Pacific Gas and Electric Company

EPIC Final Report

Program	***Electric Program Investment Charge (EPIC)***
Project	***EPIC 3.32 – System Harmonics for Power Quality Investigation***
Department	*Power Quality*
Project Sponsor	MaryAnn Dillahunty
Project Business Lead	Barry Wong
Contact Info	EPIC_Info@pge.com
Date	April 24th, 2023
Version	Final

TABLE OF CONTENTS

List of Tables

List of Figures

List of Acronyms

4G LTE	Forth Generation Long Term Evolution
AMI	Advanced Metering Infrastructure
AMPQ	Advanced Meter with Power Quality
ANSI	American National Standards Institute
CB	Circuit Breaker
CC&B	Customer Care and Billing
CEC	California Energy Commission
CPUC	California Public Utilities Commission
CSV	Comma-separated values
C&I	Commercial and Industrial
DER	Distributed Energy Resource
DG	Distributed Generation
EDPI	Electric Distribution PI System
EPIC	Electric Program Investment Charge
ESFT	Enterprise Secure File Transfer
EV	Electric Vehicle
HHF	Hand Held Format
ID	Identification
IEEE	Institute of Electrical and Electronics Engineer
IP	Internet Protocol
ITHD	Current Total Harmonic Distortion
LAN	Local Area Network
LR	Line Recloser
PG&E	Pacific Gas and Electric Company
PQ	Power Quality
PQM	Power Quality Monitor
PV	Photovoltaic
RMS	Root Mean Square
RVM	Recording Volt Meter
SCC	Short Circuit Current
SCADA	Supervisory Control and Data Acquisition
SFTP	Secure File Transfer Protocol

T&D	Transmission and Distribution
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
VAR	Volt-ampere reactive
VFD	Variable Speed Drive
VTHD	Voltage Total Harmonic Distortion

1 Executive Summary

Pacific Gas & Electric Company (PG&E) is experiencing an increase in harmonic distortion in our Transmission and Distribution (T&D) systems due to the proliferation of distributed energy resources (DERs) such as solar photovoltaic (PV), and power electronics loads such as variable speed drive (VFD), switched-mode power supply, and electric vehicle (EV) battery chargers. This modern electrical equipment are non-linear loads which produce harmonic current that flows back into the power systems.

Most power systems in North America are designed to operate within 60 Hertz. The addition of other harmonic current frequencies into the system causes harmonic voltage distortion which deteriorates the power quality (PQ) of the electrical power PG&E delivers to customers. Harmonic current also causes adverse effects on utility and customers equipment, such as overloading and heating, therefore shortening equipment's life, and reducing efficiency. On the other hand, harmonic voltage may cause mis-operation of utility and customer equipment. Utilities are responsible for limiting harmonic voltage in the supply voltage while customers are responsible for limiting their harmonic current emissions. This Electric Program Investment Charge (EPIC) project primarily focuses on harmonic voltage in PG&E distribution systems and the terms harmonic distortion and harmonics will be used interchangeably throughout this report to indicate the voltage quality in the power systems.

In recent years, PG&E has received and investigated an increasing number of customer complaints where harmonics cause customers' equipment to mis-operate and, in some cases, fail prematurely. Many other utilities are facing similar issues, where the harmonics in the power systems have steadily increased over the years. Harmonics are expected to become a significant power quality concern for utilities as the grid evolves in the future. Typically, most harmonics in the distribution systems are produced by customers' loads. A unique challenge presented by the harmonics issues in modern electrical distribution systems is that no individual customers are solely responsible for the adverse effects of harmonics in the systems. Instead, it is an aggregation of distributed harmonics sources in the electrical distribution system that collectively results in power quality problems. For the utility to investigate and resolve harmonics issues, large amount of harmonics data collected from many customers' locations are required for power quality investigation.

Advanced Meter with Power Quality (AMPQ) are now commercially available from many electric meter vendors. The AMPQ is capable of providing high-resolution power quality data including harmonics to support grid operations and troubleshooting power quality issues.

In EPIC 3.32 *System Harmonics for Power Quality Investigation* project, PG&E explored the AMPQ technology to collect harmonics data for power quality monitoring and investigation. Collecting harmonics data on a larger scale also helps PG&E better understand where there may be harmonics issues in the distribution systems and where the harmonics come from. The findings and learnings from this project will help PG&E improve the process of addressing harmonics issues.

This report details the achievements and findings of PG&E EPIC project 3.32, *System Harmonics for Power Quality Investigation.* In this project, PG&E successfully demonstrated the capabilities of AMPQ to collect harmonics data in the distribution systems for power quality investigation. Using AMPQ to collect harmonics data can potentially reduce costs, improve safety, and improve customer satisfaction by allowing PG&E to continuously monitor, detect, and proactively address harmonics issues.

Issues Addressed

Currently, PG&E primarily collects harmonics data using portable power quality monitor (PQM). There are operational gaps in the existing process of collecting harmonics data in PG&E distribution systems. Firstly, the harmonics data are often collected reactively as a response to customer complaints on a case-by-case basis. The current process does not facilitate proactive and continuous monitoring of harmonics in the distribution systems. The AMPQ can continuously collect harmonics data and transmit it on demand, allowing power quality engineers to monitor system harmonics regularly and proactively take actions to mitigate harmonics issues before it impacts PG&E and customers equipment.

Secondly, the harmonics issues in PG&E's distribution system appears to be seasonal issues because the sources of harmonics are predominantly customers' loads which vary seasonally. Therefore, harmonics investigation may require that harmonics data be collected over weeks and months from many locations to get a complete picture. The existing process of dispatching a truck roll to collect harmonics data takes up a significant time for field personnel to install, download, and remove PQMs. Customers typically report harmonics issues impacting their equipment during the summer months when the harmonics level in the distribution systems appears to be worst. This also coincides with the season when the distribution systems loads are highest, and field resources are prioritized for circuit switching, maintenance, and emergency response. The existing process also ties up the limited PQM resources and make them unavailable for other non-harmonics customer voltage complaint investigations. Using AMPQ, PG&E can free up significant resources and increase operational efficiency.

Additionally, field personnel must access live electrical panels and transformer enclosures to install PQM which exposes field personnel to electrically energized parts and creates a safety risk of electrical shock and arc flash. On the other hand, working with AMPQ is much simpler and safer because it is installed in a meter socket, accessible from the front of the meter panel where there are no exposed energized parts, thus reducing safety risk when field personnel perform the work. The AMPQ can also transmit the data remotely, eliminating the need for field personnel to re-access the panel to manually download data from the PQM, further reducing the exposure to electrical hazards. The existing revenue meter can also be upgraded to AMPQ to collect both billing data and harmonics data maximizing the use of electric meter. This can reduce costs significantly since the cost of a AMPQ is only a fraction of the cost of a PQM.

Finally, it is necessary to have sufficient harmonics data for power quality engineers to investigate customer harmonics complaints. Extensive harmonics data often needs to be collected when no harmonics data is available for analysis at all. Without historical harmonics data readily available when customers report harmonics issues, it is challenging to address and resolve customers complaints in a timely manner because after PQMs are installed, days and sometimes weeks or months must pass to collect enough harmonics data for analysis. PQM resources are also limited, so it is not feasible to use PQMs to collect harmonics data on a larger scale in the distribution systems to understand how widespread harmonics issues are and where they come from.

To help address these issues, the EPIC 3.32 project was initiated to demonstrate the feasibility of using AMPQ to collect harmonics data and build a harmonics dashboard and analysis tools that power quality engineers can utilize to investigate harmonics issues.

Objectives

The objectives of EPIC 3.32 project are as follows:

1. Demonstrate the feasibility of using AMPQ to collect harmonics data for power quality investigation.
2. Develop an IT system that automates the collection and processing of harmonics data from the AMPQs.
3. Create a Harmonics Dashboard that facilitates monitoring and analysis of harmonics in PG&E distribution systems.
4. Analyze the harmonics data to get a preliminary assessment of the harmonics in the supply voltage quality that PG&E provides to customers and determine how widespread and severe the harmonics issues are in the systems.
5. Build analysis tools that power quality engineers can use to investigate and resolve harmonics issues.

Key Accomplishments

The following is a summary of the key accomplishments of the project:

- PG&E deployed 180 AMPQs in locations across the service territory covering 125 electric distribution feeders. The AMPQs were tested and programmed to collect and transmit harmonics data remotely.
- PG&E developed a cloud-based IT network system that automates the collection and processing of harmonics data from the AMPQs. The system also pulls loads data from distribution equipment such as feeder circuit breakers (CBs), line reclosers (LRs), and demand data from revenue SmartMeters™ for harmonics correlation analysis.
- The project team created *Distribution System Harmonics Analytics* dashboard, it is a data visualization and analysis tool that power quality engineers can use to monitor and investigate harmonics in the feeders where AMPQs are installed.
- The harmonics data collected in this project help identify feeders that have high harmonics which are feeders with a lot of agricultural VFD pumps. The findings in this project led to revision of the harmonics requirements in the VFD rebate program and proposed changes to Tariff Rule 2 to include IEEE 519 harmonics requirements.

Key Takeaways

The following are the key takeaways and learnings from this project:

- AMPQ can reliably collect harmonics data including Total Voltage Harmonic Distortion (VTHD), Total Current Harmonic Distortion (ITHD). The harmonics data from AMPQs are comparable to that from PQM and can be used to detect harmonics issues in the distribution systems.
- In the summer months, up to 33 of 125 distribution feeders monitored have voltage harmonics level exceeds the recommended limits per IEEE 519 standard. In the winter months, the number of feeders having high voltage harmonics is down to 4-5 feeders. The findings confirm that the harmonics issues in PG&E distribution systems are currently seasonal.
- The results in this project show that while the voltage harmonics levels in most of the distribution feeders covered in this project are within IEEE 519 limit. However, for the feeders that have high voltage harmonics, some of them far exceed the recommended limit by as much as twice. These

feeders have voltage harmonic distortion up to 15-20% which would likely cause issues for customer sensitive equipment.

- The results in this project also revealed many distribution feeders having high level of voltage harmonics previously unknown to PG&E, mainly in agricultural distribution feeders. Additional field investigation confirmed the major source of harmonics in PG&E distribution system are variable speed drive pumps.
- Power quality engineers can analyze harmonics data from the AMPQs in conjunction with other data from electric distribution devices and revenue SmartMeters™ to determine the source of harmonics. The harmonics data can also identify issues on the utility side, such as capacitor bank resonance, that may worsen harmonics.
- The use of AMPQ to collect harmonics data significantly reduces truck rolls, speeds up power quality investigation, and reduces time to resolve harmonics issues for customers.

Challenges

The following are key challenges that the project faced:

Field installation of the AMPQs:

1. In this project, the AMPQs were installed separately alongside the existing revenue meters already installed at customer meter panels to limit impacts on the billing system due to the proof-of-concept nature of this project. This approach required that a spare meter socket is available at customer meter panels. Otherwise, a dual-socket meter adapter would have to be used.

   However, the locations for meter installation were pre-selected during the planning phase based on specific engineering criteria without site inspection in the field. It was found that the meters could not be installed in some locations due to site -specific limitations such as unavailable spare meter socket or the meter panel being too small to accommodate the wiring of dual-socket meter adapter. Therefore, new sites had to be selected causing a delay in the deployment of the AMPQs.

   The project team pivoted and worked closely with field metering department to identify new locations to install the AMPQs. The new sites were inspected, and the AMPQs were installed according to the project plan.

Integration and maintenance of data pipelines from multiple sources to the harmonics dashboard:

2. Several data pipelines were created to bring data from both the AMPQs and other electric distribution devices and existing revenue SmartMeter™. These different datasets needed to be processed and synchronized to provide data visualization and run calculations for the harmonics dashboard. There were frequent issues where the pipeline of individual data source broke, and it would affect the functionality of the harmonics dashboard.

   Initially, there was no alert mechanism built into the system to report any issues with the data pipelines at each stage of data processing. So, troubleshooting and bug fixing had to be done from end to end to identify the root cause which was very time consuming. This issue impacted the availability of the harmonics dashboard and sometimes would not be detected for a week later since the dashboard was updated weekly. To overcome this challenge, a daily report for data download and process was created to provide alerts when there were issues with the data pipelines, so that the problems could be detected and fixed as quickly as possible.

Scalability:

3. While the EPIC 3.32 project successfully demonstrated the feasibility of collecting harmonics data from 180 AMPQs over the 4G LTE cellular network. This approach may not be easily scalable if the AMPQs are read sequentially as it was the case in this project.
   The time taken to read and process harmonics data from one AMPQ over 4G LTE cellular network ranged between 5-10 minutes which some AMPQs could take significantly longer if there was poor cellular coverage at the installation sites.

   To overcome this challenge, a second server was added to help collect and process the data from the AMPQs. As the number of AMPQs increases, the data bandwidth and storage may be an issue and parallel processing will likely be needed. It is recommended that the future harmonics data collection using AMPQ will leverage the existing AMI network rather than using 4G LTE cellular network.

Harmonics impact on PG&E system and customers:

4. While this project was successful in helping PG&E collect harmonics data and better understand the harmonics issues in the distribution systems, it did not address the mitigation of harmonics impact on PG&E equipment and system. PG&E has seen harmonics impact on both customer and utility equipment in recent years. Customers have reported that solar PV inverters and EV battery chargers are not operating properly in high voltage harmonics environments. PG&E also has seen more issues with distribution capacitor banks that have abnormally high amperage readings and, in some cases, fail prematurely. PG&E recommends that the future EPIC project focus on harmonics mitigation on both utility and customer side.

Recommendations

This project has identified several areas that should have continued effort as follows.

Harmonics monitoring:

Harmonics and other power quality data collection should be explored for pathways leading to operationalization and integration into PG&E metering infrastructure in a production environment. The effort to scale the deployment of AMPQ functionality should focus on the geographical service areas identified in this project as having high harmonics level. These areas are identified as distribution feeders in the valleys serving agricultural customers running large VFD pumps. Monitoring harmonics emissions from large agricultural and industrial customers will be necessary to detect and resolve harmonics issues.

Harmonics data analysis:

The amount of harmonics data generated from AMPQs will increase with the number of AMPQs deployed in customer locations. This can result in a vast amount of data which would be impractical for power quality engineers to analyze manually. PG&E should continue to build analysis tools and process automation to help facilitate the analysis. The harmonics data analytics should also be made available to other lines of businesses that can leverage the data to improve operational efficiency, reliability, and safety. For example, harmonics have been shown to negatively affect the operation of customer solar PV inverters. Therefore, harmonics data may be useful during interconnection study of DER/DG projects.

Conclusion

The EPIC 3.32 *System Harmonics for Power Quality Investigation* project successfully demonstrated a new way of leverage AMPQs to collect harmonics data in the electric distribution systems. It demonstrated that the AMPQ could collect harmonics data comparable to power quality monitors at a lower cost since utility already has revenue electric meter installed at customer service for billing purposes.

Therefore, PG&E should operationalize and integrate harmonics and other power quality data into metering infrastructure in a production environment. The power quality data collected will be useful for power quality investigation, which has potential value related to improved reliability, safety, efficiency, and customer satisfaction. Additionally, more data algorithms may be developed to automate harmonics data analysis for engineering applications. This would help speeding up the process to identify the source of harmonics and to conduct analysis to determine whether the level of harmonics is within IEEE 519 guidelines.

The harmonics data collected in this project also revealed significant harmonic distortion in many of PG&E's electric distribution feeders, particularly in the agricultural areas. Field investigation revealed that the sources of harmonics in these areas are large variable speed drives (VFDs) running agricultural pumps which have proliferated in recent years due to energy efficiency benefits. The drought conditions in California may also have driven customers to install more and larger agricultural pumps to reach deeper water table. In many cases, these large pumps necessitate the use of VFD to allow the pump to start and run efficiently. However, VFDs also introduce significant harmonic distortion to the grid unless mitigation is taken. The results from this project helped PG&E shape policies to address the harmonics issues such as updating VFD rebate program requiring IEEE 519 compliance and updating Tariff Rule 2 to include IEEE 519 requirements.

The harmonics issues are expected to worsen in the future as the proliferation of harmonics sources such as VFDs, DERs, and EV battery chargers in the electric distribution system continue. Furthermore, modern customers' equipment is increasingly becoming more sensitive to harmonics due to the use of power electronics. This further highlights the need for continuous monitoring of the harmonics level in distribution systems, so that PG&E can proactively address the harmonics issues in before it impacts PG&E and customers' equipment.

PG&E is currently exploring different options for integrating harmonics and other power quality data from the AMPQ functionality into metering infrastructure and operational processes. The technology demonstration in this project provides valuable learnings to PG&E as it moves forward with the implementation of the next generation of advanced metering infrastructure.

2 Introduction

This report documents the EPIC 3.32 – *System Harmonics for Power Quality Investigation* project achievements, highlights key learnings from the project that have industry-wide value, and identifies future opportunities for PG&E to leverage this project's learnings.

2.1 Regulatory Background

The California Public Utilities Commission (CPUC) passed two decisions that established the basis for this pilot program. The CPUC initially issued D. 11-12-035, *Decision Establishing Interim Research, Development and Demonstrations and Renewables Program Funding Level*[1], which established the Electric Program Investment Charge (EPIC) on December 15, 2011. Subsequently, on May 24, 2012, the CPUC issued D. 12-05-037, *Phase 2 Decision Establishing Purposes and Governance for Electric Program Investment Charge and Establishing Funding Collections for 2013-2020*[2], which authorized funding in the areas of applied research and development, technology demonstration and deployment (TD&D), and market facilitation. In this later decision, CPUC defined TD&D as "the installation and operation of pre-commercial technologies or strategies at a scale sufficiently large and in conditions sufficiently reflective of anticipated actual operating environments to enable appraisal of the operational and performance characteristics and the financial risks associated with a given technology."[3]

The decision also required the EPIC Program Administrators[4] to submit Triennial Investment Plans to cover three-year funding cycles for 2012-2014, 2015-2017, and 2018-2020. On November 1, 2012, in A.12-11-003, PG&E filed its first triennial Electric Program Investment Charge (EPIC) Application at the CPUC, requesting $49,328,000 including funding for 26 Technology Demonstration and Deployment Projects. On November 14, 2013, in D.13-11-025, the CPUC approved PG&E's EPIC plan, including $49,328,000 for this program category. On May 1, 2014, PG&E filed its second triennial investment plan for the period of 2015-2017 in the EPIC 2 Application (A.14-05-003). CPUC approved this plan in D.15-04-020 on April 15, 2015, including $51,080,200 for 31 TD&D projects.

Pursuant to PG&E's approved 2015-2017 EPIC triennial plan, PG&E initiated, planned, and implemented the following project: 3.32 System Harmonics for Power Quality Investigation. Through the annual reporting process, PG&E kept CPUC staff and stakeholder informed on the progress of the project. The following is PG&E's final report on this project.

[1] http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/156050.PDF

[2] http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/167664.PDF

[3] Decision 12-05-037 pg. 37

[4] Pacific Gas & Electric (PG&E), San Diego Gas & Electric (SDG&E), Southern California Edison (SCE), and the California Energy Commission (CEC)

3 Project Summary

This project demonstrated the feasibility of using AMPQ to collect harmonics data for PQ investigation. The EPIC 3.32 *Systems Harmonics for Power Quality Investigation* was initiated to address the needs to collect harmonics data in PG&E distribution systems on a larger scale, where using traditional PQMs would have been impractical. Harmonics data analysis allows PG&E to better understand where and when PG&E has harmonics issues in the distribution systems.

The focus of this project was:

1) Deploy 180 AMPQs in 125 distribution feeders to collect harmonics data remotely.
2) Analyze the harmonics data to get a preliminary assessment of the harmonics in PG&E distribution systems.
3) Build a harmonics dashboard and analysis tools to help PQ engineers monitor and investigate harmonics issues.

This project demonstrated that AMPQ was able to provide high-resolution harmonics data to support PQ investigation. Existing PG&E electric revenue meters do not collect harmonics data. The AMPQ functionality would enable revenue meters to monitor and collect harmonics in the distribution systems at a lower cost than using portable PQMs.

3.1 Issue Addressed

3.1.1 Harmonics Data Collection

Currently, PG&E collects harmonics data using PQMs on a case-by-case basis. The PQM capable of collecting harmonics data are more expensive than basic voltage recorder because it must meet minimum hardware and software specifications to perform harmonics measurement. To collect harmonics data with PQM, field personnel also need to be dispatched to install, download, and remove the PQM from customer locations.

PG&E's PQM resources are limited because they are also used for other non-harmonics customer complaints. On the other hand, the AMPQ costs only a fraction of a PQM, and can transmit the data remotely on demand. AMPQs are also expected to replace existing revenue meters in the future, thus the deployment of AMPQ functionality would relatively be simple and inexpensive by either swapping out the existing revenue meter during regular meter maintenance, or in some cases it may be possible to update the firmware of existing revenue meter to perform AMPQ functions.

The limited PQM resources and truck rolls required make harmonics data collection in PG&E distribution systems on a large scale impractical and expensive. Installing PQM for harmonics collection also creates a safety risk because field personnel must open energized electrical panels and transformer enclosures to connect the PQM. On the contrary, an AMPQ is installed in meter socket in the front of meter panel where there are no exposed energized parts, thus reducing risk of electrical hazard.

3.1.2 Preliminary Assessment of Harmonics in PG&E Distribution Systems

PG&E has been experiencing an increase in harmonics complaints from customers in the last 6-7 years. Customers have reported that their solar PV inverters or EV chargers are not working properly causing financial losses and disrupt their businesses. The harmonics issues have got worse every year and seem to occur mostly during the summer months. To understand how widespread the harmonics issues are, PG&E need to collect harmonics data on a large scale for an extended timeframe. This effort has not been attempted before due to the limited inventory of portable PQMs and the intense labors required. By using AMPQs, PG&E can test the power quality functionality of the AMPQ and learn from the proof of concept. This allows PG&E to better understand where and when there are harmonics issues in the systems. The results will help PG&E address the harmonics issues both from the policy and technical perspectives.

3.1.3 Power Quality Investigation to resolve customer harmonics complaint

There are several gaps in PG&E's existing process of responding to customer harmonics complaints. Currently, harmonics data are collected reactively, often as a response to customer's complaint. The existing process does not facilitate continuous monitoring of harmonics and proactively detect any harmonics issues before it impacts PG&E and customer equipment. Then, the harmonics issues in PG&E's distribution system also appear to seasonally intermittent because the harmonics are primarily coming from customer's loads.

The harmonics level in the distribution systems appear to be highest during the summer months coincide with peak loads during summertime particularly loads during agricultural irrigation season. The harmonics typically subside during the winter months. This situation often requires that harmonics data be collected over a long period of time from many locations to get the complete picture for harmonics analysis.

Therefore, it can take a very long time to investigate and resolve harmonics issues for customers. Without historical harmonics data readily available, it is challenging to resolve customer harmonics complaints in a timely manner. AMPQs can make harmonics data available on demand including historical harmonics data and help address this issue.

3.2 Project Objectives

The objectives of EPIC 3.32 project were to:

1. Demonstrate the feasibility of using AMPQ to collect harmonics data for power quality investigation.
2. Develop an IT system that automates the collection and processing of harmonics data from the AMPQs.
3. Create a Harmonics Dashboard that facilitates monitoring and analysis of harmonics in PG&E distribution systems.
4. Analyze the harmonics data to get a preliminary assessment of the harmonics in the supply voltage quality that PG&E provides to customers and determine how widespread and severe the harmonics issues are in the systems.
5. Build analysis tools that power quality engineers can use to investigate and resolve harmonics issues.

3.3 Scope of Work and Project Tasks

The scope of work for this project included the tasks below:

Task 1: Install 180 AMPQs in 125 Distribution Feeders

This task focused on the deployment of the AMPQs in the field. 125 distribution feeders across PG&E divisions were selected for harmonics monitoring. The 125 feeders were selected based on certain criteria such as feeders with high DER level, feeders with large industrials and commercial customers, feeders with high agricultural loads, feeders in rural areas and in urban areas etc. It was recognized that the selected feeders are a subset of PG&E over 3,500 distribution feeders and may not be truly representative. However, it was sufficient for the proof-of-concept nature of the project.

A list of potential locations within the selected feeders was then created based on the following criteria.

- Three phase service locations.
- Meter form 9S.
- Electrical service served from distribution transformer large than 750 kVA.

The AMPQs were installed only in three phase service location and not in residential single phase service location. Most feeders had one AMPQ installed, and some feeders had a few AMPQs installed to validate consistent harmonics readings in the feeder. Services larger than 750 kVA were chosen because they were more likely to have a large panel with spare meter socket available, whereas smaller services tended to have small panels that could not accommodate an extra electric meter. All the locations were inspected and pre-wired for the AMPQ. After installation, meter technician validated the meter program and tested 4G LTE connectivity before the AMPQs were ready for the project.

Task 2: Build a Harmonics Data Collection System

This task focused on the development of an IT system that automates the collection and processing of harmonics data from the AMPQs into PG&E cloud server and data analytics platform. The system would automatically perform daily read of all the 180 AMPQs, calculate harmonics statistics on a weekly basis and then update the Harmonics Dashboard. The system also integrated other data streams from distribution equipment and existing revenue meters for data visualization and analysis.

Task 3: Create Harmonics Analysis Tools

An important task in this project is to create tools that help power quality engineer analyze the large amount of raw harmonics data including tools to automatically calculate statistical data for assessment and tools to perform correlation analysis between the harmonics and customer demands on the feeder to determine whether customers are causing harmonics.

Task 4: Analyze Harmonics Data for Overall Assessment of Harmonics in the Systems

This task focused on creating an overview of harmonics in PG&E distribution systems. So that, power quality engineers can monitor and detect harmonics issues on the feeders that were included in this project.

4 Project Activities, Results, and Findings

This section describes the activities, results, and findings from the project.

4.1 AMPQ configuration

The AMPQ has the capability to collect different load profile data over 64 channels and the data collection interval can be programmed from 1 minute to 60 minutes. To evaluate the harmonics data, the AMPQs were programmed to collect 12 channels of load profile data as shown in Table 1 below. The data interval was chosen as 15-minutes in this project to be consistent with the existing revenue meter data interval from commercial and industrial customers. This will facilitate the correlational calculations of the harmonics data from the AMPQs and the customer demand data.

Below is the list of channels and descriptions of the data collected by the AMPQ. The full list of AMPQ available channels and descriptions are included in Appendix A.

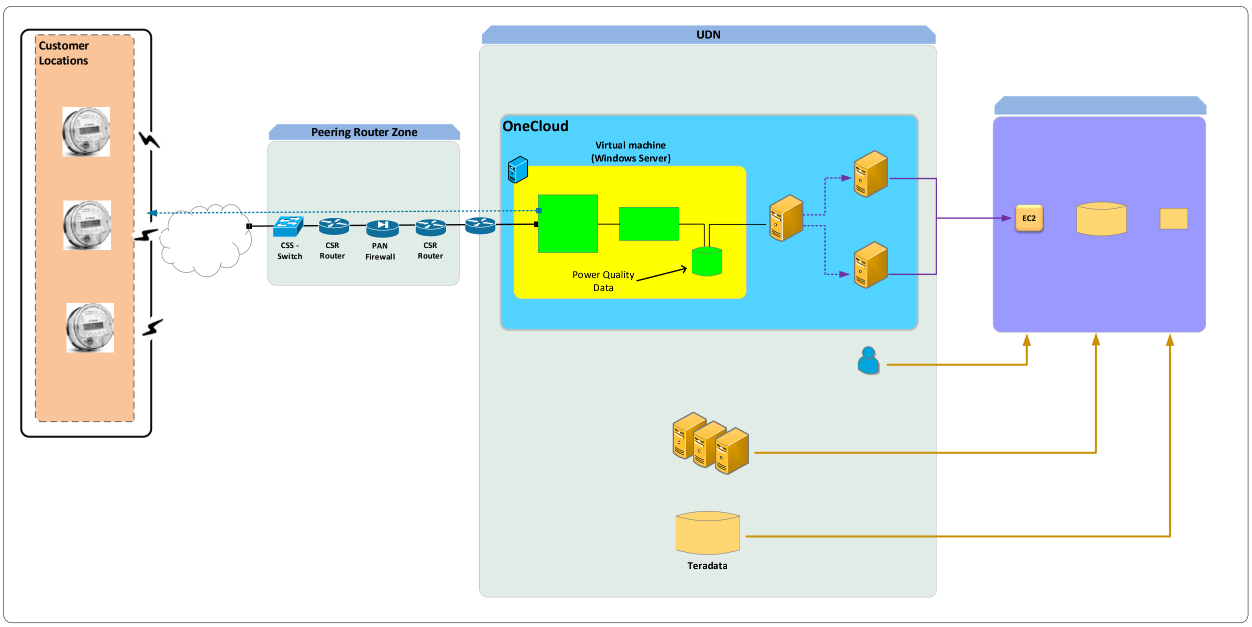
Table 1:AMPQ meter channel and descriptions of data

Channel	Description	Unit
1	Distortion VTHD Phase A - Max	%
2	Distortion VTHD Phase B - Max	%
3	Distortion VTHD Phase C - Max	%
4	Distortion ITHD Phase A - Max	%
5	Distortion ITHD Phase B - Max	%
6	Distortion ITHD Phase C - Max	%
7	Voltage Line to Neutral Phase A	Volts
8	Voltage Line to Neutral Phase B	Volts
9	Voltage Line to Neutral Phase C	Volts
10	Current Phase A	Amps
11	Current Phase B	Amps
12	Current Phase C	Amps

In addition to voltage and current data, only the total voltage and current harmonic distortions (VTHD) and (ITHD) for each phase were collected. No billing data such as power, demand, and energy consumption were collected by the AMPQs. Individual voltage and current harmonic frequencies were not collected due to data transfer bandwidth and processing time concerns. A sample of harmonics spectrum analysis from the AMPQ showed the predominant harmonics in PG&E distribution systems are characteristically the 5th (300Hz) and the 7th (420Hz) harmonics. Each additional harmonic frequency would require six additional meter channels, three for each phase of voltage and three for current. The number of meter channels would grow exponentially. It was determined that individual harmonic frequency data might not be useful at this early stage of testing the AMPQ for harmonics data collection. After the AMPQ harmonics functionality has been integrated into metering infrastructure in production, individual harmonics may be enabled and collected on a case-by-case basis to provide more details of the harmonics in specific feeder locations.

4.2 Harmonics Data Collection System Architecture

Figure 1:End-to-End network architecture



The network infrastructure for harmonics data collection system is shown in Figure 1. The main components are:

<u>AMPQ</u> - The AMPQ is an advanced electric meter capable of collecting power quality data such as harmonics data in addition to billing data. The AMPQ can communicate via the cellular 4G LTE Verizon network, and it uses standard cellular LTE authentication mechanism to encrypt the cellular traffic with a minimum of AES 128-bit encryption keys. IPv4 private network addressing further increases data transfer security by using additional VPN security mechanism using PG&E Peering Routers.

<u>Virtual Machine Server</u> - The server runs the meter software and a meter data collector application. The meter application communicates with the AMPQs over 4G LTE and download harmonics data from the AMPQ meters daily. The meter software also converts the native AMPQ meter data HHF files into CSV files and the data are stored on a local shared drive of the server. ESFT agent will access the shared drive on an hourly basis and copied the files to ESFT server. Foundry Agent will then copy the files and store the files into Foundry dataset for further processing.

Palantir Foundry - PG&E Enterprise Data Platform which supports data visualization and analytics. The Harmonics Dashboard is created on Foundry platform. The Foundry Agents are deployed at OneCloud and integrate with PG&E IT systems for collecting raw data and forward the collected data to backend Foundry infrastructure which are deployed at AWS Cloud.

EDPI System - The EDPI system houses data from SCADA-enabled electric distribution line devices such as feeder loads information. In addition to the AMPQ harmonics data, feeder circuit breaker and line recloser data are also important for the harmonic data analysis. Foundry platform retrieves line recloser and circuit breaker loads data from EDPI and transfer them to Foundry platform on a weekly basis.

Teradata - Teradata houses customer data. Customer demand data are used in correlational analysis with harmonics data from the AMPQs to determine if any customers may be causing harmonics. Foundry platform retrieves customer demand data from Teradata on a weekly basis.

Figure 2: Application interface diagram

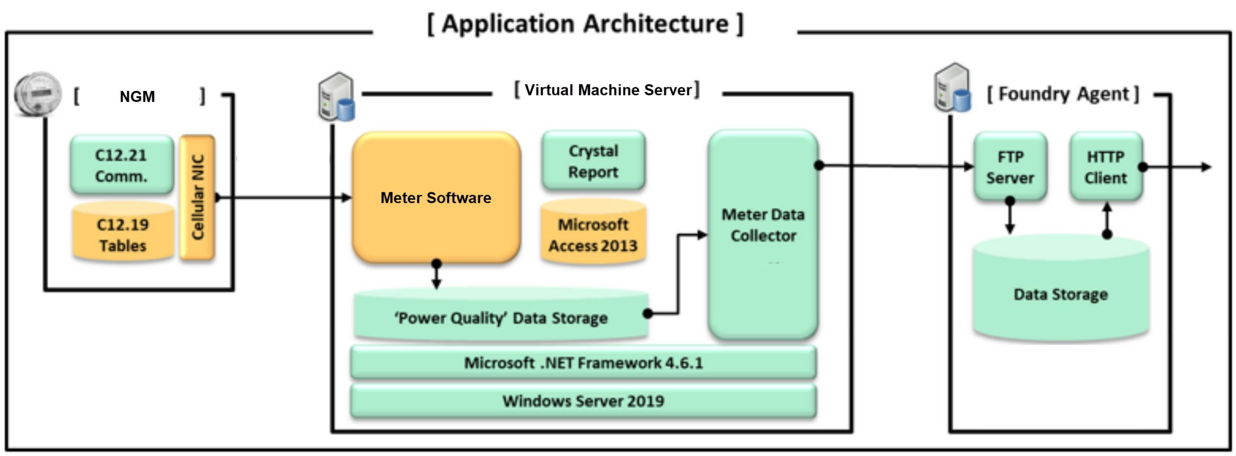
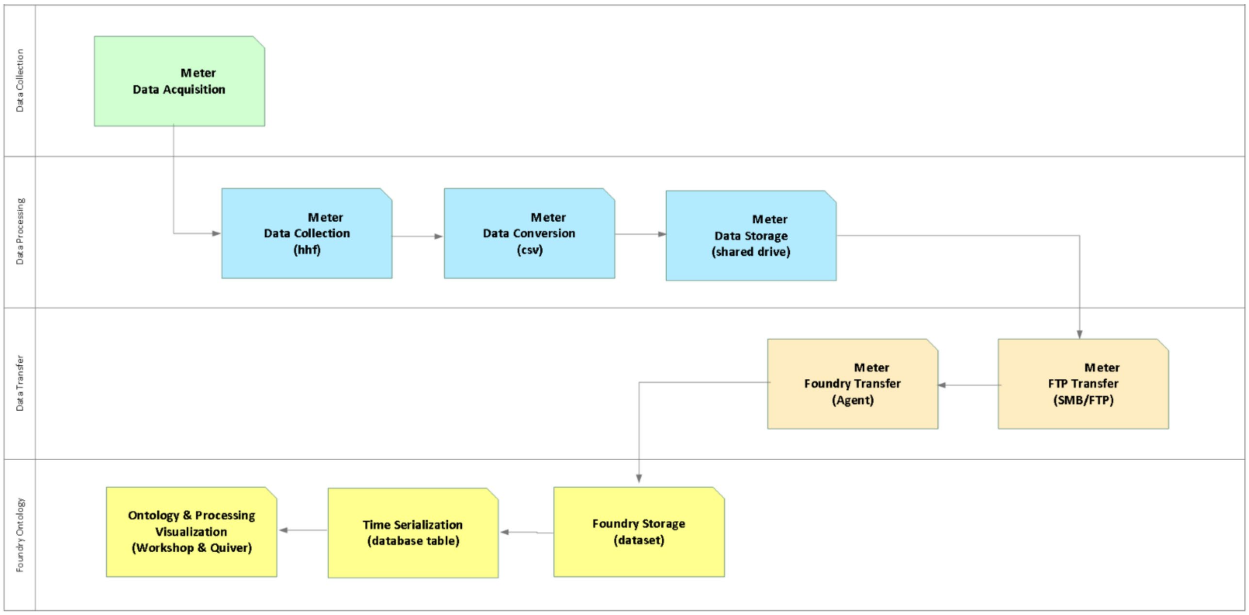


Figure 2 shows the application architecture. The meter software reads meter data on the C12.19 table. The data collector application is developed using python codes to trigger the daily AMPQ meter data collection, reset meter load profile data, and convert hhf files into CSV meter data files. The CSV data files are then copied into Foundry platform for further processing and analysis. Users can then access the harmonics data and interact with the Harmonics Dashboard on Foundry via HTTP browser. Figure 3 shows the meter data flow diagram.

The data visualization and analysis in this project is not a real time application. So, the data server does not collect, transfer and store data in real time. Instead, the data server pulls, processes and stores data from different sources daily. Then, the data are made available on the Harmonics Dashboard, which is updated on a weekly basis.

Figure 3: Meter data flow diagram



4.3 Data Calculations

The AMPQ harmonics data are imported and stored in Foundry platform. Then, several calculations are performed as described in this section.

4.3.1 Harmonics Data Calculations

The calculations of the harmonics data are performed on a weekly basis. At meter level, for each AMPQ data set, the average, minimum and maximum values of the Voltage Total Harmonic Distortion (VTHD) and Total Current Harmonic Distortion (ITHD) time series are calculated and displayed on the Harmonics Dashboard. Then, the 95th percentile values are also calculated for statistical analysis. The 95th percentile value of the VTHD is then compared to IEEE 519 voltage distortion limit which is 8.0% for system voltage below 1,000V. If the 95th percentile value exceeds 8.0%, then the AMPQ location and the distribution feeder where the AMPQ is installed are considered to have harmonics issues.

Table 2: IEEE 519 Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%) h ≤ 50	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

This is a quick method to flag whether any location in a distribution feeder potentially has harmonics issues. However, this calculation is not meant to be used to formally assess IEEE 519 compliance. Other calculations include the percentage of time that the VTHD exceeds IEEE 519 limit for a given meter location. The total system harmonics health indicator value is also calculated by taking the number of all the VTHD readings that are within IEEE 519 limit and divided by the total number of VTHD readings so that a value of 100% means that none of the VTHD readings from all AMPQs during the last one-week period exceeds IEEE 519 limit.

4.3.2 Feeder Harmonics and Customer Demand Correlation Calculations

One important aspect of harmonics investigation is determining where the harmonics are coming from. Power quality investigations show that the harmonics in PG&E system primarily come from customers' loads. Therefore, an analysis tool was created in this project to help power quality engineer identify customer locations that may be injecting harmonics into the distribution systems. The Harmonics Dashboard calculates the strength of correlation between the VTHD time series from the AMPQ and the demand of individual customers located on the same distribution feeder in the same time frame.

The calculation results in a Pearson correlation coefficient value for each individual customer. A value of 0.5 to 1.0 means a large correlation, that is this customer may likely contribute significantly to VTHD increase in the distribution system. In other words, when this customer's loads come online, the VTHD also increases in lockstep, and when the customer's loads go offline, the VTHD also decreases. Finally, a correlation coefficient value of 0.3 to 0.5 suggests a medium correlation and a value of 0.1 to 0.3 indicates a small correlation accordingly.

As a proof of concept, the project team had to limit the number of customer sample size and correlation calculations to a manageable level computationally. Therefore, the analysis tool limited the harmonics-customer demand correlation calculation to three-phase customers who are designated agricultural, commercial, and industrial account and who are served from service transformer larger than 300kVA. The intention was to prioritize screening of larger customers on the distribution feeder. In future projects and production, it is recommended to include all three phase customers on the feeder for harmonics-customer demand correlation calculations.

4.4 Harmonics Dashboard

One of the objectives in this project was to create a Harmonics Dashboard that power quality engineers can use to monitor and investigate harmonics in PG&E distribution systems.

The Harmonics Dashboard was created on Palantir Foundry platform to facilitate visualization and analysis of harmonics data from the AMPQs. The Harmonics Dashboard has the following sections:

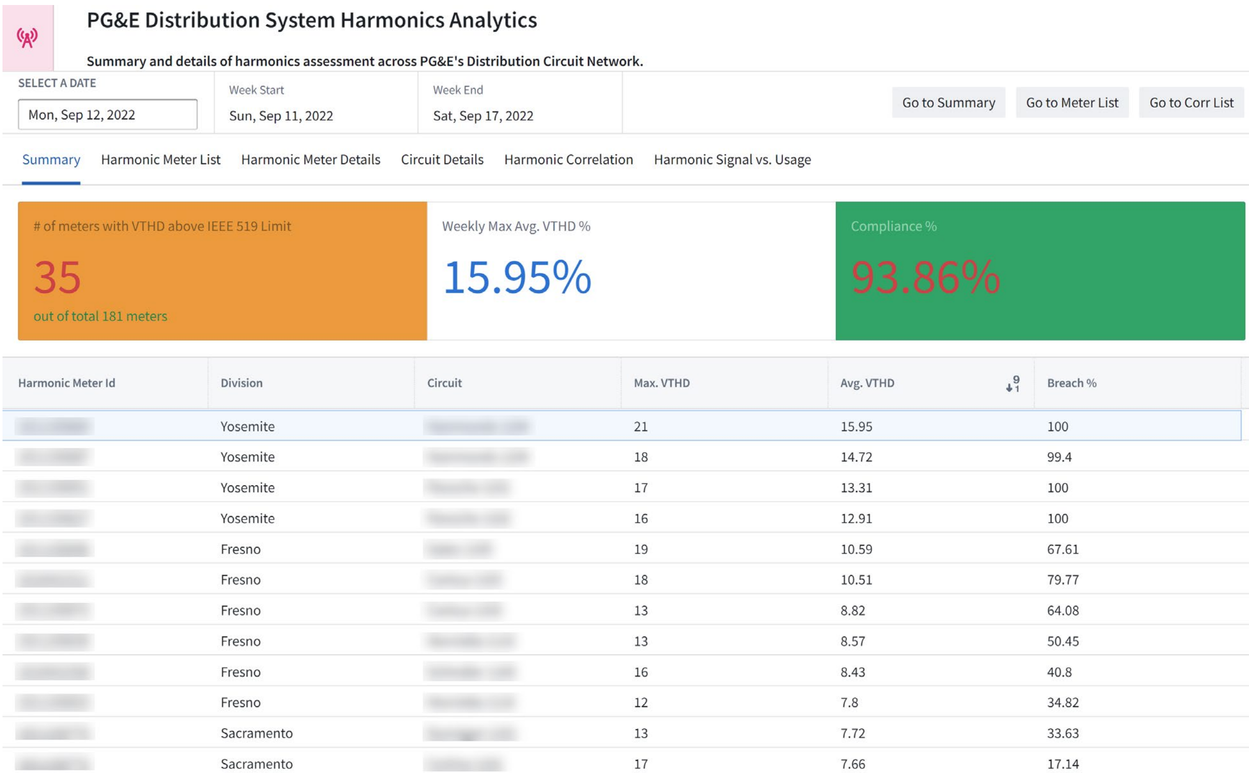
- Summary
- List of all AMPQs
- AMPQ level details
- Feeder level details
- Harmonics correlation to customer demand
- Details of harmonics correlation to customer demand

Summary of harmonics data

The *Summary* tab displays an overview of the harmonics data from all the AMPQs installed in this project. It displays a weekly data and calculations such as the number of AMPQs reporting VTHD level above IEEE

519 limit, the average VTHD level, and a metric to track harmonics performance. This page also shows a list of all the AMPQs that report VTHD level exceeding the IEEE 519 limit including the divisions and feeders where they are located. This page is designed to give an overview of the harmonics in the system weekly and flags locations where high harmonics level may be occurring.

Figure 4: Harmonics Dashboard – Summary of Harmonics data

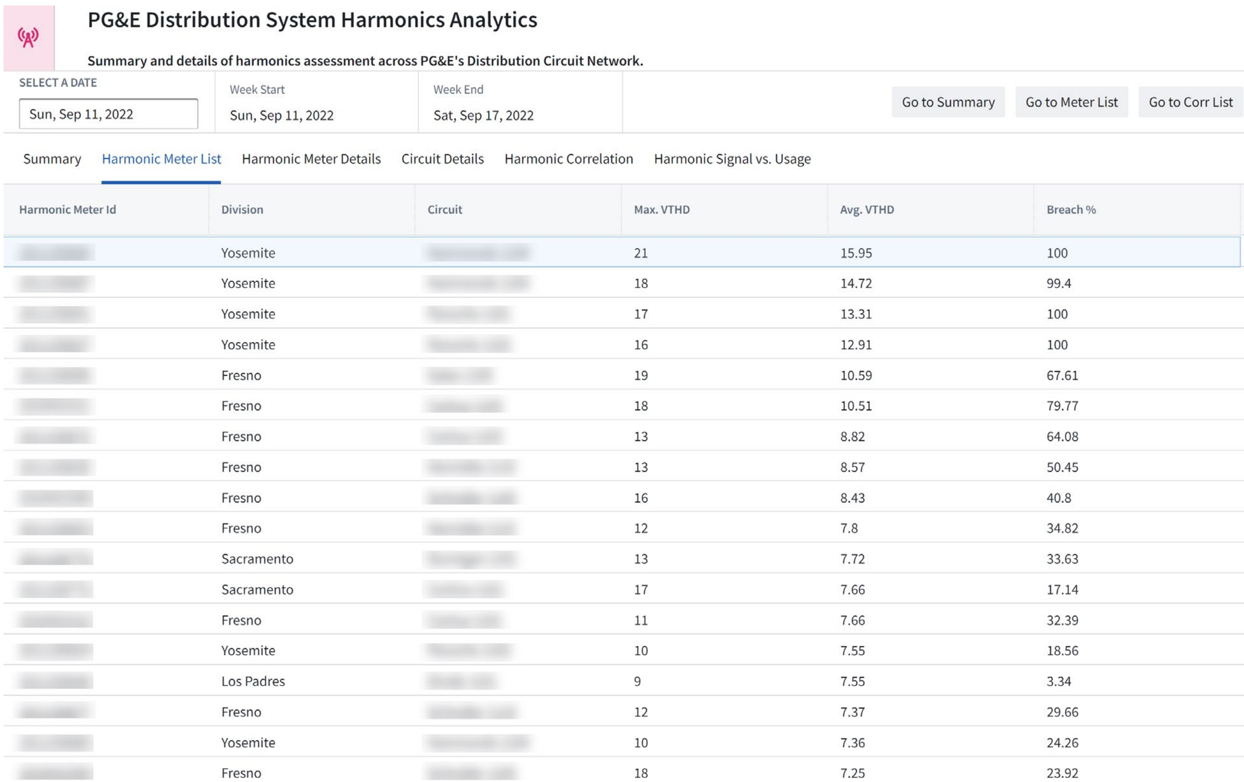


Harmonic Meter Id	Division	Circuit	Max. VTHD	Avg. VTHD	Breach %
[illegible]	Yosemite	[illegible]	21	15.95	100
[illegible]	Yosemite	[illegible]	18	14.72	99.4
[illegible]	Yosemite	[illegible]	17	13.31	100
[illegible]	Yosemite	[illegible]	16	12.91	100
[illegible]	Fresno	[illegible]	19	10.59	67.61
[illegible]	Fresno	[illegible]	18	10.51	79.77
[illegible]	Fresno	[illegible]	13	8.82	64.08
[illegible]	Fresno	[illegible]	13	8.57	50.45
[illegible]	Fresno	[illegible]	16	8.43	40.8
[illegible]	Fresno	[illegible]	12	7.8	34.82
[illegible]	Sacramento	[illegible]	13	7.72	33.63
[illegible]	Sacramento	[illegible]	17	7.66	17.14

List of all AMPQs

The *Harmonic Meter List* tab displays a list of all the 180 AMPQs including meter ID, division, feeder and VTHD data. The list can be sorted by the level of VTHD, division, and feeders. The harmonics data on this tab include maximum VTHD, average VTHD and the percentage of the time the meter reports VTHD exceeds IEEE 519 limits during the week. From this page, individual AMPQ can be selected to display further meter level details.

Figure 5: List of all AMPQs

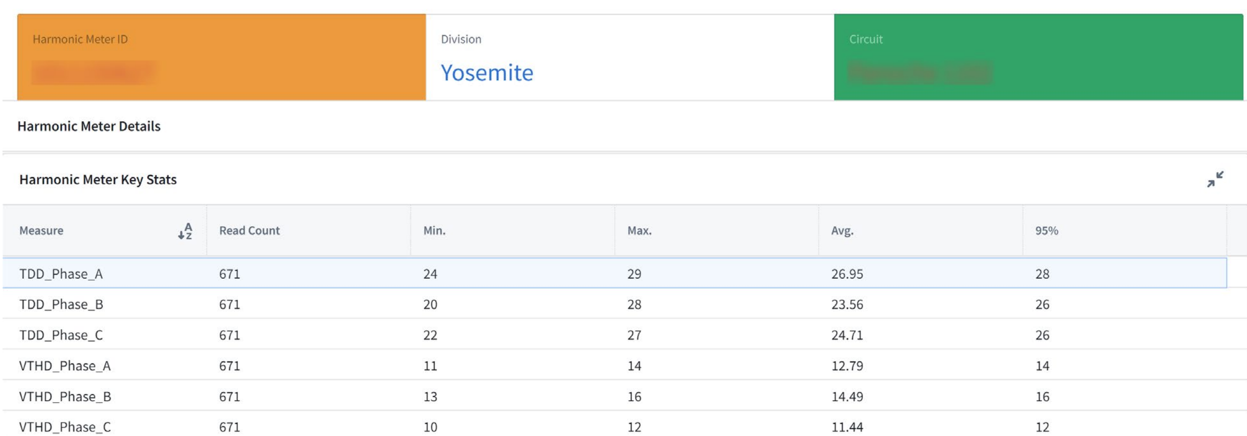


Harmonic Meter Id	Division	Circuit	Max. VTHD	Avg. VTHD	Breach %
[illegible]	Yosemite	[illegible]	21	15.95	100
[illegible]	Yosemite	[illegible]	18	14.72	99.4
[illegible]	Yosemite	[illegible]	17	13.31	100
[illegible]	Yosemite	[illegible]	16	12.91	100
[illegible]	Fresno	[illegible]	19	10.59	67.61
[illegible]	Fresno	[illegible]	18	10.51	79.77
[illegible]	Fresno	[illegible]	13	8.82	64.08
[illegible]	Fresno	[illegible]	13	8.57	50.45
[illegible]	Fresno	[illegible]	16	8.43	40.8
[illegible]	Fresno	[illegible]	12	7.8	34.82
[illegible]	Sacramento	[illegible]	13	7.72	33.63
[illegible]	Sacramento	[illegible]	17	7.66	17.14
[illegible]	Fresno	[illegible]	11	7.66	32.39
[illegible]	Yosemite	[illegible]	10	7.55	18.56
[illegible]	Los Padres	[illegible]	9	7.55	3.34
[illegible]	Fresno	[illegible]	12	7.37	29.66
[illegible]	Yosemite	[illegible]	10	7.36	24.26
[illegible]	Fresno	[illegible]	18	7.25	23.92

Meter level details

The *Harmonic Meter Details* tab displays harmonics data for selected AMPQ such as VTHD and ITHD for each phase and 95th percentile values and time series charts of the parameters during the week.

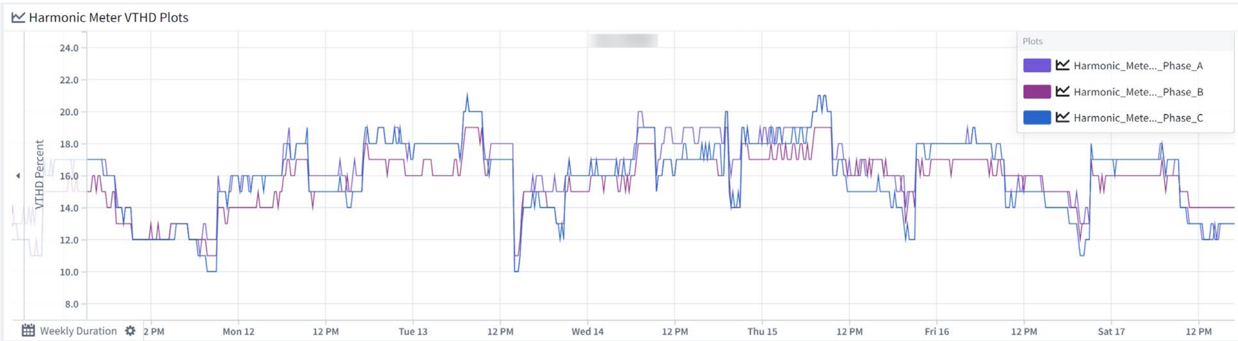
Figure 6: Meter level details



Measure	Read Count	Min.	Max.	Avg.	95%
TDD_Phase_A	671	24	29	26.95	28
TDD_Phase_B	671	20	28	23.56	26
TDD_Phase_C	671	22	27	24.71	26
VTHD_Phase_A	671	11	14	12.79	14
VTHD_Phase_B	671	13	16	14.49	16
VTHD_Phase_C	671	10	12	11.44	12

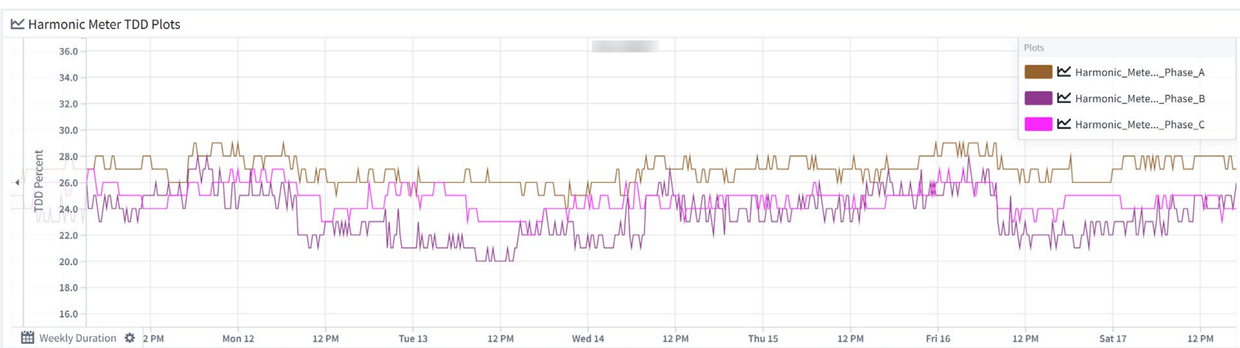
The VTHD time series chart shows VTHD trend for the AMPQ location over the week. It can help identify harmonics patterns and be used in correlation analysis with other data sets such customer demand and feeder loads.

Figure 7: VTHD time series chart



The ITHD/TDD time series chart gives an idea of how much harmonic current distortion is coming from the customer where the AMPQ is installed. The ITHD/TDD can also be assessed per IEEE 519 recommended limit. However, in this project, the focus was on the VTHD to get a picture of the voltage quality provided by PG&E to customers. The project team recommends that future works may include more analysis on the customer current harmonics especially as the number of AMPQs scale up in production environment to cover more customers especially agricultural, commercial, and industrial customers who are more likely to produce a lot of current harmonics.

Figure 8: ITHD/TDD time series chart

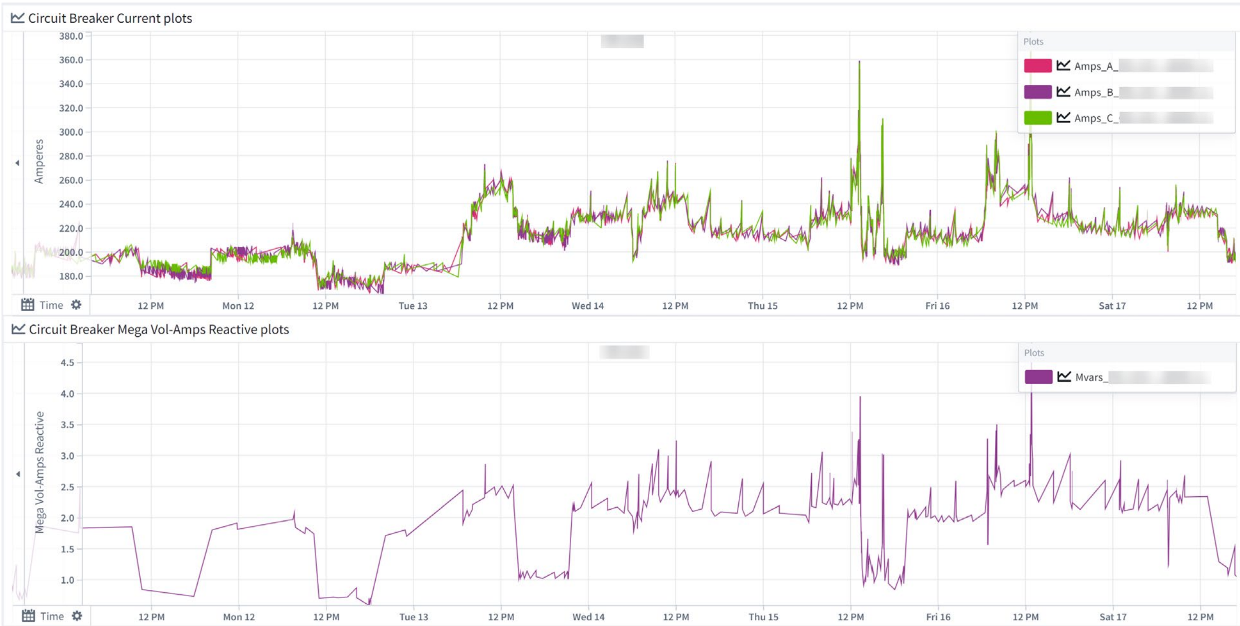


Feeder level details

The *Circuit Details* tab displays time series chart for feeder loads from feeder circuit breaker and line recloser(s) on the feeder.

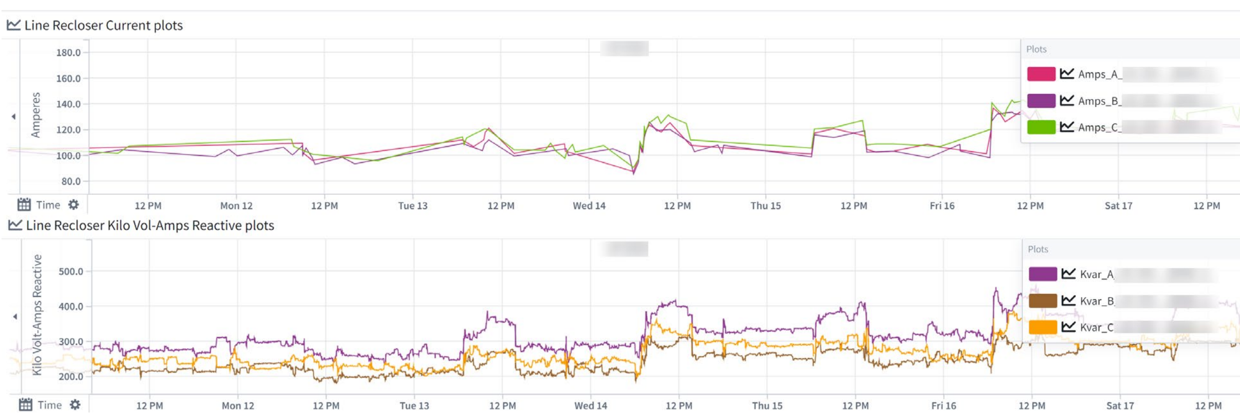
Together with the VTHD time series from the AMPQ, the circuit breaker amps and VAR time series can help determine if the harmonics level on the feeder correlates to overall loads on the feeder that is the harmonic distortion on the feeder is caused by customers loads.

Figure 9: Feeder circuit breaker amps and VAR reactive power



Furthermore, in some cases, the amps and VAR time series from line reclosers on the feeder can help determine section(s) of the feeder where harmonics-producing loads are located. This depends on the number of available line reclosers and their locations on the feeder. For example, if the voltage harmonics on the feeder correlates to loads downstream on a line recloser but not on another line recloser, it may be suspected that the loads downstream on the first line recloser are rich in harmonic current which distorts the feeder voltage as it flow back to the substation.

Figure 10: Feeder line recloser amps and VAR reactive power



Harmonic correlation to customer demand

One of the objectives in this project is to create an analysis tool that helps power quality engineers investigate harmonics, specifically to help determine potential sources of harmonics. Since, harmonic distortion on distribution feeders are primarily caused by non-linear loads. The project team looked at the correlation between the VTHD trends from the AMPQ and customer demand trends on the same feeder during the same period of one week. Figure 12 in the *Harmonic Correlation* tab displays a list of customers on the feeder and their corresponding harmonics correlation score. On this page, individual customer can be selected to display the VTHD and the customer demand time series side-by-side for comparison as shown in Figure 11. Power quality engineers can use this tool to identify the customers who may be injecting excessive harmonic current into the distribution systems.

Figure 11: Harmonics correlation - Feeder VTHD and customer demand time series

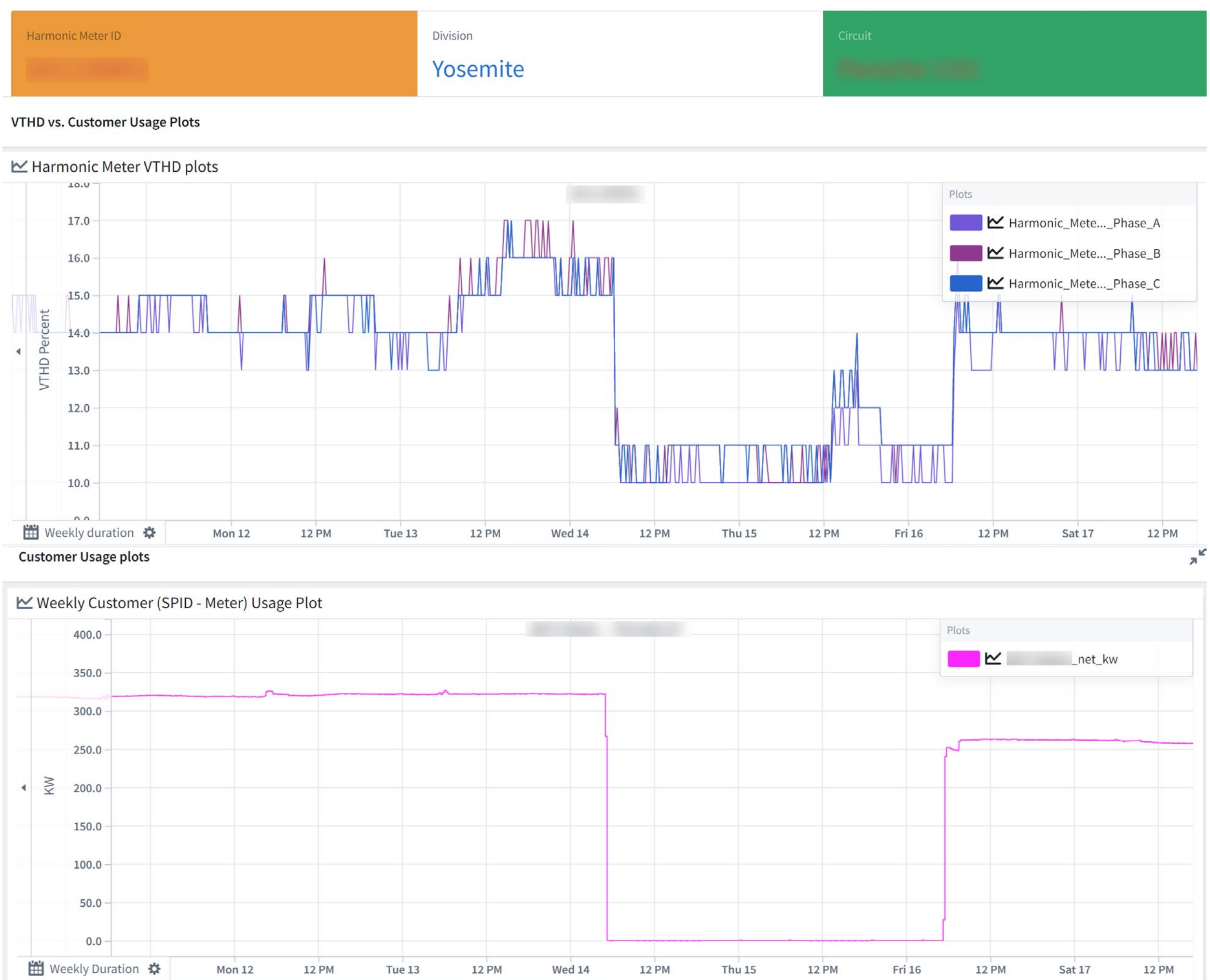


Figure 12: Harmonic Correlation - Correlation scores for customer demands to feeder VTHD

Harmonic Meter ID	Division	Circuit
[illegible]	Yosemite	[illegible]

Correlation with Customer Usage

SP ID	Meter ID	Corr Counts	Correlation
[illegible]	[illegible]	671	0.9017
[illegible]	[illegible]	671	0.8706
[illegible]	[illegible]	671	0.8327
[illegible]	[illegible]	671	0.5246
[illegible]	[illegible]	671	0.3968
[illegible]	[illegible]	671	0.2338
[illegible]	[illegible]	671	0.2098
[illegible]	[illegible]	671	0.1325
[illegible]	[illegible]	671	0.1272
[illegible]	[illegible]	671	0.084
[illegible]	[illegible]	671	0.0473
[illegible]	[illegible]	671	0

4.5 Challenges

Initially, the project team encountered a challenge related to field installation of the AMPQs, the AMPQs were installed separately alongside the existing revenue meters already installed at customer meter panels to limit impacts on the billing system due to the proof-of-concept nature of this project. This approach required that a spare meter socket is available at customer meter panels. Otherwise, a dual-socket meter adapter would have to be used. However, the locations for meter installation were pre-selected during the planning phase based on specific engineering criteria without site inspection in the field.

It was found that the meters could not be installed in some locations due to site -specific limitations such as unavailable spare meter socket or the meter panel being too small to accommodate the wiring of dual-socket meter adapter. Therefore, new sites had to be selected causing a delay in the deployment of the AMPQs. To overcome this challenge, the project team pivoted and worked closely with field metering department to identify new locations to install the AMPQs. The new sites were inspected, and the AMPQs were installed according to the project plan.

During the development of the harmonics data collection system, several data pipelines were created to bring data from both the AMPQs and other electric distribution devices and existing revenue SmartMeter™. These different datasets needed to be processed and synchronized to provide data visualization and run calculations for the harmonics dashboard. There were frequent issues where the pipeline of individual data source broke, and it would affect the functionality of the harmonics dashboard.

Initially, there was no alert mechanism built into the system to report any issues with the data pipelines at each stage of data processing. So, troubleshooting and bug fixing had to be done from end to end to identify the root cause which was very time consuming. This issue impacted the availability of the harmonics dashboard and sometimes would not be detected for a week later since the dashboard was updated weekly. To overcome this challenge, a daily report for data download and process was created to provide alerts when there were issues with the data pipelines, so that the problems could be detected and fixed as quickly as possible.

Another significant challenge in the project was that the harmonics data from the AMPQs was collected over the 4G LTE cellular network sequentially one meter at a time. The time taken to read and process harmonics data from one AMPQ over 4G LTE cellular network ranged between 5-10 minutes. Some AMPQs could take significantly longer if there was poor cellular coverage at the installation sites. This issue would sometimes cause the meter data transfer to time out, and some harmonics data would be missing from the harmonics dashboard.

To overcome this challenge, a second server was added to help collect and process the data from the AMPQs. As the number of AMPQs increases, the data bandwidth and storage may be an issue and parallel processing will likely be needed. It is recommended that the future harmonics data collection using AMPQ will leverage the existing AMI network rather than using 4G LTE cellular network.

While this project was successful in helping PG&E collect harmonics data and better understand the harmonics issues in the distribution systems, it did not address the mitigation of harmonics impact on PG&E equipment and system. PG&E has seen harmonics impact on both customer and utility equipment in the recent years. Customers have reported that solar PV inverters and EV battery chargers are not operating properly in high voltage harmonics environments. PG&E also has seen more issues with distribution capacitor banks that have abnormally high amperage readings and, in some cases, fail prematurely. PG&E recommends that the future EPIC project focus on harmonics mitigation on both utility and customer side.

4.6 Results and Findings

The goal of this project was to demonstrate that AMPQ could be used to collect harmonics data and to evaluate how widespread the harmonics issues in PG&E distribution systems were.

4.6.1 AMPQ Harmonics Data

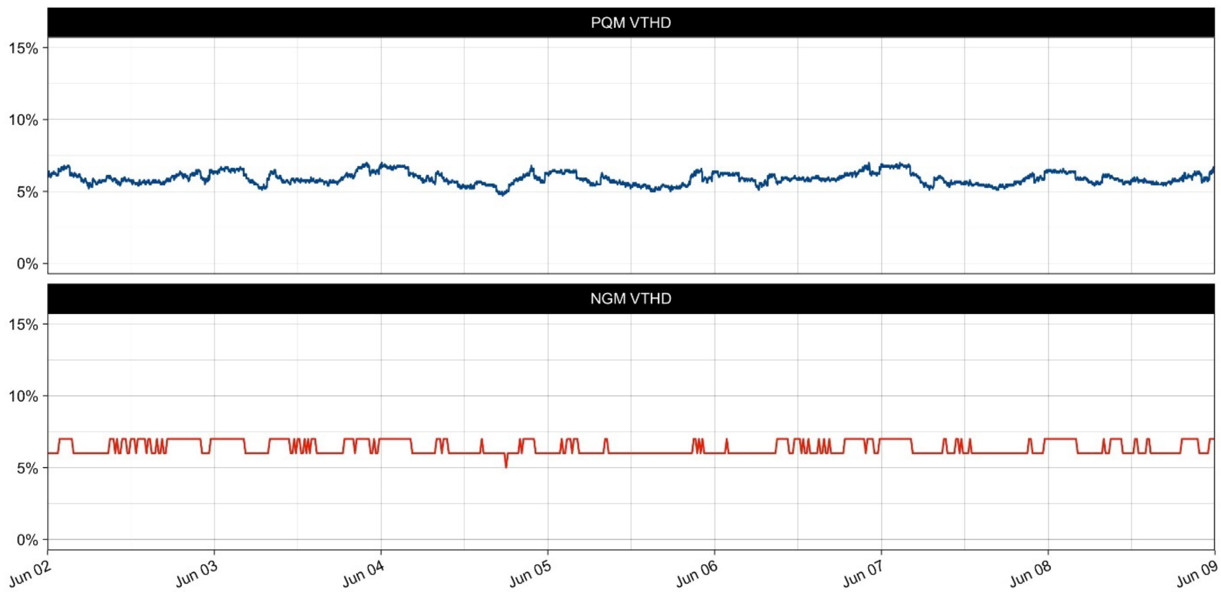
Figure 13 shows a comparison between the voltage total harmonic distortion (VTHD) data from the AMPQ and from a traditional PQM that was installed at the same location. The data from both devices show similar readings. However, there are some differences:

1. The AMPQ harmonics data was 15-minutes interval while the PQM data interval was one minute. Therefore, the data from PQM are much more granular.
2. The VTHD readings from the AMPQ is rounded up to the nearest integer whereas the VTHD readings from the PQM contain two decimals. So, the PQM provide more data precision.

In this project, the AMPQ was programmed to collect harmonics data at 15-minutes interval mainly to facilitate easy computation of correlation coefficient between the AMPQ harmonics data and customer demand data from PG&E existing revenue meters, which are collected at 15 minutes interval for commercial and industrial customers. It was found that the correlation coefficient calculation was much more accurate when both datasets were synchronized on the same time interval.

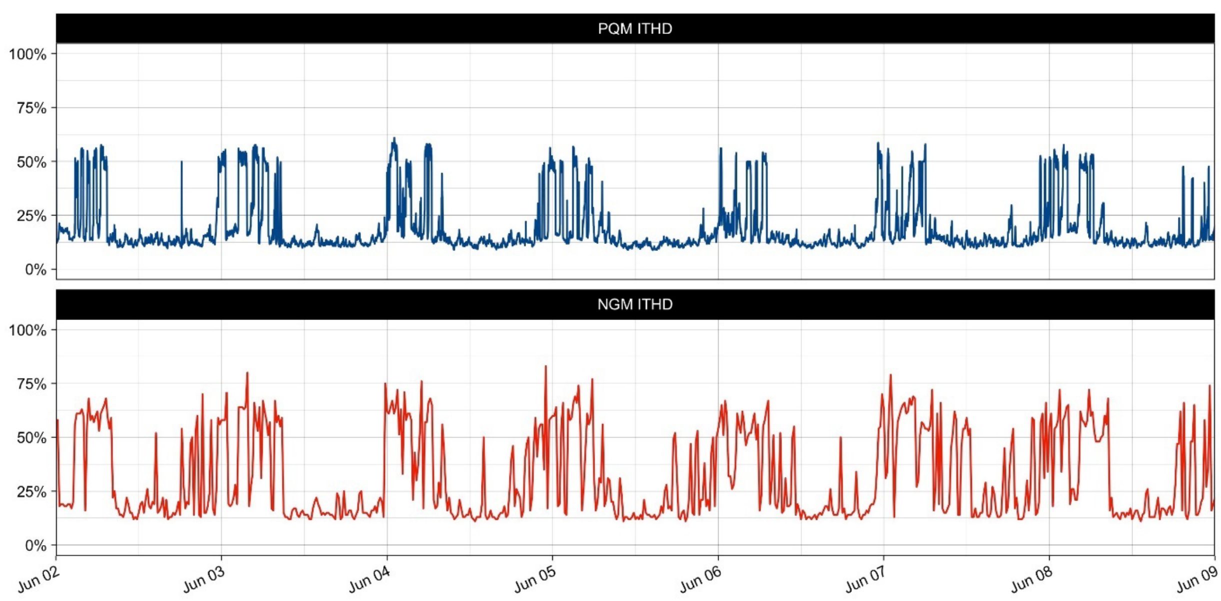
However, the AMPQ can be programmed to collect data at any interval from 1 minute to 60 minutes allowing for flexibility if more granular data is required. Regarding the precision of the data, the harmonics data from the AMPQ is not as precise as PQM data. However, it is sufficient for the purpose of measuring general level of harmonics and detect when the harmonics in the systems are changing.

Figure 13: Comparison of VTHD data from AMPQ and PQM



The current total harmonic distortion (ITHD) data from the AMPQ is also compared with the data from PQM in figure 14 below. The results show the ITHD data from both devices are comparable. Again, the AMPQ data is not as granular and precise as the PQM data, but it is sufficient for preliminary assessment of customers' harmonic loads. The data comparison shows that the AMPQ can collect reliable harmonics data which could replace the needs to use PQM in most cases.

Figure 14: Comparison of ITHD data from AMPQ and PQM



4.6.2 Voltage Harmonics in PG&E Distribution Systems

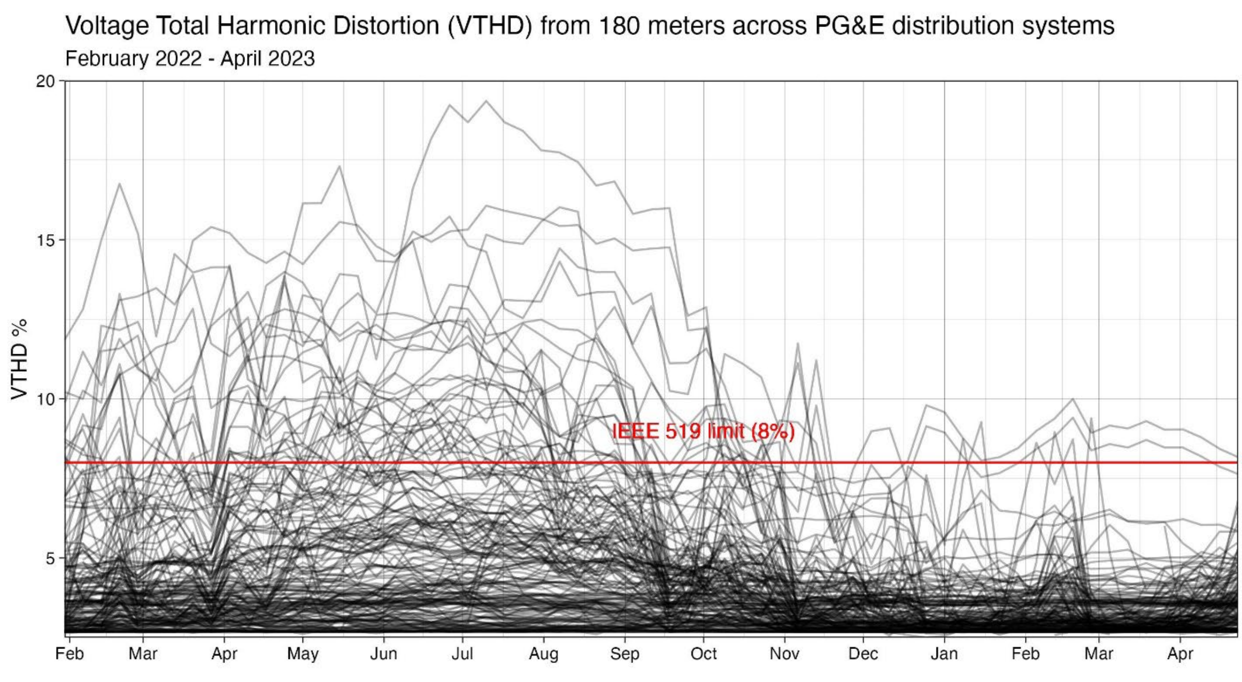
One of the objectives in this project is to get preliminary assessment of the voltage harmonics level in the distribution systems. It must be stated that because only 180 AMPQs were installed which covered about 125 feeders out of over PG&E 3,500 distribution feeders. The results from this project may not be truly representative and comprehensive. Nevertheless, the goal was to get an idea where PG&E may potentially have high harmonics issues, when they occur, and where the harmonics come from.

Overall voltage harmonics results

Figure 15 shows the VTHD time series charts from all the 180 AMPQ locations from February to November. The VTHD readings range from 2% up to 20% for some meters. The results in this figure suggest that:

1. The majority of the AMPQ locations are showing VTHD readings below the IEEE 519 limit of 8% as represented by the thick black lines on the bottom portion of the chart.
2. For the AMPQ locations that show VTHD exceeding IEEE 519 limit, they exceed the limit by a significant margin. In some cases, the VTHD reading are as high as 15-20% on some locations. This means the voltage harmonic distortion on these feeders is severe and more likely to cause issues for customers equipment.
3. The level of harmonics appears to directly correlate to the loads in the distribution system specifically, the loads in agricultural feeders during irrigation season.

Figure 15: VTHD readings from the 180 AMPQs



Meters and feeders level results

Figure 16 shows the number of AMPQs with VTHD readings exceeding IEEE 519 limit on a weekly basis. The number ranges from 5 meters to up to 55 meters out of 180 meters installed. This was determined by calculating the 95th percentile of the VTHD interval readings over a period of one week and compared to the IEEE 519 limit of 8%.

The results show that the number of AMPQs with high voltage harmonics readings significantly increased in April 2022 and stayed high through the summer months before falling in November 2022.

Figure 16: Number of AMPQs with VTHD readings exceeding IEEE 519 limit

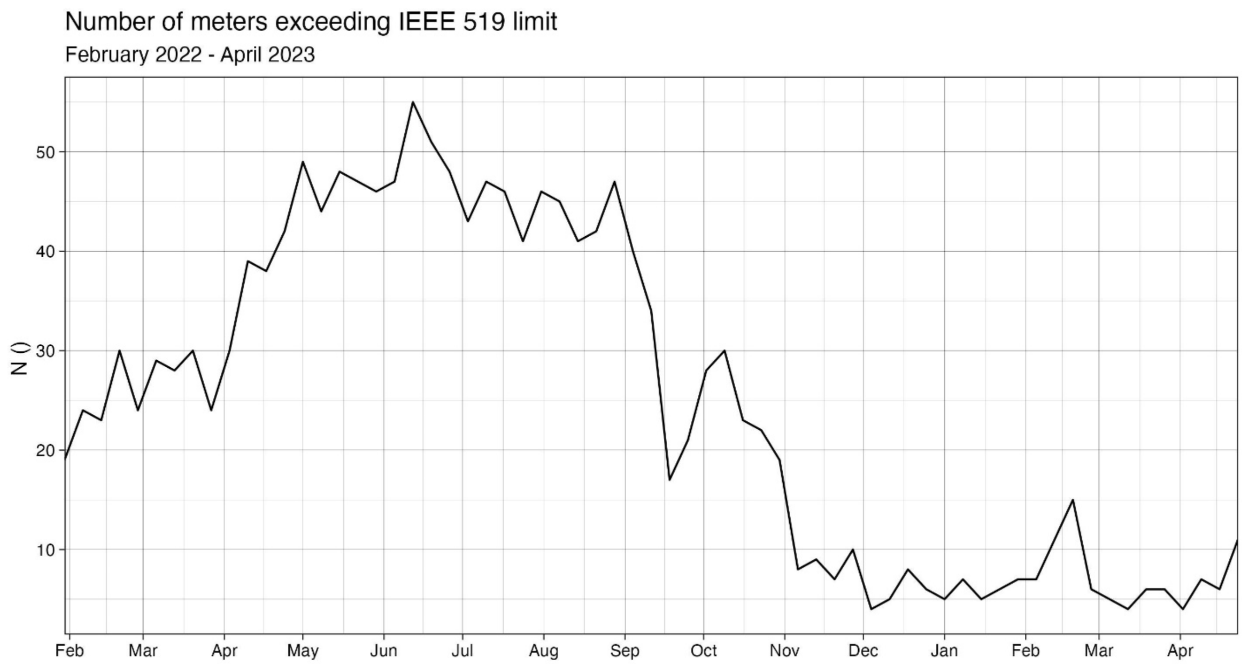
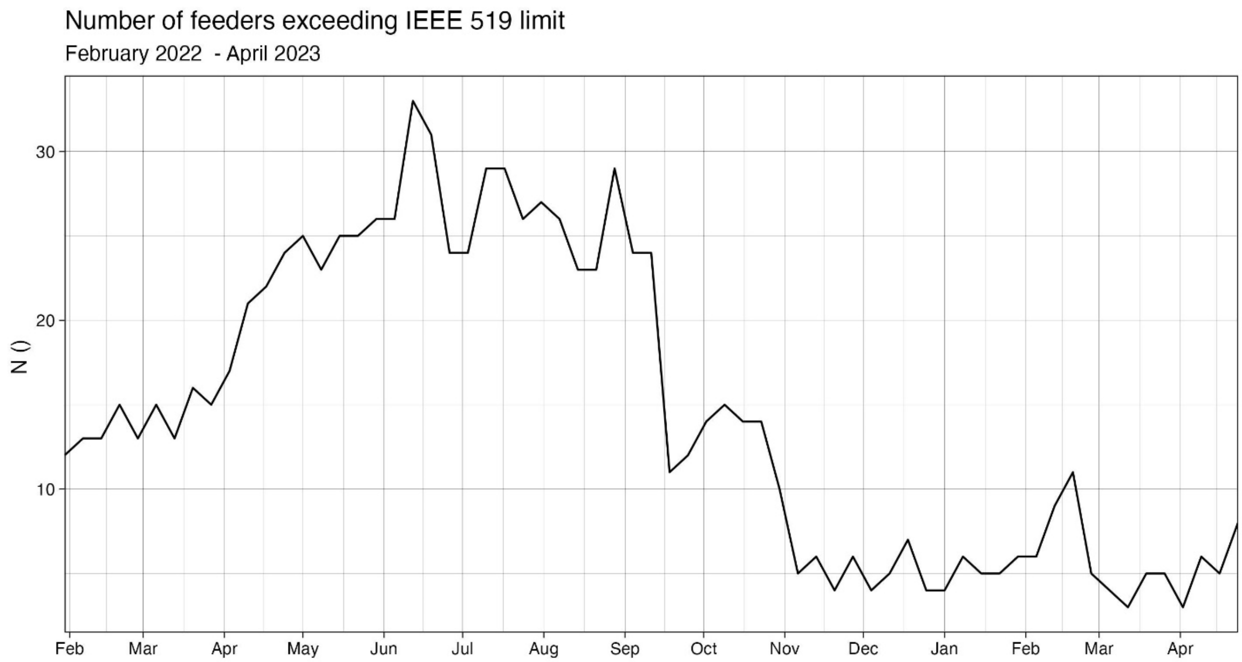


Figure 17 shows the number of feeders that have AMPQs reporting VTHD higher than IEEE 519 limit. The chart shows a similar trend to Figure 16. The number of feeders with high harmonics readings ranges from 4 up to 33 feeders out of 125 feeders monitored. However, the numbers are smaller because some feeders have more than one AMPQ installed.

Some feeders have up to 3-4 AMPQs installed to validate whether the VTHD is high across the feeder or only in isolated locations. The results show that on feeders with high VTHD, the VTHD seems to be elevated across the feeders and vary by a few percentages. In the other words, the voltage harmonic distortion is likely seen by all customers on the feeder.

Figure 17: Number of feeders with VTHD readings exceeding IEEE 519 limit



Harmonics seasonality

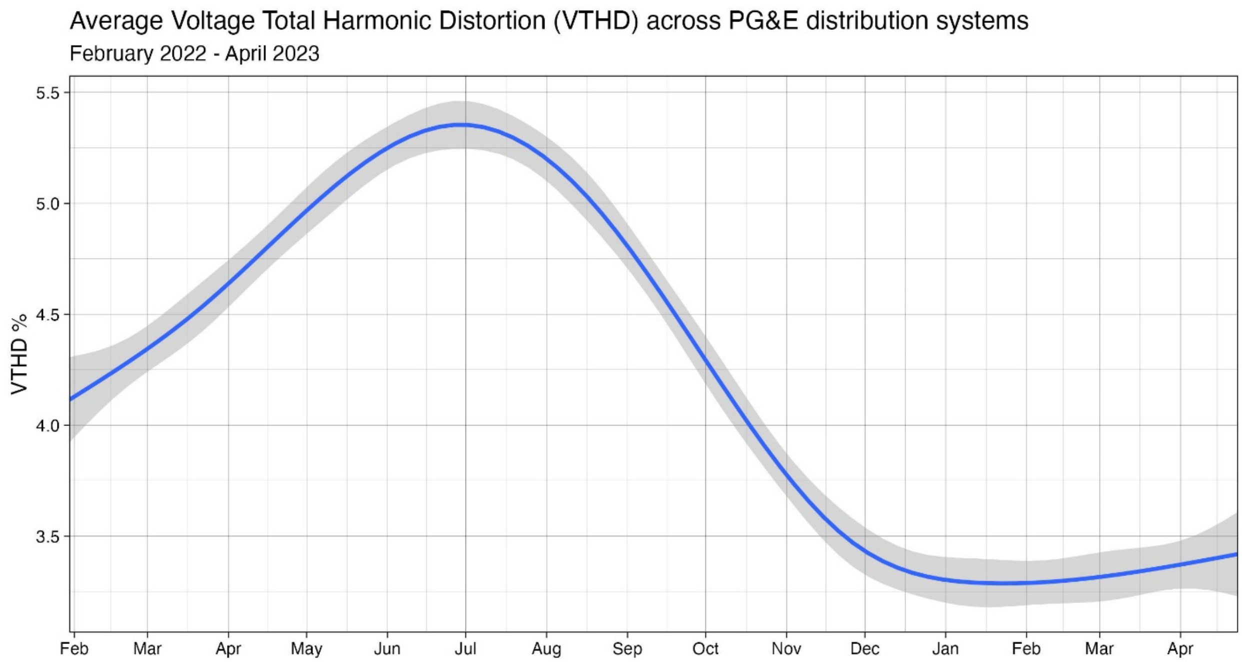
The aggregated average VTHD from all the AMPQs is shown in Figure 18 below. The trend shows that the harmonics level in the systems increases from spring and peak in July before declining in late fall. The findings suggest that harmonics issues in PG&E are seasonal and appears to correlate to seasonal loads in the distribution systems.

Generally, PG&E is seeing the distribution system voltage harmonics increases in lockstep with seasonal loads in feeders that have high level of agricultural loads. PG&E conducted field measurement and investigation and found that most harmonics in these feeders come from large VFD running agricultural pumps. These VFD pumps can be quite large ranging from 100 – 500 Horsepower and the harmonics output from them add up on the primary voltage of the distribution system causing signification deterioration of the service voltage quality.

The investigation also showed that no single customer was responsible for the harmonic distortion on the feeder. Instead, it was an aggregation of many disperse harmonics sources on the feeder. Especially because the VFDs did not have any harmonic filter installed to limit their harmonics output.

It is seen that the number of AMPQs with high harmonics readings remains relatively low in April 2023 compared to the previous year. This is because California has received a lot of rainfall in the winter of 2022 – 2023 which delayed the start of the irrigation season in 2023. The harmonics level is expected to climb in the summer as soon as the irrigation season starts.

Figure 18: Average VTHD readings of all 180 AMPQs



Where PG&E has high harmonics and where it comes from

In this section, the VTHD readings are broken down by division as shown in Figure 19 and Figure 20. The results show a significant increase in harmonics in Yosemite, Fresno, Sacramento, and Kern divisions during the summertime while the harmonics level in other divisions remains relatively flat throughout the year.

PG&E conducted field investigation to determine where the harmonics come from and found that the main source of harmonics on these agricultural feeders from the variable speed drive (VFD) running these pumps. When a standard 6-pulse VFD operates without any harmonics mitigation, it does not draw current linearly, and therefore creating current harmonic distortion which in turn results in voltage harmonic distortion in the utility distribution systems.

One of the characteristics of the feeders chosen for monitoring in these divisions is that they are considered agricultural feeders because they serve a lot of agricultural customers and are in farmland. There are many large irrigation pumps typically 100-500 horse powers in size on these feeders. The combined irrigation pumps served by each of these feeders can be up to thousands of horse powers. From the harmonics data obtained in this project, the results show that the increase in harmonics in PG&E distribution systems directly corresponds to the start of the irrigation season typically around March and April, and then the harmonics subsides when the irrigation season ends in October and agricultural customers turn off their VFD irrigation pumps.

Feeders with small number of VFDs may not experience harmonic issues. However, the harmonics from these VFDs are additive. So, in feeders where there are a lot of VFDS, the harmonics are adding up in the distribution systems and can results in severe harmonic distortion of the voltage waveform that utility provides to all customers the feeder, which may then impact customers if their equipment is sensitive to harmonics. Several harmonics mitigations for VFD are available in the industry such as harmonics filter and VFD with harmonics mitigating design such as VFD with active frontend, 12-pulse and 18 pulse VFD etc. Currently, these VFD harmonics mitigations are not widely used in PG&E distribution systems.

Figure 19: Average VTHD readings by division

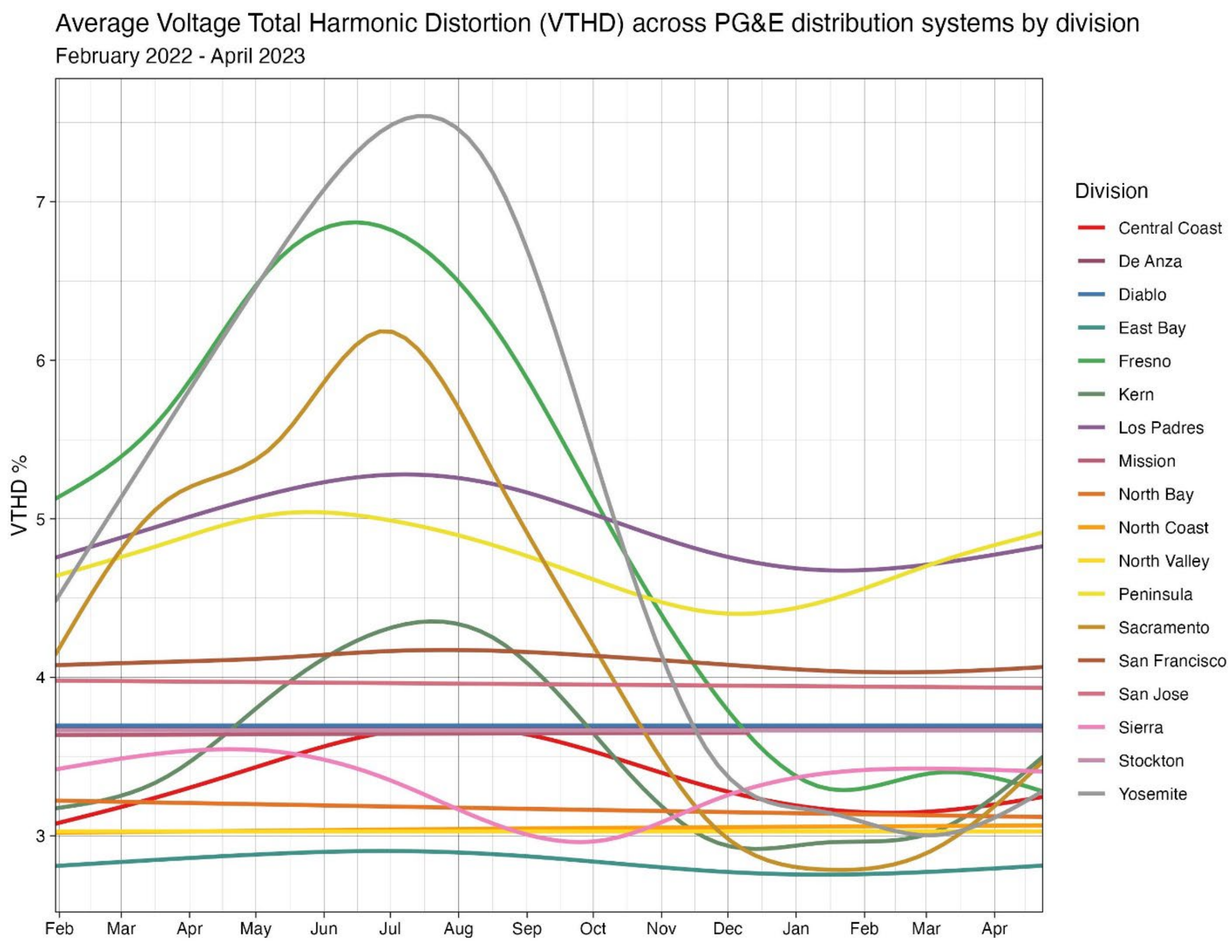
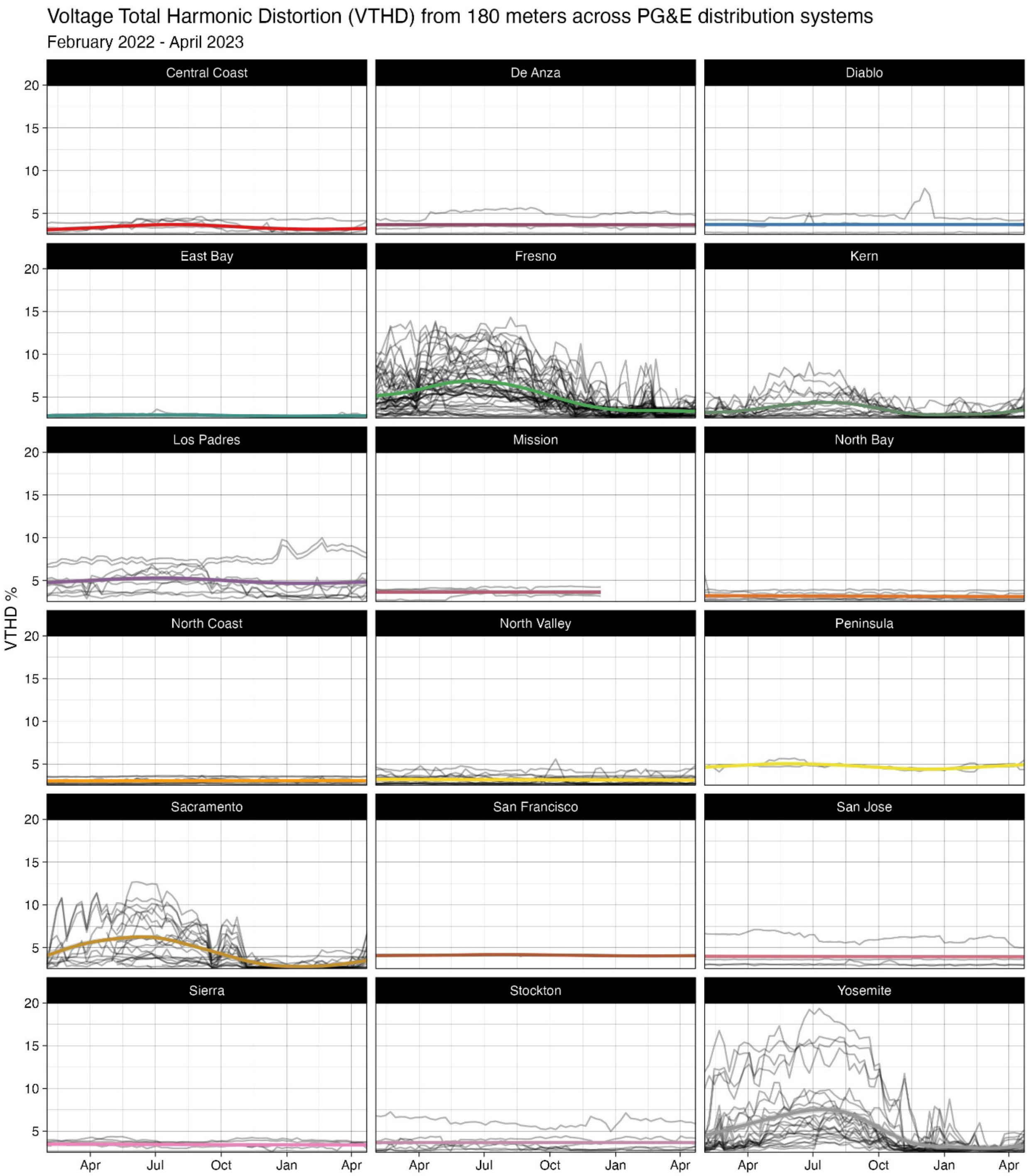


Figure 20: VTHD readings by divisions



Systems Harmonics Monitoring

The Harmonics Dashboard also displays a key performance indicator used to monitor the overall harmonics. It is based on aggregated VTHD readings from all the AMPQs assessed per IEEE 519 limit. The graph in Figure 21 generally represents the health of the systems from harmonics perspective which is about 85% at the lowest point in the summer and about 98-99% in the winter and spring. As PG&E continues to address and mitigate harmonics issues in the distribution systems, these numbers should improve over years especially during the summertime.

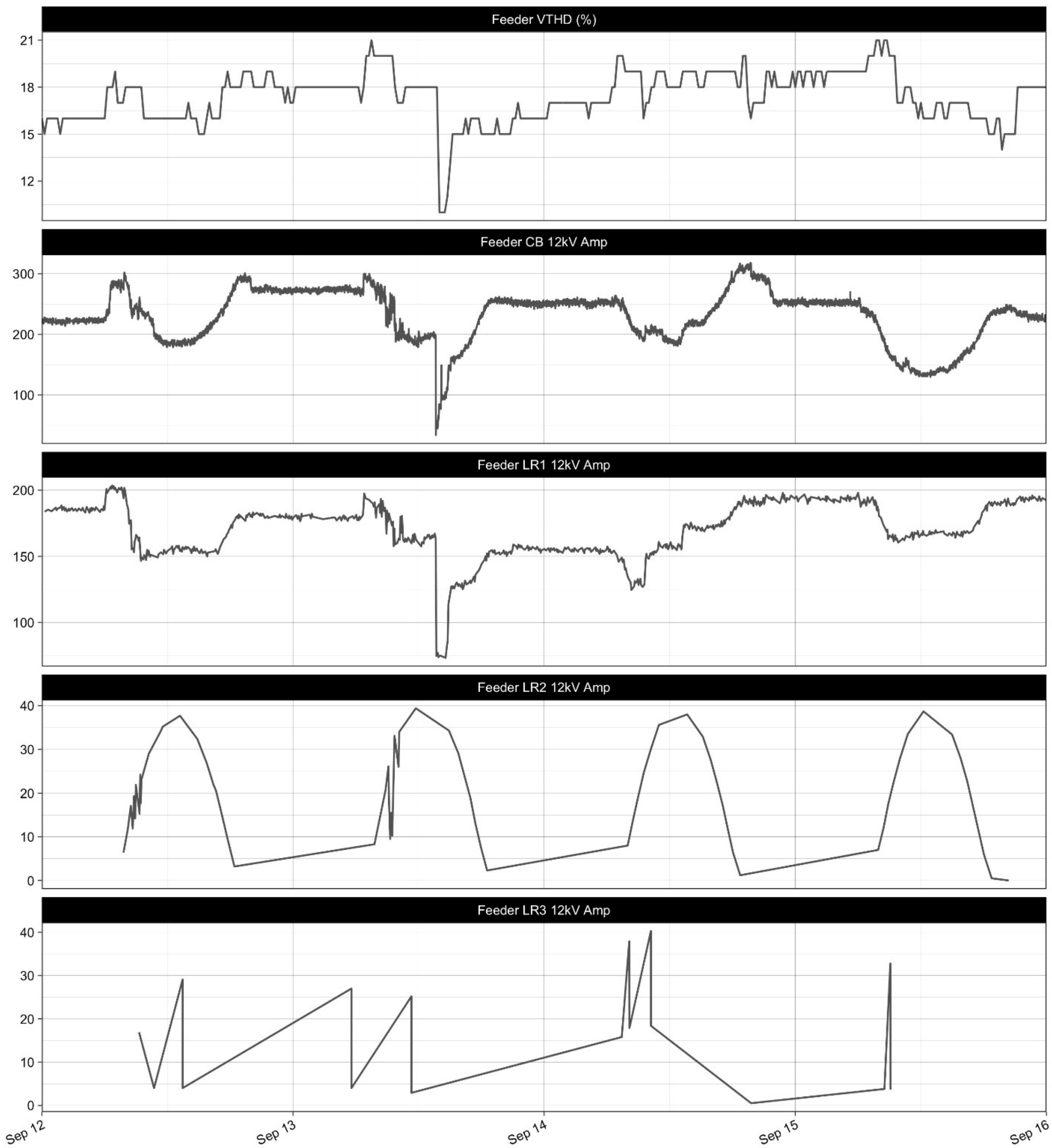
Figure 21: System Harmonics Health

Correlation of feeder voltage harmonics and feeder loads

For harmonics analysis, the Harmonics Dashboard also imports SCADA data from feeder circuit breaker (CB) and feeder line reclosers (LR). The harmonics data from the AMPQs and SCADA data show that there is a very strong correlation between the feeder loads and voltage harmonics level, further supporting the findings that most voltage harmonics in PG&E distribution systems are caused by loads, specifically certain type of loads such as VFDs. By looking at the feeder loads from CB and LRs, in some cases it may be possible to determine the general area where most of the harmonics sources are located on the feeder.

Figure 22 shows an example of comparing feeder VTHD variation with the feeder loads from CB and LR. It is seen that the VTHD drops sharply on September 13th when the CB loads drop suggesting that the harmonics is caused by loads. Then, looking at the loads on the three LRs on the feeder, the loads of LR1 strongly correlates to the VTHD on the feeder suggesting that the sources of harmonics are located on the load side of LR1 whereas the loads on LR2 and LR3 does not show any correlation. As a matter fact, the loads pattern of LR2 is typical of a solar generation profile which may reduce the overall VTHD on the feeder because the solar generation masks the demand from harmonics-producing loads, thus reducing harmonic current flowing back to PG&E source. The analysis of feeder harmonics and loads correlation can be complicated depending on the number of SCADA data available, the sources of harmonics, and the present of DER on the feeder. In any case the harmonics data from the AMPQ and SCADA data help PG&E power quality engineers to conduct a preliminary assessment of where the harmonics come from.

Figure 22: Harmonics VTHD vs Feeder loads (CB and LR)



Correlation of feeder voltage harmonics and customer demand

One of the objectives in this project is to create an analysis tool that help power quality engineer investigate harmonics. Since the feeder loads data suggest that feeder voltage harmonics may be caused by customer's loads, the next logical step is to investigate which customers may be injecting excessive harmonics into the systems.

Using VTHD trend from the AMPQ as a reference for the feeder harmonics level, an algorithm was created to compute a correlation coefficient value between each customer's demand trend and the VTHD trend during a weekly data calculation timeframe. The result is a list of customers on the feeder and their corresponding harmonics correlation "score".

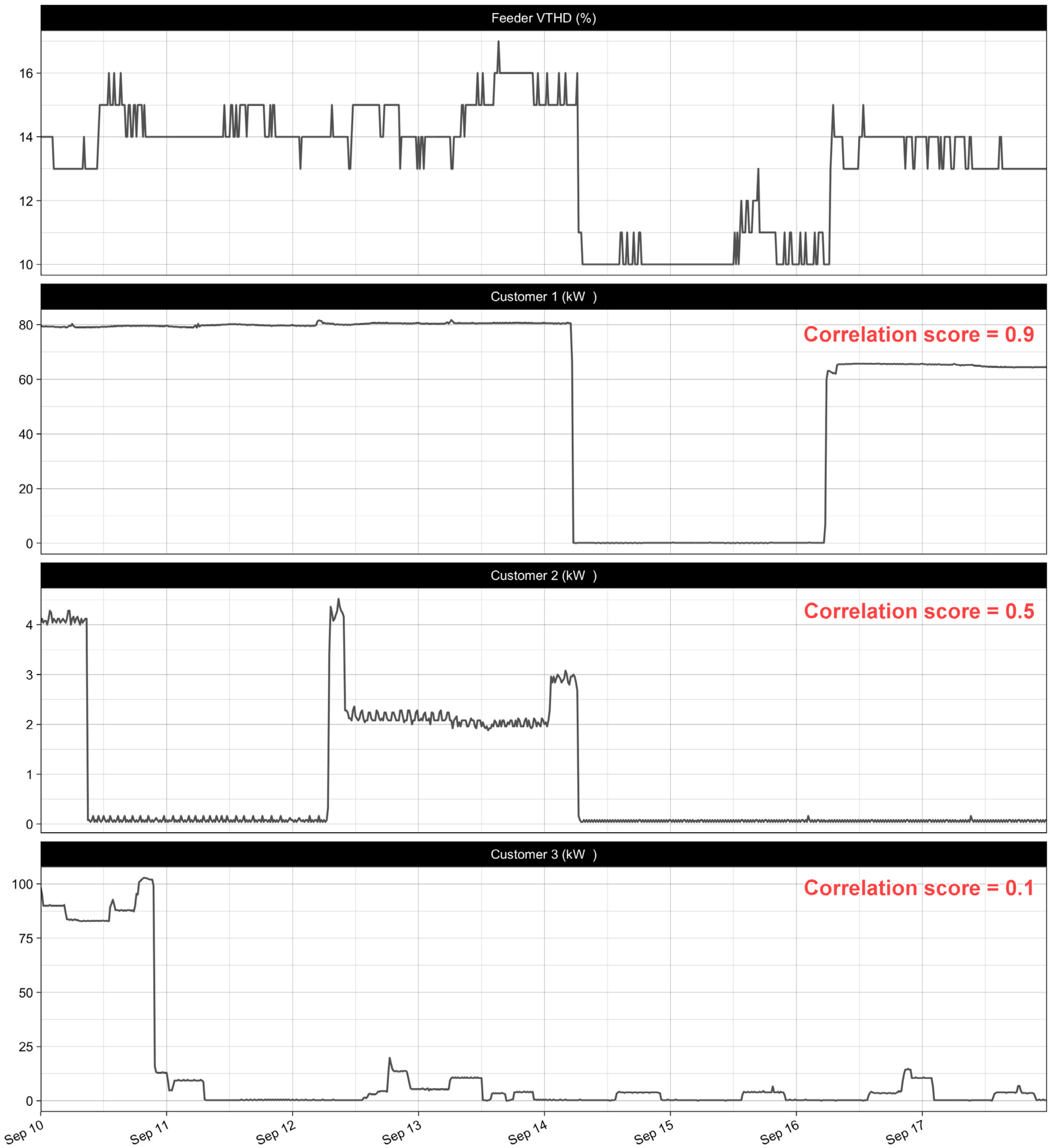
Figure 23 shows an example of feeder harmonics and different value of customer demand correlation score. Customer 1 demand with correlation score of 0.9 shows a very strong correlation to feeder harmonics variation. In other words, when Customer 1 loads go offline, the feeder VTHD decreases and when Customer 1 loads come online, the feeder VTHD increases in lockstep.

This suggests that Customer 1 may have electrical loads that inject significant harmonics into the system. Customer 2 demand with correlation score of 0.5 shows relatively smaller correlation and the demand is very small. So, Customer 2 loads do not appear to be a major source of harmonics. Finally, Customer 3 demand with correlation score of 0.1 show very little correlation to the feeder VTHD, even though the demand is relatively high. So, Customer 3 loads are not causing harmonic distortion.

The data analysis in this project suggests that customer with harmonics demand correlation score of > 5.0 should be investigated further as they may be potentially injecting harmonics into the distribution systems.

Importantly, it must be emphasized that this correlation analysis only suggests correlation and not causation. Further field investigation and harmonics measurement must be conducted to validate the results. The correlation analysis is not meant to be used to determine customer IEEE 519 compliance, but rather as a tool that PG&E power quality engineers can use to quickly identify potential sources of harmonics to speed up harmonics investigations.

Figure 23: Feeder harmonics and customer demand correlation



5 Value Proposition

The purpose of EPIC funding is to support investments in technology demonstration and deployment projects that benefit the electricity customers of PG&E, San Diego Gas and Electric (SDG&E), and Southern California Edison (SCE). EPIC 3.32 project has demonstrated that it was feasible to use advanced meter to collect harmonics data for power quality investigation.

5.1 Primary Principles

The primary principles of EPIC are to invest in technologies and approaches that provide benefits to electric ratepayers by promoting greater reliability, lower costs, and increased safety. This EPIC project contributes to these primary principles in the following ways:

- **Greater reliability**: Harmonics data from AMPQ enable power quality engineers to monitor and detect harmonics in PG&E distribution systems and provide visibility to potential harmonic issues that can be addressed proactively before impacting utility and customer equipment.
- **Lower costs**: EPIC 3.32 contributes to overall lower costs of collecting harmonics data through operational efficiencies and reduces labor costs by eliminating truck roll that would otherwise be dispatched to install portable power quality monitors. The harmonics correlation analysis tool also helps reduce the labor of power quality engineers to analyze and troubleshoot harmonics problems.
- **Increased safety**: The automation of harmonics data collection using AMPQ reduces the exposure of field personnel to high voltage that may be present when installing a power quality monitor on service equipment.

5.2 Secondary Principles

EPIC also has a set of complementary secondary principles. This EPIC project contributes to the following three secondary principles: societal benefits, economic development, and efficient use of ratepayer funds.

- **Societal benefits:** Harmonics is a growing power quality problem that impacts many power electronics electrical equipment such as solar PV inverters, DERs, EV chargers and energy efficiency devices. By addressing harmonics issues, the adoption and integration of these new technologies is not hindered.
- **GHG emissions reduction:** Most PG&E customer complaints related to harmonics involve solar PV customers whose solar systems cannot operate due to excessive grid harmonic distortion. By providing harmonics visibility and facilitate troubleshooting and resolving harmonics issues, these distributed energy resources will operate more efficiently, thereby reducing GHG emissions.
- **Efficient use of ratepayer funds:** Operational efficiencies achieved through EPIC 3.32 would result in lower costs of collecting harmonics data which would improve the efficiency of ratepayer funds used towards operations.

5.3 Accomplishments and Recommendations

Key Accomplishments

The EPIC 3.32 project was the first utility project that attempts to bring harmonics data via electric revenue meter in addition to billing and voltage data. It paved the way for future power quality application of using electric meter such as power quality events and waveform analysis.

The following summarize some of the key demonstration and accomplishments of the project:

- Successfully deployed 180 AMPQs in locations across the service territory covering 125 electric distribution feeders.
- Tested and programmed the AMPQs to collect and transmit harmonics data remotely.
- Developed a cloud-based IT network system that automates the collection and processing of harmonics data from the AMPQs.
- Created a Harmonics dashboard, a data visualization and analysis tool to facilitate harmonics monitoring, data analysis, including developing algorithms to help identify potential sources of harmonics for power quality investigation.

5.3.1 Key Recommendations

Next Generation Metering Platform: EPIC 3.32 demonstrated that it was possible to use AMPQ to collect harmonics data which are useful for power quality investigation. Therefore, harmonics and other power quality data should be operationalized and integrated into PG&E metering infrastructure in production environment such as the AMI platform to leverage in-service revenue SmartMeter to collect power quality data in addition to billing and voltage data. The additional power quality data will be useful for grid operations, asset management, and with troubleshooting power quality issues. The recommendation is to deploy or enable the AMPQ power quality functionality in agricultural, commercial, and industrial customer services to provide harmonics visibility to all PG&E distribution feeders.

Power Quality Data Analytics and Automation: The harmonics data collected from EPIC 3.32 project provide important grid analytics from power quality perspective. As the deployment of the AMPQs increase, so will the amount of power quality data generated. The analysis of large amount of power quality data can be very time consuming. It is recommended that further automations of data analysis that support power quality troubleshooting and testing be developed and improved.

5.4 Technology Transfer Plan

5.4.1 IOU's Technology Transfer Plans

A primary benefit of the EPIC program is the technology and knowledge sharing that occurs both internally within PG&E, and across the other IOUs, the CEC and the industry. In order to facilitate this knowledge sharing, PG&E will share the results of this project in industry workshops and through public reports published on the PG&E website. Specifically, below is information sharing forums where the results and lessons learned from this EPIC project were presented or plan to be presented:

Information Sharing Forums Planned

- CEATI Power Quality Conference in 2022 - 2023

- IOU meetings between PG&E, SCE, SDGE in 2022 – 2023

Path to Production

The AMPQ harmonics data collection system and Harmonics Dashboard are fully operational as designed in this project. Both systems were built with scalability in mind, the Harmonics Dashboard will process and integrate harmonics data from any sources as long as they are in the right format.

To integrate the AMPQ harmonics functionality into PG&E existing metering infrastructure will require:

- Enable power quality soft switches in the revenue meters for the existing revenue Smartmeters™ that support harmonics functionality via software update.
- Engage existing AMI/Meter vendors and explore bringing the harmonic functionality to PG&E headend system for large-scale deployment.
- Create and test a new meter program that combines billing data, voltage data, and power quality (harmonics) data.
- System integration and end-to-end testing for the harmonics data in the existing AMI environment to ensure there are no impacts on customer care and billing systems or other distribution management systems that rely on meter data.
- Develop data pipeline from AMI systems to Foundry Harmonics Dashboard.

Therefore, additional development and demonstration are needed to adapt the harmonics data collection in the standard metering infrastructure in production environments for operational use.

5.4.2 Adaptability to Other Utilities and Industry

The following findings in this project are relevant and adaptable to other utilities and the industry:

- AMPQ is revenue grade electric meter that meets national standards and facilitates interoperability. Many utilities are likely going to implement the next generation of metering technology capable of collecting power quality data in the future.
- Harmonics is a growing power quality concern among utilities because the grids and loads characteristics are rapidly evolving due to the proliferation of DER/DG and non-linear loads.
- AMPQ reduces high voltage exposure, improves safety for field personnel, and supports low costs in materials and labor of collecting harmonics data.
- Power quality data from electric meter is useful for grid operations, troubleshooting, and investigation.

5.5 Data Access

Upon request, PG&E will provide access to data collected that is consistent with the CPUC's data access requirements for EPIC data and results.

6 Metrics

The following metrics were identified for this project and included in PG&E's EPIC Annual Report as potential metrics to measure project benefits at full scale. Given the proof-of-concept nature of this EPIC project, these metrics are forward looking.

Table 3. Project Metrics

D.13-11-025, Attachment 4[5]. List of Proposed Metrics and Potential Areas of Measurement (as applicable to a specific project or investment area)	Reference
3. Economic benefits	
a. Maintain / Reduce operations and maintenance costs	5.1, 5.2
b. Maintain / Reduce capital costs	5.1, 5.2
e. Non-energy economic benefits	5.1, 5.2
4. Environmental benefits	
a. GHG emissions reductions (MMTCO2e)	5.2
5. Safety, Power Quality, and Reliability (Equipment, Electricity System)	
d. Public safety improvement and hazard exposure reduction	5.1
e. Utility worker safety improvement and hazard exposure reduction	5.1
f. Reduced flicker and other power quality differences	5.1
h. Reduction in system harmonics	5.1
i. Increase in the number of nodes in the power system at monitoring points	5.1, 5.2
7. Identification of barriers or issues resolved that prevented widespread deployment of technology or strategy	
Increased use of cost-effective digital information and control technology to improve reliability, security, and efficiency of the electric grid (PU Code § 8360)	5.1
Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services (PU Code § 8360)	5.2

[5] https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M081/K773/81773445.pdf

7 Conclusion

The EPIC 3.32 *System Harmonics for Power Quality Investigation* project successfully demonstrated a new way of leverage AMPQs to collect harmonics data in the electric distribution systems. It demonstrated that the AMPQ could collect harmonics data comparable to power quality monitors at a lower cost since utility already has revenue electric meter installed at customer service for billing purposes.

Therefore, PG&E should explore pathways to operationalize and integrate harmonics and other power quality data into metering infrastructure in production environment. The power quality data collected will be useful for power quality investigation, which has potential value related to improved reliability, safety, efficiency, and customer satisfaction. Additionally, more data algorithms may be developed to automate harmonics data analysis for engineering applications. This would help speeding up the process to identify the source of harmonics and to conduct analysis to determine whether the level of harmonics is within IEEE 519 guidelines.

The harmonics data collected in this project also revealed significant harmonic distortion in many of PG&E's electric distribution feeders, particularly in the agricultural areas. Field investigation revealed that the sources of harmonics in these areas are large variable speed drives (VFDs) running agricultural pumps which have proliferated in recent years due to energy efficiency benefits. The drought conditions in California may also have driven customers to install more and larger agricultural pumps to reach deeper water table. In many cases, these large pumps necessitate the use of VFD to allow the pump to start and run efficiently. However, VFDs also introduce significant harmonic distortion to the grid unless mitigation is taken. The results from this project helped PG&E shape policies to address the harmonics issues such as updating VFD rebate program requiring IEEE 519 compliance and updating Tariff Rule 2 to include IEEE 519 requirements.

The harmonics issues are expected to worsen in the future as the proliferation of harmonics sources such as VFDs, DERs, and EV battery chargers in the electric distribution system continue. Furthermore, modern customers' equipment is increasingly becoming more sensitive to harmonics due to the use of power electronics. This further highlights the need for continuous monitoring of the harmonics level in distribution systems, so that PG&E can proactively address the harmonics issues in before it impacts PG&E and customers' equipment.

PG&E is currently exploring different options for integrating harmonics and other power quality data from the AMPQ functionality into metering infrastructure and operational processes. The technology demonstration in this project provides valuable learnings to PG&E as it moves forward with the implementation of the next generation of advanced metering infrastructure.

Appendix A: AMPQ data channels

Channel	Channel Description	Channel	Channel Description
1	Delivered Energy kWh	41	% Voltage Harmonic Value 1 thru 24, Phase C
2	Received Energy kWh	42	Harmonic Voltage Angle Value1 thru 24, Phase C
3	Total Energy (Del+Rec)	43	% Current Harmonic Value 1 thru 24, Phase A
4	Net Energy (Del-Rec)	44	Harmonic Current Angle, Value 1 thru 24, Phase A
5	Instantaneous Voltage	45	% Current Harmonic Value 1 thru 24, Phase B
6	Instantaneous Power	46	Harmonic Current Angle, Value 1 thru 24, Phase B
7	Reactive Energy, Lag (kilovar-hour (kVARh)	47	% Current Harmonic Value 1 thru 24, Phase C
8	Reactive Energy, Lead kVARh	48	Harmonic Current Angle, Value 1 thru 24, Phase C
9	Net Reactive Energy (Del– Rec)	49	Distortion Power (Volt-Ampere (VA)) Phase A
10	Tamper Switch	50	Distortion Power (VA) Phase B
11	Power Factor	51	Distortion Power (VA) Phase C
12	Apparent Power Factor	52	Distortion Power (VA) Total
13	Displacement Power Factor	53	Distortion Power Factor Total
14	Distortion Power Factor	54	Total Harmonic Distortion (THD) Voltage %
15	4 Quadrant Metering	55	THD Current %
16	Multi-Dwelling Flag	56	Voltage Sag Counter
17	Maintenance Info (Dates, Names, Work Done)	57	Minimum Voltage during Sag Event, Phase A
18	Frequency, Hertz (Hz)	58	Minimum Voltage during Sag Event, Phase B
19	Outage Monitor-Voltage - 30 Min	59	Minimum Voltage during Sag Event, Phase C
20	Voltage Phase A to Neutral, F+H	60	Duration of Sag Event (cycles)
21	Voltage Phase B to Neutral, F+H	61	Voltage Swell Counter
22	Voltage Phase C to Neutral, F+H	62	Maximum Voltage during Swell Event, Phase A
23	Voltage Phase A to Phase B, F + H	63	Maximum Voltage during Swell Event, Phase B
24	Voltage Phase B to Phase C, F + H	64	Maximum Voltage during Swell Event, Phase C
25	Voltage Phase C to Phase A, F + H	65	Duration of Swell Event (cycles)
26	Current Magnitude Phase A	66	Latitude/Longitude
27	Current Magnitude Phase B	67	Accelerometer, Acc X axis
28	Current Magnitude Phase C	68	Accelerometer, Acc Y axis
29	Current Magnitude Neutral	69	Accelerometer, Acc Z axis
30	Voltage Angle, Phase A	70	Accelerometer, Gyro X axis
31	Voltage Angle, Phase B	71	Accelerometer, Gyro Y axis

32	Voltage Angle, Phase C	72	Accelerometer, Gyro Z axis
33	Current Angle, Phase A	73	RF Data – 460 MHz
34	Current Angle, Phase B	74	RF Data – 900 MHz
35	Current Angle, Phase C	75	RF Data – 4G LTE
36	Diagnostic Counters	76	RF Data – Bluetooth
37	% Voltage Harmonic, Value 1 thru 24, Phase A	77	RF Data – Wi-Fi
38	Harmonic Voltage Angle, Value 1 thru 24, Phase A	78	RF Data – Reserved
39	% Voltage Harmonic, Value 1 thru 24, Phase B	79	Data Usage (megabyte (MB)/gigabyte (GB))
40	Harmonic Voltage Angle, Value 1 thru 24, Phase B	80	4G LTE Signal Strength

Appendix B: IEEE 519 Standard Harmonics Limits[6]

Voltage distortion limits:

Bus voltage V at PCC	Individual harmonic (%) $h \leq 50$	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

[a]High-voltage systems are allowed to have up to 2.0% THD where the cause is an HVDC terminal whose effects are found to be attenuated at points in the network where future users may be connected.

Current distortion limits for systems rated 120 V through 69 kV:

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order[b]						
I_{SC}/I_L	$2 \leq h < 11$[a]	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a] For $h \leq 6$, even harmonics are limited to 50% of the harmonic limits shown in the table.

[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c] Power generation facilities are limited to these values of current distortion, regardless of actual I_{sc}/I_L unless covered by other standards with applicable scope.
where:
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current at PCC under normal load operating conditions

[6] https://standards.ieee.org/ieee/519/10677/