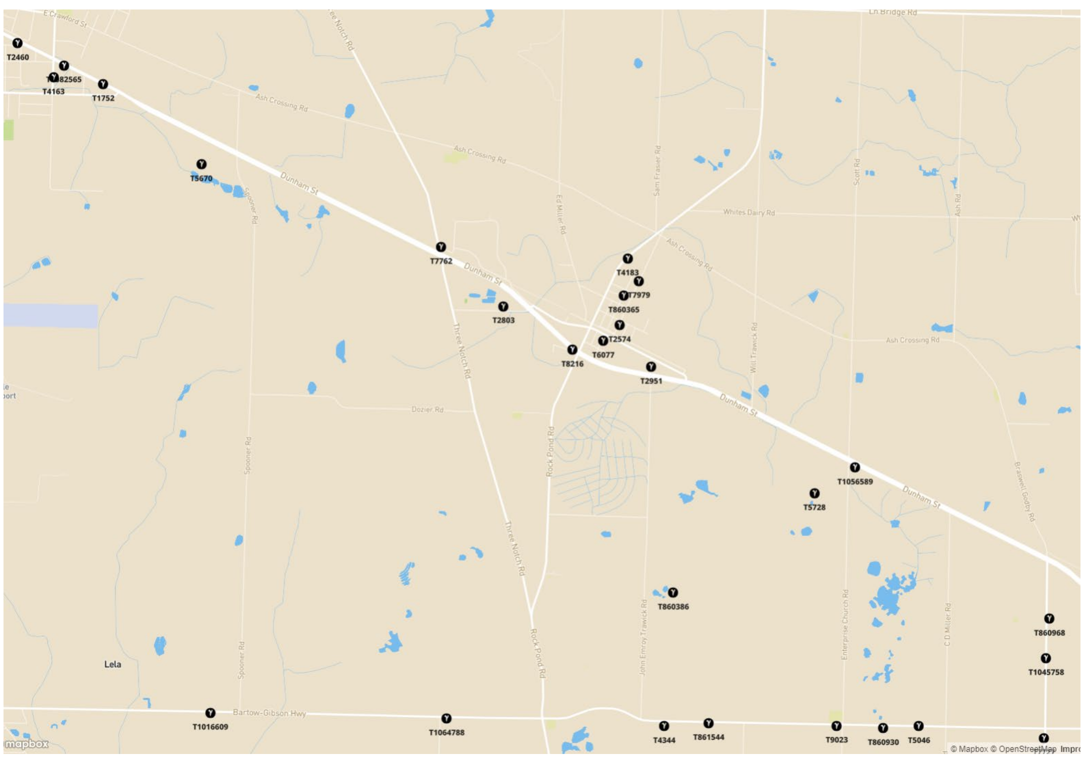

Figure 7: Map location of all 50 units in Donalsonville, GA

Data Collection

Once the devices were installed, the data generated by the devices were collected through the GAMMA data mule mobile phone application via BLE communications.

The mobile phone app is a quick way to visualize data and device status and alerts as shown below –

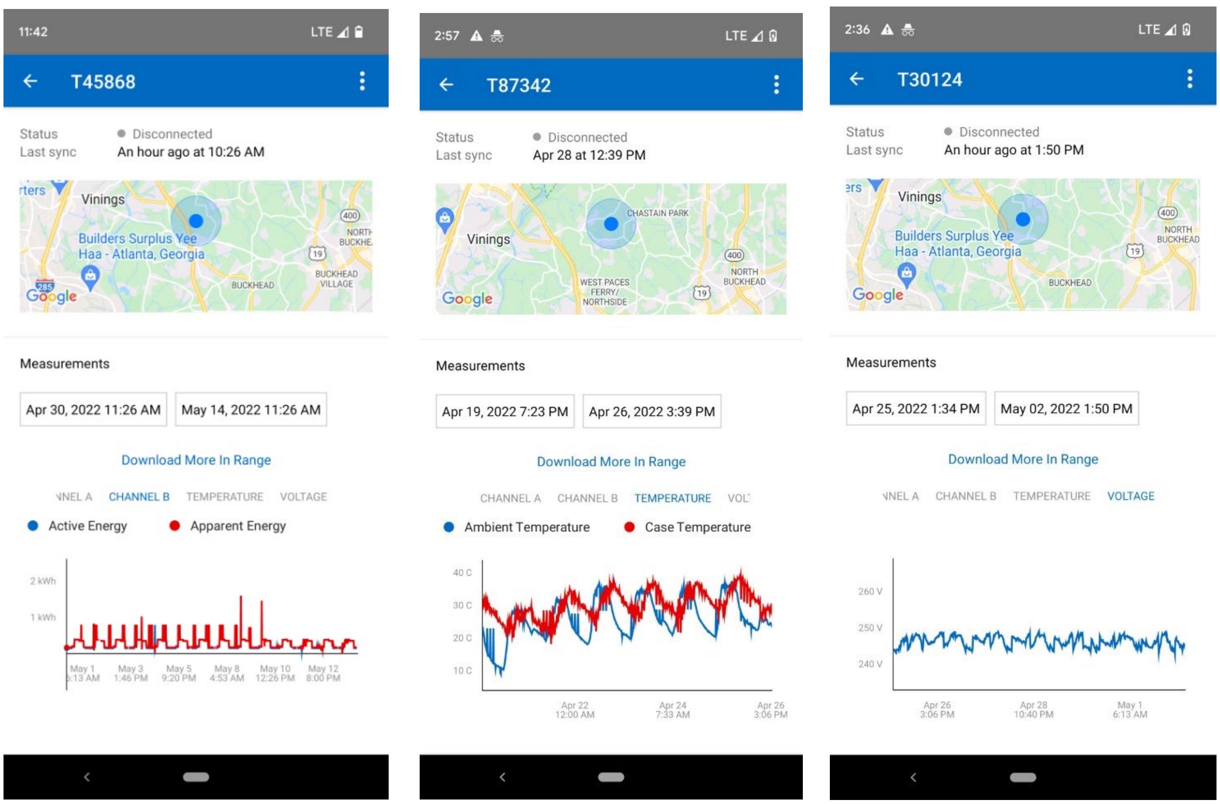

Figure 8: GAMMA Data Mule Application showing data from sensors

Figure 9: Web UI portal showing data on T101246 from the Paces Ferry Fleet

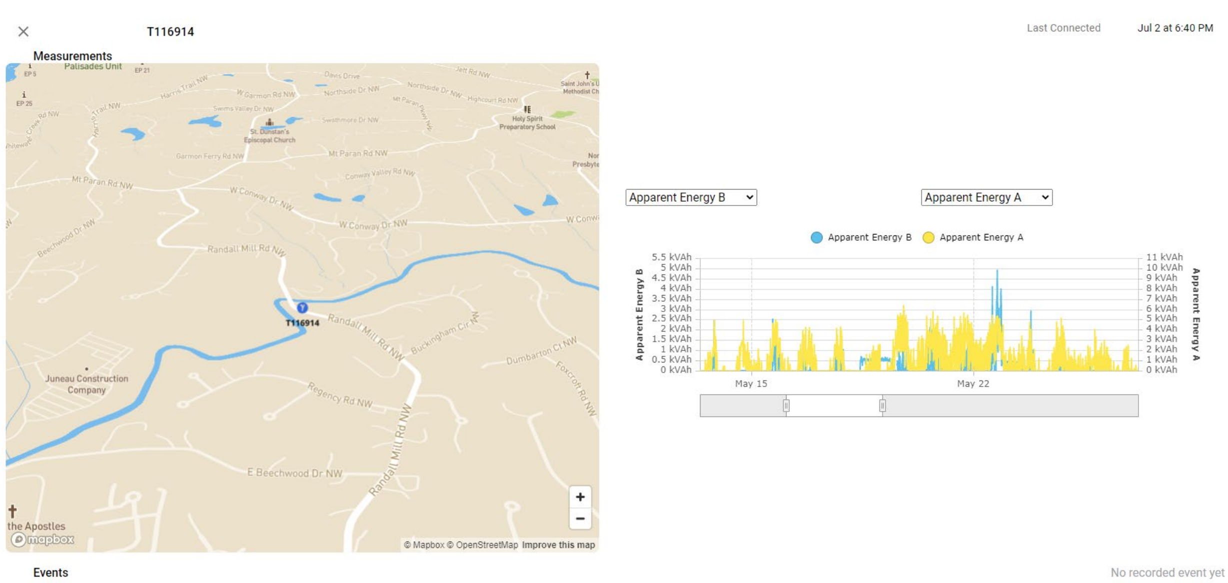

Figure 10: Web UI portal showing Energy Profiles on T116914 from the Paces Ferry Fleet

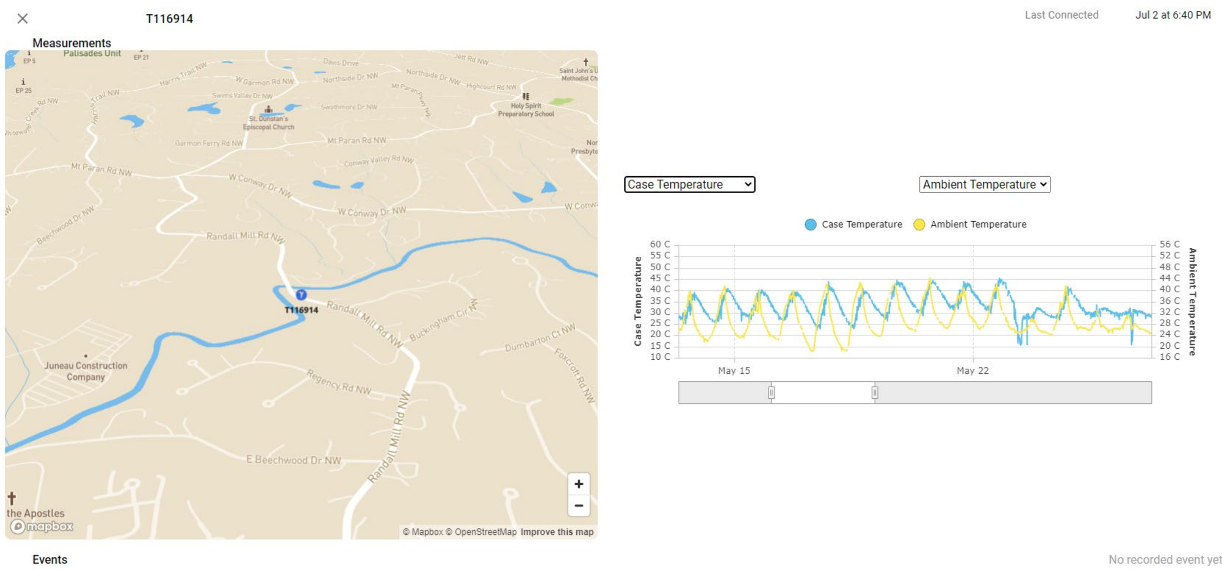

Figure 11: Web UI portal showing Temperature Profiles on T116914 from the Paces Ferry Fleet

Data Analysis and Conclusions

The operated devices in both the locations provided a rich data set to validate the data analytics stack that was developed, to showcase the value proposition of advanced visibility and situational awareness in distribution networks.

Following figure shows an aggregated view of the voltage profile for the feeder, as captured by the 50 units in the Paces Ferry Feeder.

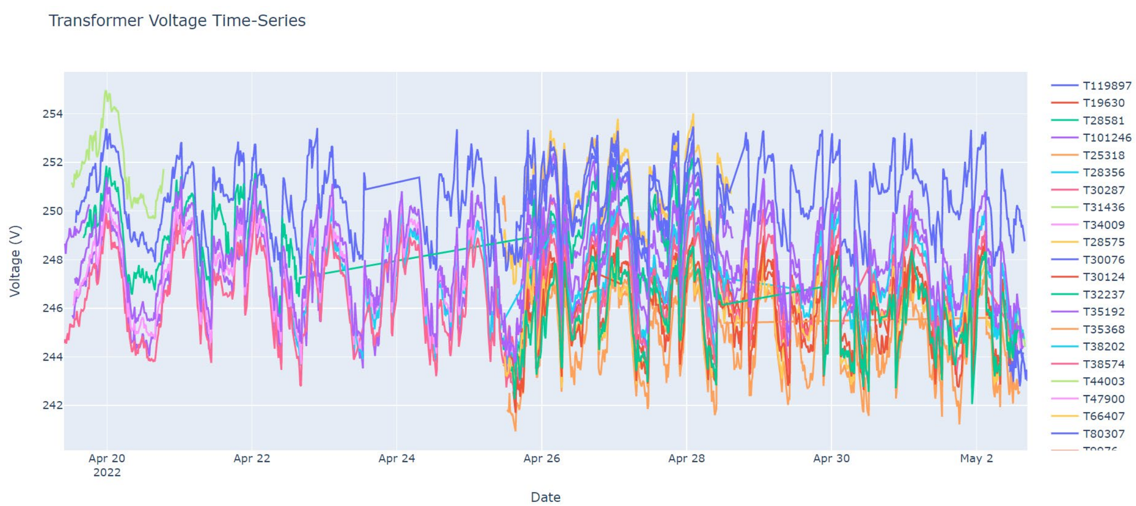

Figure 12: Time series voltage data from 50 units

Based on the voltage and power profiles recorded by the sensors, a complete feeder topology map can be developed. The details behind the algorithm can be found in [4].

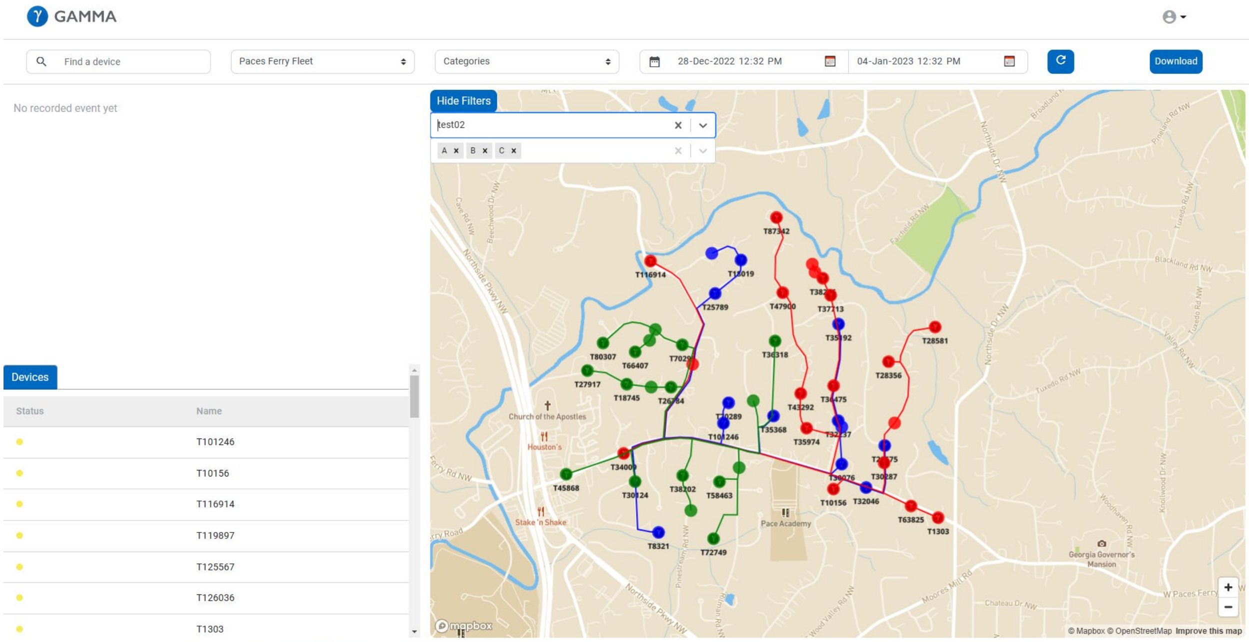

Figure 13: Phase map for the feeder

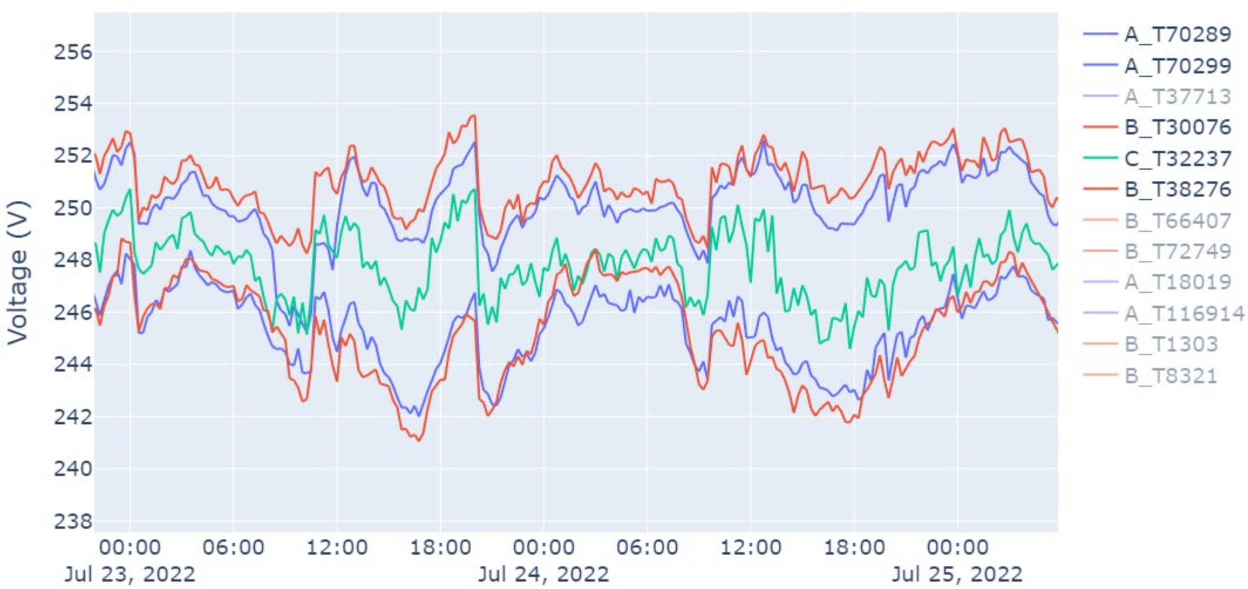

Figure 14: Time series voltage data for transformer cluster

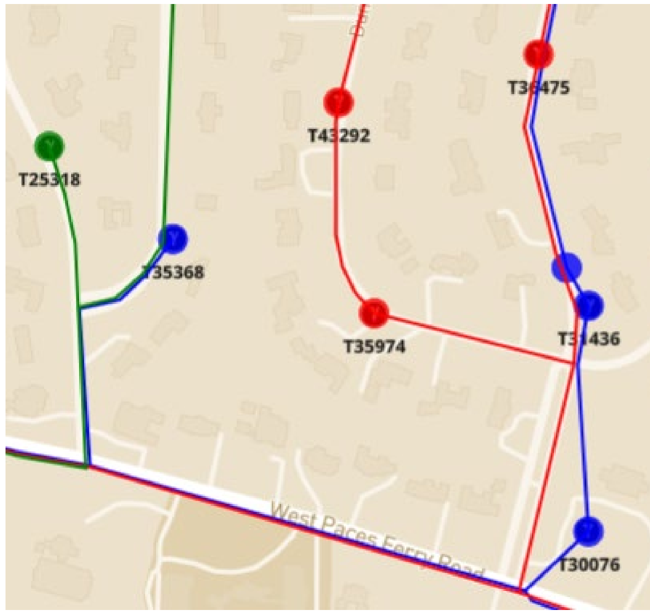

Figure 15: Cluster of transformers grouped by phases

Using measured power, ambient and case temperature, several insights can be derived with respect to the available capacity of the transformer. The recorded temperature data is also indicative of weather events and anomalies as shown in Fig. 17 and 18.

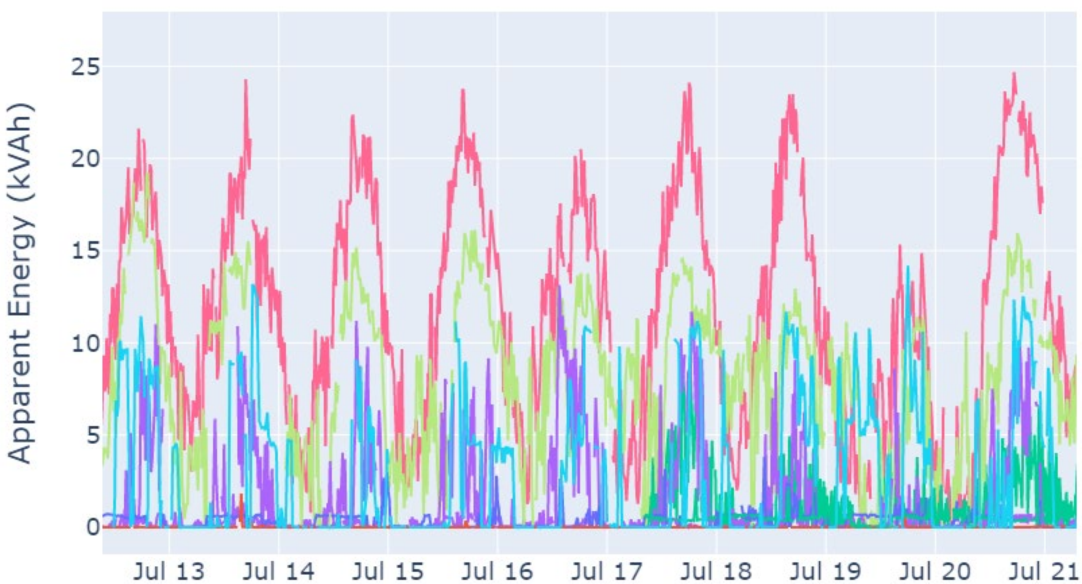

Figure 16: Time series power/energy data from 50 units

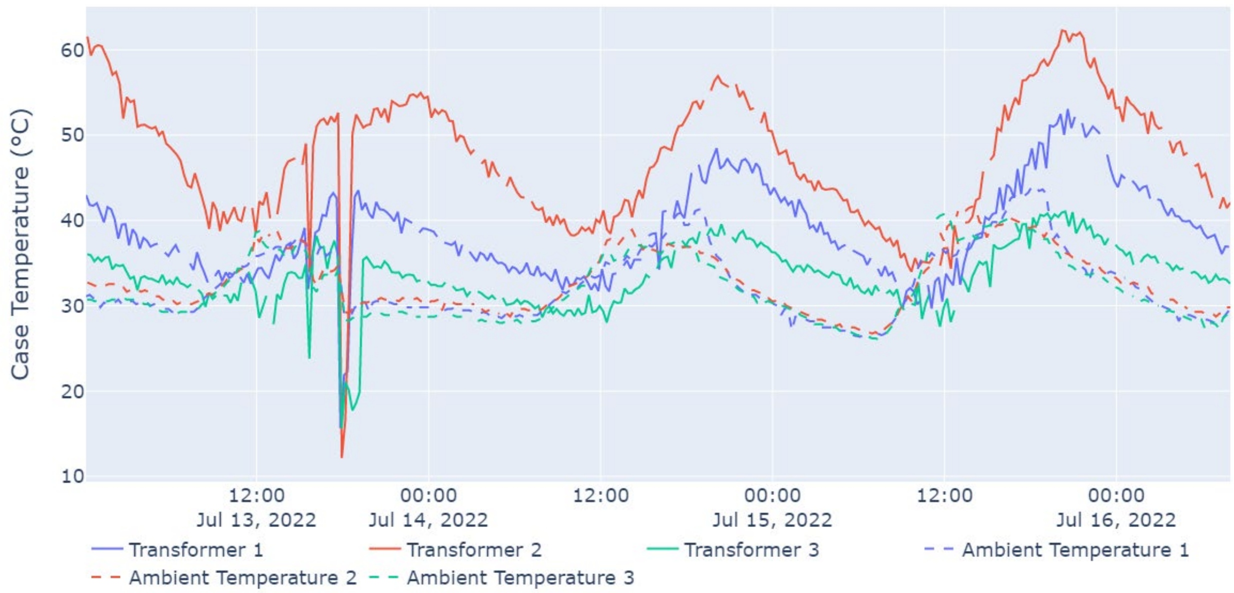

Figure 17: Time series case temperature data from 50 units – Weather events can be detected

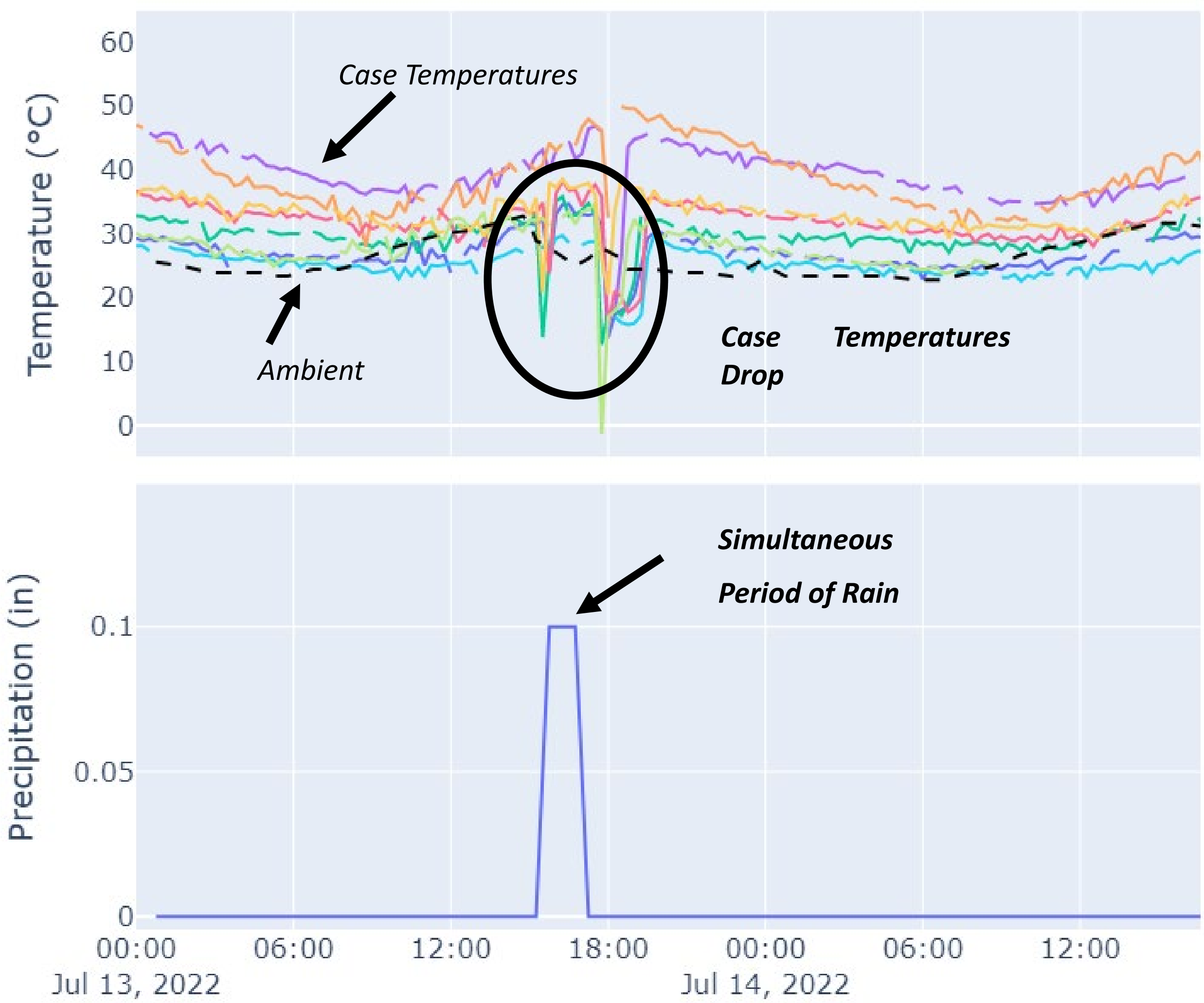

Figure 18: Weather event correlation

The IEEE Thermal Model for Transformer loading (IEEE C57.91-2011 equations [5]) relate ambient temperature, transformer loading and specific parameters like total capacity, cooling mode etc to the hotspot temperature, which is an important factor that determines overall asset lifespan and accelerated degradation/ageing. The data captured by the sensors is able to compute the risk of accelerated degradation due to the hotspot temperature falling outside of safe bounds as shown below. More details on the model and computation of the hotspot temperature can be found in [6].

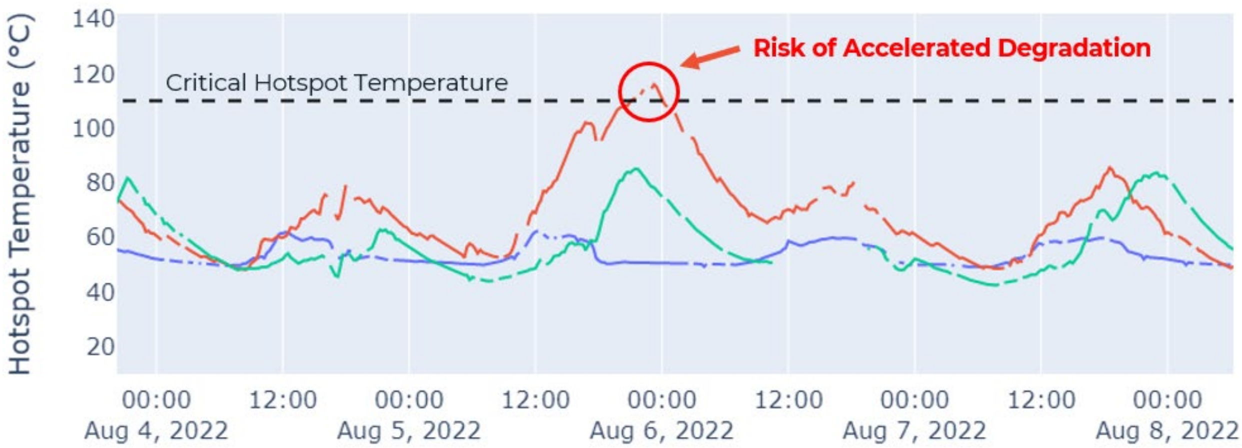

Figure 19: Transformer detailed thermal model and hotspot estimation

The demonstration validated the design, the overall architecture of the system and the various components comprising it. Through the field trial, the team had a chance to test the sensors and the platform in a real-world setting and subject the system to extreme test cases and ensure the system works as intended. The design for the sensors was validated through inputs from the manufacturing partner as well as the utility crew. The system was subjected to several steps from device provisioning, database entries, factory testing and calibration, commissioning and field installations as well as data collection in the field. This exercise ensured that the platform has been well designed and validated end to end.

The data collected through the project has delivered several insights into the asset management and the overall performance of the distribution system. Typically, utilities have visibility on customer usage only for billing purposes and seldom the loops are closed on operational considerations in the distribution network. Through this project, a solution for gaining advanced visibility into the network, the asset performance, the networked effects for loading, power events etc was demonstrated.

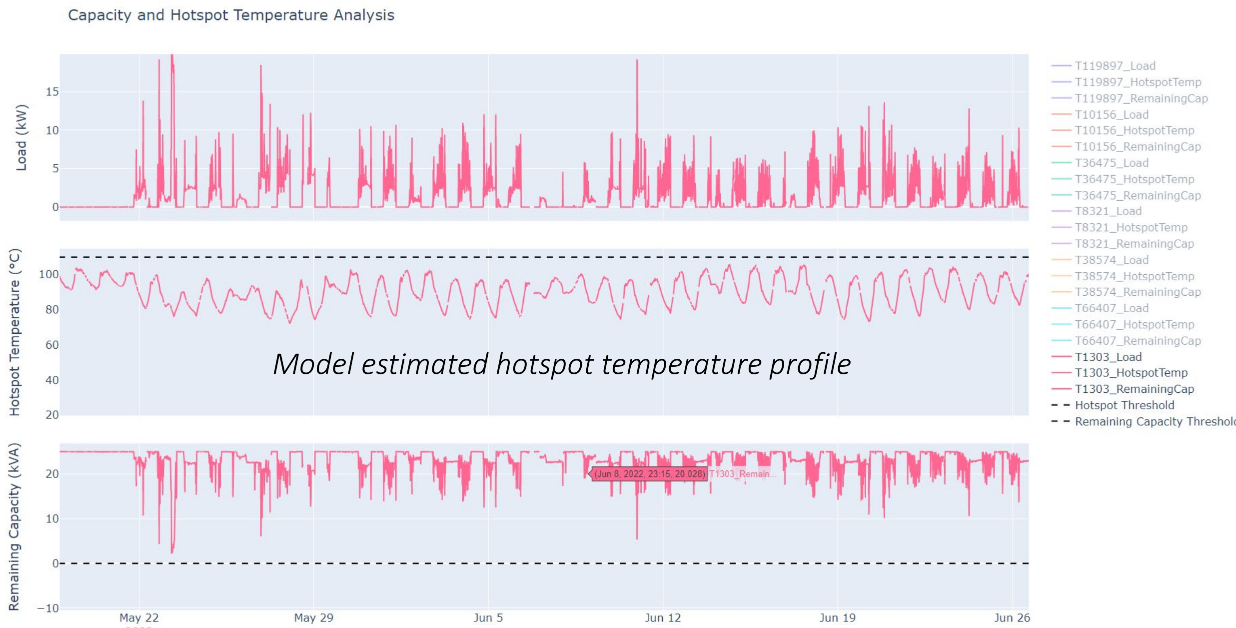

Figure 20: Transformer detailed thermal model and hotspot estimation showing asset utilization

For instance, through the loading and temperature profile data recorded by the sensors along with the thermal models developed, the utility operators can gather insights into the overall asset loading, and remaining capacity for planning and operational purposes. This is depicted in Figure 20. Additionally, the sensors and the data recorded by them can be leveraged to estimate and track the voltage profiles in the primary network. Typically, more advanced, expensive and bulky sensors are needed to measure medium voltage networks. However, the GAMMA Platform capability allows utilities to obtain insights into the primary network at a low cost as shown in Figure 21. It allows the utilities to get a secure, bird's eye view in terms of situational awareness and network performance.

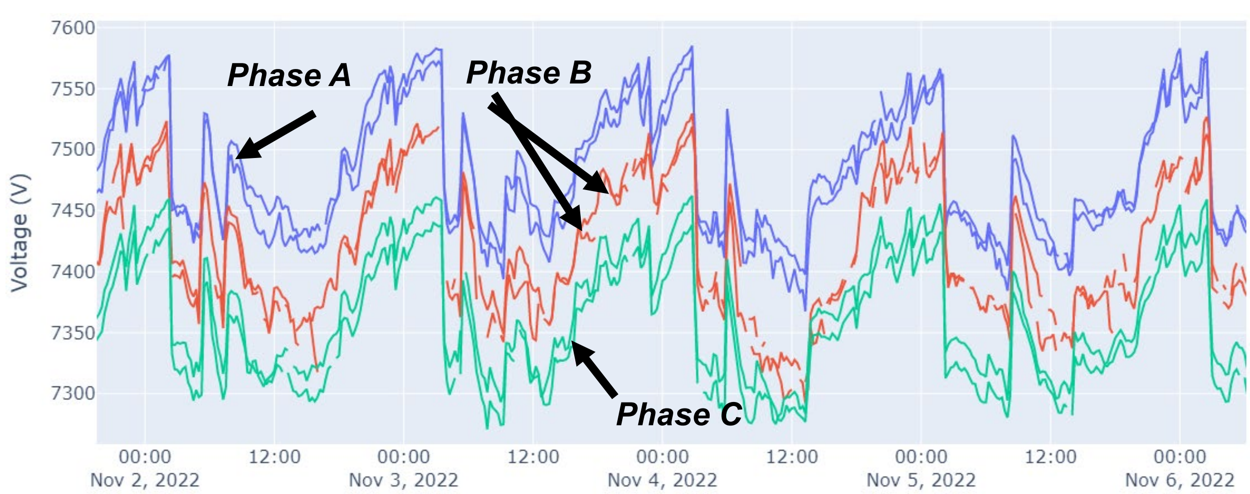

Figure 21: Primary Voltage Estimation and Feeder Mapping

Table 1 summarizes the features and benefits of the SENSE system. The specifications for the sensors are captured in Table 2. It can be seen that the sensors and overall system developed through the course of this project was able to capture specific transformer health parameters through the advanced sensing modalities. This was achieved in an overall package that was low cost and easy to install and operate in the field, making it a scalable solution for distribution asset monitoring.

Table 1 Summary of SENSE sensor features

Sensor Attribute	Units	Performance Target	Assumptions and Comments	Achieved
Ease of Deployment - Time Required to Deploy Sensors	minutes /sensor	15		10 min
Ease of Deployment - Hot Stick Capability	N/A	Hot Stick Capable	Sensor package hotstickable or capable of being installed with hotstick without de-energizing equipment	Not hot-stickable, but can be installed on a live system without de-energizing the transformer
Calibration	hours/sensor	Self calibration	Self calibration with verification from cloud data	Self calibration
Calibration	$/sensor	No additional cost		N/A
Maintenance	hours/sensor	Not required	Replace if found faulty. No field repairs will be conducted.	Not required
Maintenance	$/sensor	Not required	Replace if found faulty. No field repairs will be conducted.	Not required
Maintenance Cycle	time between maintenance events	Not required	Replace if found faulty. No field repairs will be conducted.	Not required
Life Expectancy	years	10 years		10 years

Table 1 Summary of SENSE sensor features (cont.)

Power Consumption	Watts	< 1 watt		1 W
Response Time	ms	20		< 1 ms
Environmental	Operating Temperature Range (ºC)	60 to -40 degC	Operating Temperature Range for the Integrated Sensor Package	60 to -40 degC
Case	UL rating	IP66		IP66
Tamper Proof Packaging	Security Measures	Sealed GPS location	Sealed packaging and ability to detect movement based on GPS location helps in identifying theft	Sealed packaging
Cybersecurity	Security Measures	Cyber secure	Cybersecurity throughout components and systems, utilizing open standards and other cybersecurity best practices	Cyber security through AES-128 bit encryption

Table 2 Summary of SENSE sensor specifications – Voltage, Current, Temperature, Frequency

Sensor Type	Technical Specs	Units	Target Value	Comments	Achieved
Voltage	Measurement Range	Volts	240 V +/- 20 %		0 – 300 V
	Limit of Detection	Volts	120 V (50 %)		0 V
	Response Time	cycle	1		1
	Accuracy	% Full Scale	5% (FS = 240V)		2%
	Resolution	Volts	1		1 mV
Current	Measurement Range	Amperes	200 A max		20,000 A
	Limit of Detection	Amperes	20		0.025 A
	Response Time	ms	20		1 ms
	Accuracy	% Full Scale	5% (FS: 200 A)		1%
	Resolution	Amperes	2		0.025 A
Temperature	Measurement Range	(ºC)	-40 to 150	Temperature range provided is for the estimated transformer hot spot temperature	-40 to + 150
	Limit of Detection	(ºC)	150 (ºC), -40 (ºC)		-40 to + 150
	Response Time	seconds	10		60 s
	Accuracy	% Full Scale	3%		10%
	Resolution	(ºC)	1		1
Frequency	Measurement Range	Hz	55 - 65		30 – 100 Hz
	Limit of Detection	Hz	55		30 Hz
	Response Time	ms	20		0.01 ms
	Accuracy	% Full Scale	0.3 Hz (0.5%)		0.1%
	Resolution	Hz	0.1		0.01 Hz

Transformer overloading, the resulting heating and loss of life are the main causes for unexpected failures. Transformers get overloaded due to newer load types getting adopted in residential customer premises. EVs are one such example. As more and more EVs get adopted on the road, residential customers will need solutions that can enable EV charging which has a minimal impact on the grid assets. This “smart, grid-aware EV charging” can allow utilities to support the growth of newer load types like EVs while meeting overall demand as well as decarbonization goals. The sensors demonstrated in this project serve as a means to record and track grid asset performance, loading patterns, thermal effects as well as the coupled power grid trends.

The team demonstrated the system performance at scale with a single utility partner at two live locations with distinct characteristics. The project showcased a way to gather necessary data pertaining to the asset performance at a low-cost – both in terms of initial capital expenditure as well as ongoing operational costs. In the US, each utility has a different operational regimen, budgets and priorities and there are opportunities to expand the coverage for the monitoring and the proactive asset management that has been summarized in this project. For pushing this envelope furher, the GAMMA technology stack has been licensed for commercialization by Endeavour Energy LLC. The team at Endeavour is working on developing and improving the advanced sensors to be deployed in the distribution network, using the GAMMA Platform.

In conclusion, the field demonstration validated the technology stack that was developed through this project. Specifically, the team was able to demonstrate the feasibility of GAMMA platform for managing and monitoring a fleet of devices, recording rich data pertaining to asset performance and overall power grid network effects. The team was able to show that the sensing technology can be viable in a commercial setting and the novel IP developed through the project has practical path to market.

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