Article

Design, Implementation, and Evaluation of Open Power Quality

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Abstract: Modern electrical grids are transitioning from a centralized generation architecture to an architecture with significant distributed, intermittent generation. This transition means that the formerly sharp distinction between energy producers (utility companies) and consumers (residences, businesses, etc) are blurring: end-users both produce and consume energy, making energy management and public policy more complex. The goal of the Open Power Quality (OPQ) project is to design and implement a low cost, distributed power quality sensor network in order to make useful information about electrical grids (and their stability) available to producers, consumers, researchers, and policy makers. In 2019, we performed a pilot study where 15 OPQ hardware devices were deployed across the University of Hawaii microgrid for three months. Results of the pilot study provide evidence that OPQ provides a variety of useful monitoring services and that the system could be scaled to service larger geographic regions. We conclude that OPQ provides a new and useful approach to power quality monitoring that can be used in conjunction with other technologies .

Keywords: Power Quality, Open Source, Renewable Energy, Grid Stability

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1. Introduction

1.1. Motivation

Power quality is not currently a concern for most people in developed nations. Just like most people in developed nations assume that their tap water is of adequate quality to drink, most also assume that their electricity is of adequate quality to power their homes and appliances without causing harm. And, in both cases, most people assume that public utilities will appropriately monitor and correct any quality problems if they occur.

Successfully maintaining adequate power quality and providing sufficient amounts of it to meet the rising needs of consumers has been a triumph of electrical utilities for over 100 years. In recent times, however, there have been changes to the nature of electrical generation and consumption that make power quality of increasing concern and interest. First, there is a global need to shift to renewable energy sources. Second, traditional approaches to top-down grid power quality monitoring may not be well suited to bottom-up, distributed generation associated with renewable energy sources such as rooftop photovoltaic panels (PV). Third, modern consumer electronics place more stringent demands on power quality. Finally, effective public policy making in this modern context can be aided by public access to power quality data. Let's look at each of these in a bit more detail.

1. We need more renewable energy. Concerns including pollution, environmental degradation, and climate change have produced a global movement away from centralized, fossil-fuel based forms of electrical energy generation and toward distributed, renewable alternatives such as wind and solar. But the economic, environmental, and political advantages of renewable energy comes with significant new technical challenges. Wind and solar are intermittent (for example, solar energy cannot be harvested at night) and unpredictable (for example, wind and solar energy fluctuate based upon cloud cover and wind speed). In addition, renewable energy generation is often distributed throughout the grid (such as in the case of residential rooftop photovoltaic (PV) systems).

One impact of adding renewable energy generation to an electrical grid is that maintaining adequate power quality is much more challenging. This problem is inversely proportional to the size of the electrical grid. For example, each island in the State of Hawaii maintains its own electrical grid, ranging from a 1.8 GW grid for the island of Oahu to a 6 MW grid for the island of Molokai. (In contrast, the size of the European electrical grid is approximately 600 GW and the size of the U.S. continental grid is over 1000 GW.) For small grids, the unpredictable nature of power generation by distributed, intermittent renewables can quickly create problems for grid stability. In the case of Hawaii, consumer demand for grid-tied rooftop solar exceeded the ability of Hawaiian Electric to manage, resulting first in complex and expensive "interconnection studies" [1,2], and later in the requirement for new installations to include batteries and grid-disconnected operation.

2. Traditional top-down monitoring is not well-suited to bottom-up energy generation. For traditional grid architectures where generation is centralized and under the complete control of the utility, it is common to monitor power quality only to the substation level, because it can be assumed that the power quality experienced at the substation is a reasonably accurate proxy for the power quality experienced by the 1,000 or so end-users serviced by the substation. Furthermore, if an end-user experiences a power quality problem not experienced by the substation, then it is mostly likely due to equipment or electrical issues local to that end-user and not a grid-level problem.

These assumptions might not hold in grids with distributed, intermittent generation by end-users, such as is the case with roof top solar. In these cases, the unpredictable nature of generation can lead to local power quality problems that are not experienced by the substation, and that are not due to any single individual, but rather the bottom-up power generation architecture of the grid. Nakafuji notes that Hawaiian Electric is contending with PV penetrations in excess of 60% on certain distribution circuits, for which traditional rules of thumb for design of protection and distribution systems might not hold [3].

3. Consumer electronics require higher quality power. The rise of consumer electronics has raised the bar for what constitutes “adequate" power quality. Only a few decades ago, computers were a rare presence outside of labs and large institutions. Today, computers are everywhere: embedded in phones, washers, refrigerators, thermostats, and so forth. These electronic devices not only have higher power quality requirements, but some of them actually introduce power quality problems in the form of harmonic distortion. Poor power quality can result in electronic devices failing unpredictably, and/or decreasing their lifespan.

4. Power quality data should be publicly available. Electrical utilities are not required to be totally transparent about the quality of power they provide to consumers. For example, in Hawaii, utilities are only required to make a "best effort" to provide non-harmful voltage and frequency values, and are only required to publicly report about power outages of more than 3 minutes. There is no requirement for utilities to report potentially harmful levels of voltage, frequency, THD, or transients as long as they do not lead to outages. Indeed, in places like Hawaii, there is not yet even infrastructure in place to enable utilities to collect that information, even if they were asked to report on it. Providing a high quality, third party, publicly available source of power quality data not only benefits the public, it makes it much easier to perform research on ways to improve grid stability in the presence of renewable energy generation.

Providing power quality data to address the above issues requires solving several difficult technical problems. First, monitoring below the substation level increases the number of required monitoring devices by two to three orders of magnitude. This has significant implications for the cost of monitoring in terms of the devices, and the sheer amount of low-level power quality data that will be produced. Second, this low-level data must be processed in a manner that does not require inordinate amounts of processing, network bandwidth, or storage. Finally, collecting the data is not useful if it cannot be converted into actionable information in a reasonable amount of time.

1.2. Goals of the Open Power Quality Project

The goal of the OPQ Project is to provide a scalable source of actionable power quality data about electrical grids, particularly those with high levels of distributed, intermittent power generation. OPQ accomplishes this through the design and implementation of a low-cost sensor network for power quality using custom power quality monitors with real-time, two way communication to a set of cloud-based services. An OPQ sensor network is designed to be useful to: consumers who want to better understand the performance of their public utilities; utilities who desire a low-cost, easily deployable and re-deployable sensor network to gather information about grid stability that complements their existing infrastructure; to researchers who wish to design improvements to grid management and need a low cost mechanism for measuring the impact of their improvements; and to public policy makers responsible for designing and implementing regulatory frameworks for electrical utilities. Several key features of our project emerge from these goals.

OPQ Box. First, our custom power quality monitoring hardware device, called "OPQ Box" can be produced for approximately US$75. This is from 10 to 100 times less expensive than commercial power quality monitors. This cost differential means, for example, that instead of monitoring power quality at the level of individual buildings, OPQ makes it economically feasible to monitor power quality on each floor or even in each room of a building. Similarly, instead of monitoring power quality at the substation level of the grid, OPQ Boxes make it feasible to deploy dozens or hundreds into a community to obtain fine-grained data about the impact of solar or other renewables as directly perceived by the customer.

Cloud-native information architecture. Second, our information architecture is "cloud native", which means that OPQ Boxes are not designed for stand-alone, autonomous use, unlike current commercially available power quality monitors. Instead, our hardware boxes and cloud-based services perform real-time, two-way communication over the Internet to determine what power quality data must be gathered and with what fidelity in order to most efficiently produce actionable information. Two-way communication between the OPQ Boxes and could services creates the ability to control individual OPQ Boxes based upon the global state of all OPQ Boxes in an OPQ sensor network. As a result, OPQ cloud services can obtain and analyze high fidelity wave form data only when desired, without the prohibitive network overhead of constantly communicating this data from boxes to the cloud. This enables OPQ installations to be simultaneously responsive and scalable.

Plug-in analysis architecture. Third, all OPQ software services are designed for extensibility and interoperation. Our middleware components (Mauka and Makai) provide a plugin architecture. Our visualization component (View) is built from modular UI elements using React. This means that OPQ is not a monolithic, closed system with a frozen feature set, but rather a design environment for experimentation with advanced classification and analysis of power quality data.

Open Source. Fourth, our software and hardware designs and implementations are made available using open source licenses. This means that organizations choosing OPQ do not face the business risk of committing resources to a single vendor with proprietary hardware and software. Our goal is to facilitate the creation of a community of researchers and industry practitioners to replicate, extend, and apply the insights gained from the OPQ system.

While we believe OPQ offers a compelling combination of capabilities, we want to be clear that all sensor network designs involve trade-offs. As we will show below, other commercial and research solutions have features not provided by OPQ that may be important depending upon an organization's specific needs. In some cases, OPQ may not be the appropriate choice. In other cases, a hybrid solution consisting of OPQ in combination with other technologies for grid monitoring and analysis may be most appropriate.

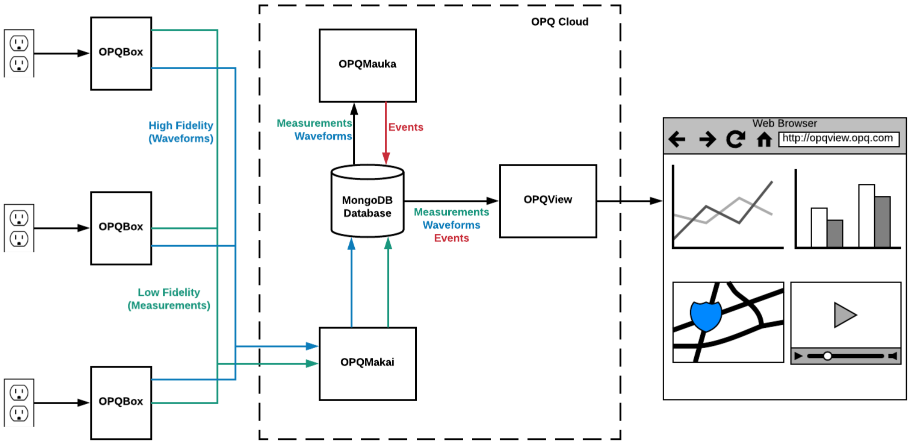


Figure 1. High level system architecture of an OPQ Sensor Network

1.3. *Structure of this paper*

The remainder of this paper is organized as follows. Section 2 presents an overview of the OPQ system architecture and information architecture. Section 3 presents related research and technology. Section 4 discusses OPQ Box and Section 5 its triggering system. Section 6 describes our analysis services, and Section 7 our user interface. Section 8 discusses the pilot deployment of a sensor network and its results. Section 9 concludes with some proposals for future research.

2. OPQ Architecture

2.1. *System Architecture*

At its most basic, the OPQ system architecture is this: OPQ Boxes are plugged into wall outlets, they monitor the quality of power at their wall outlets, and the results are communicated via the Internet to a software system called OPQ Cloud. To see the results, users login to the system using a browser.

A slightly less basic description is this: the OPQ system architecture consists of four major open source hardware and software components that provide end-to-end support for the capture, triggering, analysis, and reporting of consumer level local and global PQ events:

1. OPQ Box is a hardware device that detects the electrical waveform from a standard residential outlet and communicates both low and high fidelity representations of the waveform to other OPQ system components either at predefined intervals or upon request.
2. OPQ Makai monitors incoming low fidelity data from OPQ Boxes, requests high fidelity data when necessary, and stores the results in a MongoDB database.
3. OPQ Mauka analyzes low level data and analyzes it to produce higher-level representations according to the information architecture described below, and can tell OPQ Makai to request high fidelity data from one or more OPQ Boxes to facilitate analysis.
4. OPQ View is a browser-based visualization platform for displaying the results for data capture and analysis.

Figure 1 illustrates how these components work together to take information from wall outlets (on the left side) to the display of analyses in a browser (on the right hand side). First, OPQ Boxes analyze power from wall outlets, and send low fidelity measurements to OPQ Makai. OPQ Makai analyzes low fidelity measurements, and requests high fidelity waveforms when desirable. Both measurements and waveforms are saved in a MongoDB database. OPQ Mauka analyzes low and high fidelity data, and creates "events" to represent anomalies. OPQ View notifies users of events and allows them to drill down into low and high fidelity data.

OPQ Makai, OPQ Mauka, and OPQ View are all cloud-based software services that collectively form a single "instance" with respect to data transmission, storage, analysis, and visualization. We refer to this collection of software-side components as OPQ Cloud. Every OPQ Box connects to a single instance of an OPQ Cloud. It is possible to have multiple OPQ Cloud instances. For example, a company might install an OPQ Cloud instance behind their firewall along with OPQ Boxes to provide a private mechanism for collecting and analyzing power quality data.

This architecture has a number of benefits. The combination of low and high fidelity data reduces both network overhead and storage requirements, which increases the scalability of the system in terms of the number of OPQ Boxes that can be tied to a single OPQ Cloud instance. OPQ Makai and OPQ Mauka have a plugin architecture, making it easier to extend their functionality to incorporate new triggers for high quality data (in the case of OPQ Makai) and new events and analyses (in the case of OPQ Mauka). Finally, the open source licensing of both hardware and software makes it possible to incorporate new ideas, bug fixes, and enhancements from technologists across the power quality community.

2.2. Information Architecture

OPQ's "information architecture" is designed to facilitate the process of generating actionable, useful insights into the nature of the electrical grid starting with the data collected from a wall outlet. The information architecture must address several requirements. First, it must support analyses that require access to high fidelity data, which in the case of power quality is wave form data produced by sampling the wave form 256 times per cycle, which means there are approximately 1.3 billion data points generated per day per OPQ Box. Second, for typical grids that are generally stable, only an extremely small fraction of these data points are actually interesting. Third, as will be discussed in more detail later, what constitutes "interesting" data in one box might be dependent upon the state of data in other nearby boxes. Finally, network and storage limitations preclude a solution in which all data is sent from OPQ Boxes to the cloud, and so the information architecture must provide a "smart" mechanism for identifying data of interest on the boxes, as well as discarding data in the cloud if it is found to be not useful.

To address these requirements, the OPQ information architecture is organized as a five layer pyramid as summarized in Table 1. This table illustrates an important conceptual feature of the OPQ information architecture called "TTL", or Time To Live. The OPQ information architecture implements an active, "use it or lose it" approach to information management, in which a data item must either be associated with a higher level of the system within its Time To Live, or else it will be automatically deleted. So, for example, the high fidelity waveform data on an OPQ Box have a TTL of one hour: if that data is not requested from a box by a higher layer in the information architecture within an hour of it being generated, it will be lost. Similarly, data points in the Measurement layer will be deleted after one day if they are not associated with an Event.

Let's now discuss how information moves through these levels.

The bottom layer of the information architecture is called Box, and represents all of the OPQ Box hardware devices in an OPQ sensor network. Each box maintains onboard storage of the latest hour of high quality waveform data in a circular buffer.

Approximately once a second, each Box sends a Measurement data object to the sensor network's cloud services, which we refer to in aggregate as OPQ Cloud. Measurements are the second layer of the information architecture, and provide "low fidelity" summary statistics regarding four power quality measurements (Frequency, Voltage, THD, and Transients). Measurements give OPQ Cloud basic situational awareness of the grid without the overhead of transmitting, storing, and analyzing high fidelity wave form data. Measurements exist for one day, though a daily roll-up of Measurement summary statistics called "Trends" persists longer.

Table 1. OPQ Information Architecture Levels

Layer	TTL	Purpose
Box	1 hour	Collects and holds a rolling one hour window of "high fidelity" wave form data for a single location.
Measurement	1 day	Measurements provide "low fidelity" summary statistics regarding four power measurements (Frequency, Voltage, THD, Transients).
Event	1 month	When OPQ Cloud's Makai service detects non-nominal values in the stream of Measurements, it can decide to request an "event": wave form data from one or more boxes for a specific time interval (typically just a second or so).
Incident	6 months	An Incident is created when an Event satisfies a standard (such as IEEE 1159, ITIC, or SEMA) for a significant power quality problem.
Phenomena	1 year	Phenomena classify Incidents when they are predictable and/or have a known causal explanation.

When OPQ Cloud's Makai service detects non-nominal values in the stream of Measurements, it can decide to request wave form data from one or more boxes for a specific time interval (typically just a second or so). Note that Makai only has one hour to request high fidelity wave form data before it is lost.

Not every non-nominal power data value is significant, or in other words, meaningful for gaining insight into the grid. Over the years, the power community has developed a variety of standards (IEEE 1159, ITIC, SEMA, etc.) for characterizing significant power quality events. OPQ Cloud's Mauka service provides classification algorithms to analyze each Event to see if it satisfies any of the standards for significance. If so, an Incident is created, indicating that a significant PQ event has occurred at a specific time in a specific location. Each Incident can also be annotated with context, which is additional information about the environment or other physical factors present at the time and location of this incident. Context can be manually provided by users or automatically associated with Incidents through APIs to online services.

All of the prior levels represent behaviors of a individual Boxes in a single location at a given point in time. This final level of OPQ's information architecture is premised on the idea that insightful, actionable information results from the ability to either explain or else predict multiple Incidents. First, a Phenomena can be created in order to collect data from multiple Incidents with a common cause. An example of this form of phenomena is "the voltage drop experienced by all boxes in Kailua on 5/22/18 at 1:03pm was caused by a transformer trip at the Kailua substation." Second, a Phenomena can collect data from multiple Incidents in order to predict future Incidents. For example, "when winds exceed 40 knots in Kahuku, data from prior Incidents leads to the prediction that there will be a voltage surge of approximately 5V for approximately 3 seconds in all boxes located within 1 mile of Kahuku."

3. Related Work

This section explains how OPQ fits into current industry solutions as well as academic research on power quality monitoring and analysis. For the purposes of this review, we exclude utility-side power quality monitoring and analysis systems.

Section 3.1 discusses commercial power quality monitoring devices and how they compare to OPQ Box. Section 3.2 discusses commercial power quality database software and how they compare to OPQ Cloud. The final subsection discusses recent research systems and how they compare to OPQ as a whole.

3.1. Commercial PQ devices

Fluke [4] provides a variety of Power Quality tools. These tools typically measure voltage, current, frequency, dips, swells, power factor, harmonic, current unbalance, inrush current values, and light flicker. They generally adhere to power quality standards such as IEEE 1159, and use current transformers rather than plugging into a wall outlet. Depending on the model, these devices cost from approximately $2,000 to $10,000, and are designed for use by power engineers to diagnose power quality problems resulting from industrial machinery.

Dranetz [5] provides the HDPQ family of power quality analyzers. These are similar to Fluke devices in that they require connection to mains using current transformers and are intended for use by power quality engineers. They cost from $5,000 to $17,000 depending upon the model. They also sell a set of software answer modules to provide additional analyses regarding the raw power quality data collected by the device. For example, the Sag Directivity module detects a voltage sag, identifies its characteristics, and determines whether the source is upstream or downstream of the monitoring point. Answer modules cost approximately $1,000 each.

Elspec [6] provides the BlackBox family of multi functional waveform recorders. These devices perform transient recording, disturbance recording, phasor measurements (synchrophasor), power quality analysis, and sequence of events recording. They cost from $6,000 to $12,000 depending upon the model.

PowerSide (formerly Power Standards Lab) [7] provides the PQube3 family of power monitors. Unlike the above devices, PQube is both a revenue-grade energy meter as well as a power quality monitor. It can also record environmental data such as temperature, humidity, barometric pressure, and certain process parameters such as fuel level and water flow. QubeView is a Windows-based software package that provides real-time monitoring of multiple PQube devices and trends and statistics over the data collected.

ACR Systems [8] manufactures the PowerWatch Voltage Disturbance Recorder. Unlike the above devices, this device connects to a wall outlet. It measures surges and sags and is meant for monitoring medical instrumentation, point-of-sale terminals, computer servers, and other sensitive electronic equipment. It costs approximately $625. A Windows-based program is available for a separate cost of $135, and can be used to extract data from the device using a USB cable, and then display graphs of power quality.

Comparison with OPQ Box

All of these commercially available devices contrast with the OPQ Box in similar ways. First, all of them collect a wider variety of power quality measures than OPQ Box, and most have been certified according to one or more industry standards. They are generally designed to support industrial applications, where the goal is to ensure that the power being supplied to a building or plant is of adequate quality, and/or that the machinery in the plant is not degrading power quality. Apart from the PowerWatch monitor, all of them are attached to electrical mains using current transformers. Finally, all of them are designed for "stand alone" operation: each device can independently gather and assess power data.

While the OPQ Box has much more limited functionality, it is designed to be manufactured for approximately $75, which is 10 to 100 times less expensive than these devices. OPQ Boxes are "cloud native", which means that they have no "stand alone" capabilities. Instead, they must be connected to an OPQ Cloud instance in order for power quality data to be collected and analyzed.

3.2. Commercial PQ software

PQView [9] is a database system developed by Electrotek and EPRI to integrate data from a wide variety of digital relays, fault recorders, power quality monitors, smart meters, and SCADA historians into a relational database. PQView is not designed for real-time display, instead, the normal mode of operation is to poll the various devices containing power data once per day and upload the results, although polling as fast as once per minute is supported. The software can generate reports regarding voltage sags, swells, and interruptions, THD, and overlay voltage sags/swells on CBEMA curves to indicate which ones exceed tolerances. PQView is built on Windows software and the data is stored in a SQL Server database. PQView costs $5000 and is available as an EPRI Product.

PQSCADA Sapphire [10] is another vendor-independent system for collecting and displaying data from a variety of power quality monitoring devices. It comes in three versions, a free "Express" version with limited import and analysis tools. To obtain additional capabilities, user can purchase the professional version for $2500 or the Enterprise version for $6400. The data visualizations include trend charts, scatter event charts, histograms with summary statistics, and phasor charts.

PQDif [11], the "Power Quality Data Interchange Format", is a binary file format that specifies voltage, current, power, and energy measurements in standard fashion that allows this data to produced and consumed by devices in a vendor-independent fashion.

The Grid Protection Alliance [12] produces a suite of open source software products for addressing various issues in power data management and analysis, including data collection, archiving, notifications, event analysis, and visualization.

Comparison with OPQ Cloud

The differences between the way OPQ and the above systems store and manipulate power quality data arise from fundamentally different architectural assumptions and the historical background of the technology. PQView and PQSCADA Sapphire are designed to operate in a technology environment consisting of a large number of installed, "stand alone" power quality monitors built by different vendors. Their goal is to aggregate the data collected by these devices, and in order to do so, they depend upon the PQDif standard as a way to obtain power quality data independent of the vendor and device generating it. This results in a kind of "store and forward" process: power quality data is captured and stored on the device, and then periodically bundled into a PQDif file and sent to the database software.

OPQ Cloud, on the other hand, is designed only to support the capabilities of OPQ Boxes. OPQ Boxes, furthermore, have no "stand-alone" capability; they maintain continuous connection to the Internet and upload power quality data to cloud-based services as needed. This means that OPQ implements a very different approach to representing and transmitting data than PQDif. For details on the representation, see the OPQ Data Model, and for details on communication, see the OPQ Protobuf protocol.

Note that it would be straightforward to develop an export function in OPQ Cloud to provide power quality data in PQDif format, but that functionality is not currently available.

3.3. Research systems

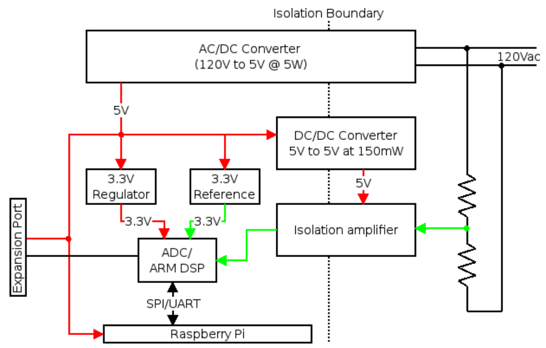
Di Manno et al [13] describes a PQ monitoring system called PiKu. Unlike OPQ, PiKu is designed as a hardware device for sensing power quality that is directly integrated into a PC. Systems with similar architectures include TRANSIENTMETER, described in Da Ponte et al [14], BK-ELCOM, described in Bilik et al [15], and a system described in Xu et al [16].

There are also research projects based upon leveraging existing monitoring infrastructure. Suslov et al [17] describes a distributed power quality monitoring system based upon existing phasor measurement units installed by utilities. Sayied et al [18] describes a system designed using existing smart meters. Kucuk et al [19] describes a similar system for the Turkish National Grid using utility grid monitoring infrastructure.

The research system most similar to OPQ is FNET, which is described in a recent publication by Liu et al [20]. Like OPQ, the FNET system consists of custom hardware that monitors the electrical signal from a wall outlet, and uploads data to the cloud for further processing. Unlike OPQ, FNET is designed for monitoring of frequency disturbances, how they propagate across wide area (i.e. nation-wide) utility grids, and, if possible, where the frequency disturbance originated. This means that FNET devices must be synchronized using GPS, and that the data collected consists of frequency and voltage angle. OPQ is designed for more "local" grid analysis, and we are not interested in propagation. As a result, OPQ Boxes are synchronized using NTP rather than GPS, which reduces cost and simplifies installation (OPQ Boxes do not need line of site to a GPS satellite). Finally, FNET hardware appears to support only "one way" communication from device to the cloud, while OPQ Boxes support "two way" communication (from box to cloud, and from cloud to box).

4. OPQ Box

OPQ Box is a hardware device designed to provide inexpensive, extensible and accurate residential power quality measurements. A block diagram of OPQ Box is shown in Figure 2a. A complete device is shown in Figure 2b.



(a) OPQ Box Block Diagram. The power path is in red, signal path is in green and the digital IO is in black.

(b) OPQ Box in an ABS plastic enclosure.

Figure 2. (a) OPQ Box block diagram and (b) production OPQ Box ready for deployment

4.1. Hardware

The power system of the OPQ Box electrically isolates most of the device from the AC mains power. An isolated AC-DC converter generates $5V_{dc}$ from the mains $120V_{ac}$. 5V is used to power the Raspberry Pi, the equipment connected to the expansion port, the 3.3V regulators and voltage reference and an isolated DC/DC converter. 3.3V is used to power the isolated end of the isolation amplifier as well as the STM32F3 analog to digital converter/digital signal processor (ADC/DSP). The hot side of the isolation amplifier is powered from the isolated DC/DC converter. This allows OPQ Box to function with a battery attached to the expansion port, so that it may retain data and continue to operate during a power outage.

The analog signal path of the OPQ Box is complicated by the fact that the STM32F3 ADC/DSP is electrically isolated from the mains power. A previous iteration of the OPQ Box overcame this by employing a small circuit board mount isolation transformer. Unfortunately it was found that the frequency response of these transformers varied wildly between individuals, thus incurring a lengthy calibration process for each device. The current OPQ Box design solved this issue by using an AMC1100 isolation amplifier as the isolation component. Internally, the AMC1100 consists of a single die comprised of a $\Sigma\Delta$ analog to digital and digital to analog converters. These converters are separated by a silicon glass region on the integrated circuit which acts as a coupling capacitor. Since the signal passes the isolation boundary as a $\Sigma\Delta$ encoded digital signal, it incurs no distortion and no additional calibration is required. In order to match the dynamic range of the AMC1100, the $120V_{ac}$ is passed through the resistor divider to attenuate it to $120mV_{ac}$. The input and output of the isolation amplifier is filtered with a passive first order anti-aliasing filter. The isolated signal is then digitized via a 16bit ADC of the STM32F3 DSP at $12KSps$, which gives 200 data samples per grid cycle. Internally, the digitization process runs asynchronously with respect to the DSP CPU, in order to minimize timing jitter. We verified that the sampling jitter of the ADC is less than 1us, however, due to the limited precision of our equipment, an exact figure was not established. The data stream in its digital form is transferred to the Raspberry Pi single board computer (SBC) for analysis.

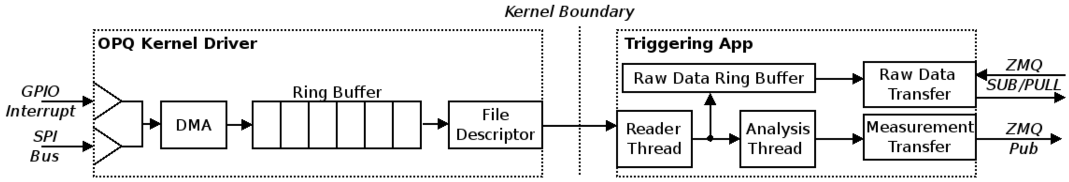


Figure 3. Block diagram of the OPQ Box 2 software stack.

A Raspberry Pi single board computer (SBC) is responsible for signal analysis and anomaly detection. The Raspberry Pi model used in OPQ Box is the Pi Zero W equipped with 256MB of main memory and a single core 1GHz ARM11 CPU. It also contains an on-board 802.11n WIFI transceiver, which removes the need for an external WIFI dongle.

4.2. Software

The software stack of the Raspberry Pi aims to deliver an accurate and precise power quality analysis framework despite the rather limited capabilities of the hardware. A block diagram of the software stack is shown in Figure 3. Digital data is transferred from the DSP to the Raspberry Pi via Serial Peripheral Interface, with the Pi acting as the master and the DSP as a slave device. A hardware interrupt line is used to inform Pi software that the DSP is ready for the data transfer, and a kernel driver provides management of the SPI bus. Internally, the OPQ driver maintains a ring buffer of 16 windows, each of which is 200 data samples in size. Upon receiving the interrupt for the DSP, the CPU sets up the DMA transfer and the DMA engine transfers a 200 sample window into the kernel memory without CPU interaction. This scheme requires the CPU to only service 60 interrupts a second, with each interrupt requiring on the order of 100 instructions, for a CPU utilization of less than 1% in normal operation. Userland applications communicate with the kernel driver using a file descriptor, where every *read* system call yields 200 samples of raw waveform. As a result, the smallest window that a userland application may process is a single AC cycle of the grid mains.

The userland component of the OPQ Box software is a multi-threaded extensible analysis framework called Triggering. The reader thread is responsible for transferring and accumulating data from the kernel driver. The smallest data buffer that the Triggering application processes at any given time is 10 grid cycles or 2k samples. Once the cycles are transferred to the userland and timestamped, they are passed to the analysis thread for feature extraction, as well as to the Raw Data Ring Buffer (RDRB). Since internally all data is addressed using shared pointers, during data duplication no copying is required. RDRS is capable of buffering up to an hour of data before it is overwritten, resulting in the RDBS maximum size of 100MB.

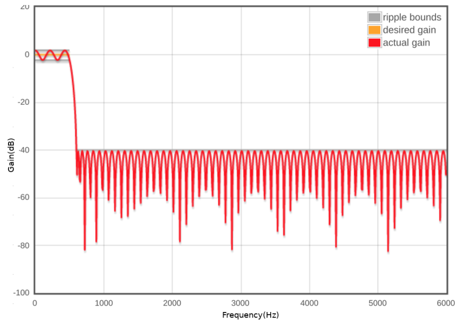
The analysis thread of the Triggering application performs feature extraction of the raw data windows of 2000 samples. Four metrics are extracted from the data stream: (1) Fundamental frequency, (2) RMS Voltage, (3) Total Harmonic Distortion, and (4) Transients. Let's briefly discuss how each of these are computed.

4.2.1. Fundamental Frequency

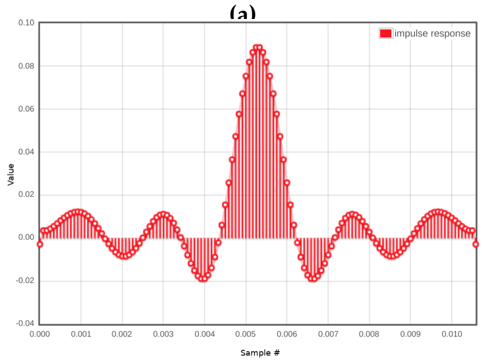
The fundamental frequency is calculated by computing the zero crossings of the AC waveform. Since a sinusoid has two zero crossings for a full cycle, the frequency can be calculated as:

$$f = \frac{1}{\frac{2}{n}\sum\limits_{k=0}^{k=n} \Delta t_k} \tag{1}$$

Where the Δt_k is the k'th time between two adjacent zero crossings.



(a)



(b)

In order to improve the accuracy of the frequency calculation one must first filter out as much noise as possible. Since our sampling rate is quite high (12kSps) and the fundamental frequency is quite low (60Hz), it is very computationally expensive to perform this filtering in a single step. Instead, filtering is accomplished via a set of two finite impulse response (FIR) filters shown in Figure 4b and 4d. First, the Down sampling filter is applied to the raw waveform, which results in the frequency response shown in Figure 4a. As is evident by the plot, the frequency content of the result is 0-600Hz, Thus, it can be downsampled to the $\frac{N}{10}$, or 200 samples without aliasing.

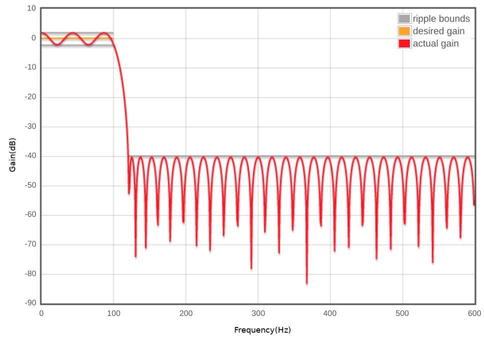
Next, the low pass filter is applied to the downsampled waveform with the frequency response shown in Figure 4c.This resulting frequency content is 0-100Hz, thus all of the higher frequency harmonics and noise are removed.

Finally, the twice filtered downsampled waveform is used to estimate the fundamental frequency according to the Equation 1. The zero crossings themselves were calculated by using linear interpolation between two points which bracket the time axis.

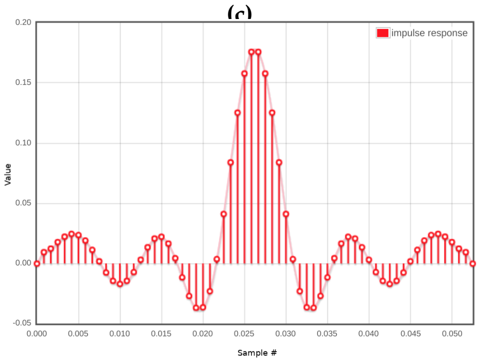
4.2.2. Root Mean Square Voltage

Root mean square voltage (V_{rms}) in electrical power is the equivalent value of DC voltage which would dissipate the same power in the resistive load. V_{rms} is a convenient measure for detecting voltage sags and swells, since they result in nominally higher and lower computed value. For a sinusoidal signal, V_{rms} can be calculated from the peak to peak value (V_{pp}) as:

$$V_{rms} = \frac{V_{pp}}{2\sqrt{2}} \tag{2}$$



(c)



(d)

Figure 4. Filters used for mains frequency calculation. (a) Downsampling filter gain. (b) Downsampling filter impulse response. (c) Lowpass filter gain. (d) Lowpass filter impulse response.

It is common for multimeters to employ the equation above for computing V_{rms}. However, this equation is only valid for a perfect sinusoid, and thus does not result in a suitable metric for identifying power quality disturbances. Instead, OPQ Box computes V_{rms} as follows:

$$V_{rms} = \sqrt{\frac{1}{n}\sum_{k=0}^{k=n} V_k^2} \tag{3}$$

Similarly to the frequency calculation, OPQ Box uses a 10 cycle window for a single V_{rms} calculation, however unlike the frequency calculation the input is not filtered a priori.

An example of a power quality disturbance which exhibits low V_{rms} is shown in Figure 5a and 5b. These disturbances are the result of a lighting strike recorded by two OPQ Box devices on Nov 1, 2017.

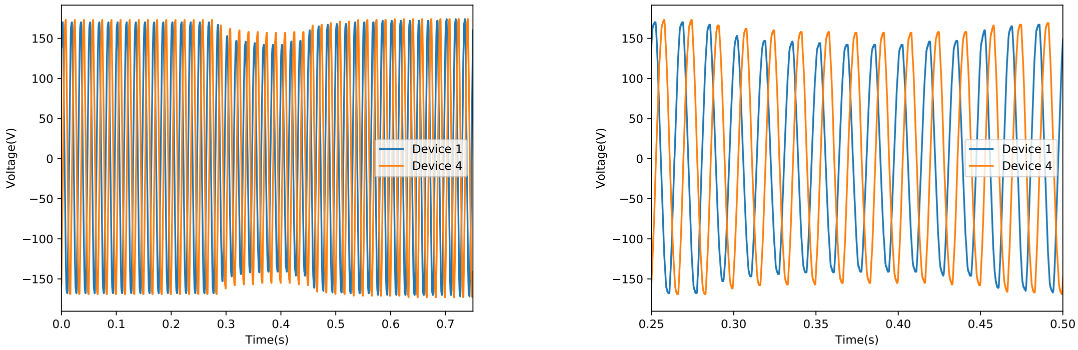
4.2.3. Total Harmonic Distortion

The OPQ Box calculates total harmonic distortion (THD) using the industry standard methodology. In the power delivery industry, THD is defined as:

$$THD = \frac{\sqrt{\sum V_n^2}}{V_f} * 100\% \tag{4}$$

Where V_f is the fundamental 60Hz power and V_n is the power at n^{th} harmonic.

It should be noted that in the power quality domain THD is expressed as a percentage as opposed to $\frac{dB}{\sqrt{Hz}}$ as used in other disciplines. Operationally, OPQ Box computes THD for 10 cycles of the fundamental frequency. First an FFT transforms the real voltage samples into its frequency components. Next, the square of the harmonic bins is accumulated and scaled by the magnitude of the fundamental power.



(a) **(b)**

Figure 5. A lightning strike recorded by two OPQ Box 2 devices separated by 10 miles. (a) A lightning strike manifested as a V_{rms} dip which lasted 11 cycles. (b) As a consequence of using NTP these devices have a $\frac{1}{2}$ cycle mismatch in reported timestamps.

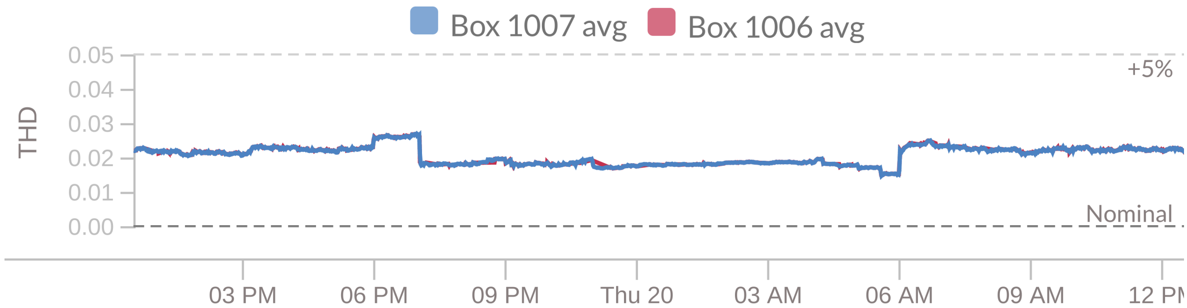


Figure 6. A common THD trend across two OPQ Box devices deployed in two buildings on the University of Hawaii campus.

Figure 6 shows a common trend observed by OPQ Box devices installed on the UH campus. For clarity, only two devices are shown. It is assumed that the large drop observed daily from approximately 6pm to 6am corresponds to the automatic response of the power delivery system to the reactive power in the grid, by deploying a large capacitor bank to compensate for the current phase lag.

4.2.4. Transient Detection

OPQ Box transient detection is performed via filtering out of the fundamental frequency via an FIR high pass pass filter and searching for a maximum value in the remainder. The high pass filter has a cutoff of $400Hz$, and the filter coefficients and response are shown in Figure 7b and Figure 7a respectively. The result of the high pass filter operation is shown in Figure 7. Figure 7c shows a synthetic signal generated via a SDG1025 signal generator and fed into the OPQ Box. This signal contains a $5V_{pp}$ transient injected at 11ms. The filtered signal is shown in Figure 7d, with the fundamental removed and the transient preserved. OPQ Box scans for the highest sample in the filtered waveform and uses its magnitude as a transient detection metric.

It should be noted that this transient detection method is susceptible to THD fluctuations, since any harmonic above $400Hz$ will remain in the filtered waveform. However, since the THD information is transmitted along with the transient detection metric, they can be correlated in downstream transient detection. This effect can be seen in Figure 8. This figure shows both the THD and transient detection metric during a transient event. A small transient of approximately 1.6V was observed occurring at 2600s, while the sensitivity of the transient metric is clearly visible, particularly between 3000s and 4500s.

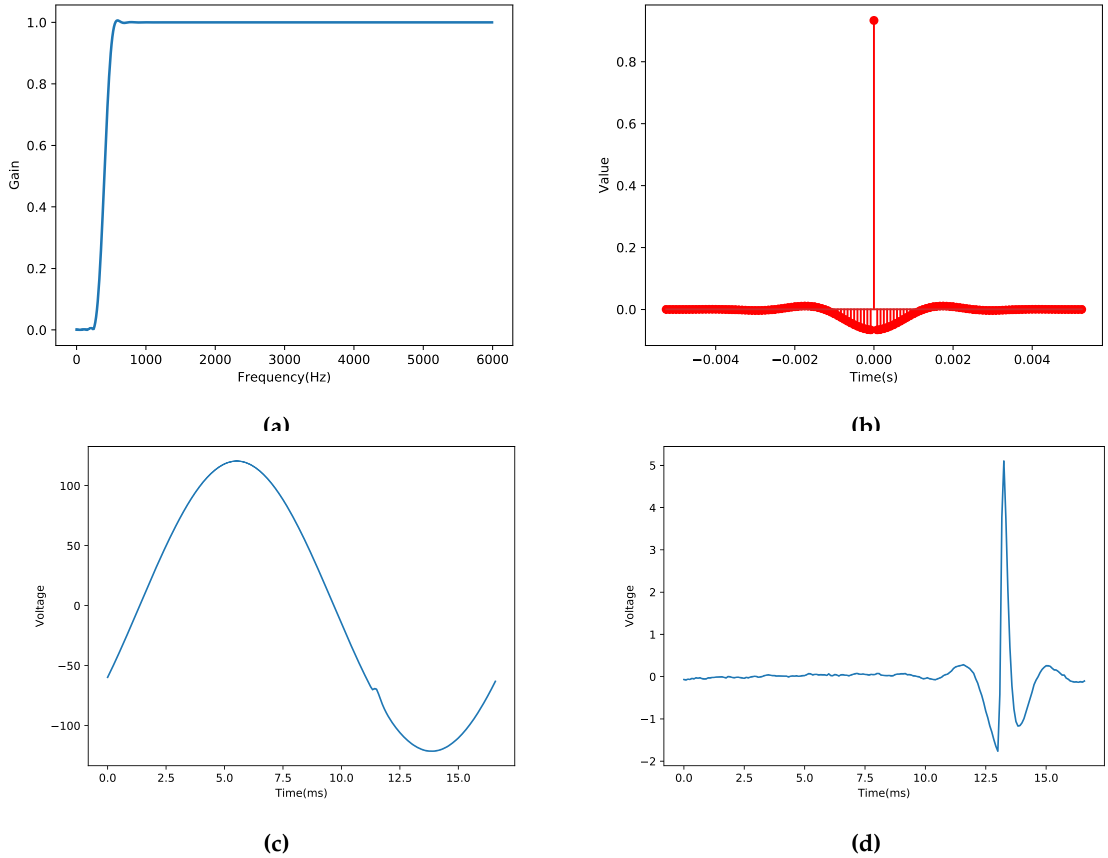


Figure 7. THD detection filtering. (a) Filter gain. (b) Filter response. (c) A 5V transient superimposed onto a fundamental. (d) Filter result from (c).

4.2.5. Network Communication

The computed fundamental frequency and V_{rms} are transmitted to the Makai service for aggregation. Data transmission is handled using ZeroMq software stack with Curve25519 elliptic curve encryption. Each device holds a unique private and public key, as well as the servers' public key, allowing both the Makai service and the OPQ Box to verify its peer. Internally, metrics transmission uses ZeroMq's PUB/SUB protocol. This protocol is a publish subscribe topology, with each message containing the topic, and a payload. Additionally, ZeroMq allows for multiple sub peers with subscriptions forwarded to the publisher automatically via a side channel. This allows for the aggregation service to be spread across multiple nodes, with minimal network overhead.

If the aggregation service determines that an anomaly has occurred, it is able to request raw waveform from the OPQ Box RDRB via a separate ZeroMq pub sub channel. If the RDRB buffer contains data for the requested temporal range, OPQ Box transmits the available data to the aggregation service via a push pull ZeroMq channel. Protobuf message serialization is used to encode messages across the OPQ ecosystem.

In order to make a distributed measurement, all of the OPQ Boxes on the OPQ network need to maintain an accurate time reference. Time synchronization across multiple OPQ Boxes is accomplished using the Network Time Protocol. The expansion port of the OPQ Box supports a GPS receiver. However, since GPS receivers require line of sight to the sky, it was not used for deployment. NTP performance has been verified against GPS resulting in time error of $8ms \pm 5ms$ which is typical for NTP running over the Internet with a close by NTP server. This error is visualized in a Figure 5b. With a large coincidental V_{pp} drop across two devices, a 7ms phase error is clearly visible.

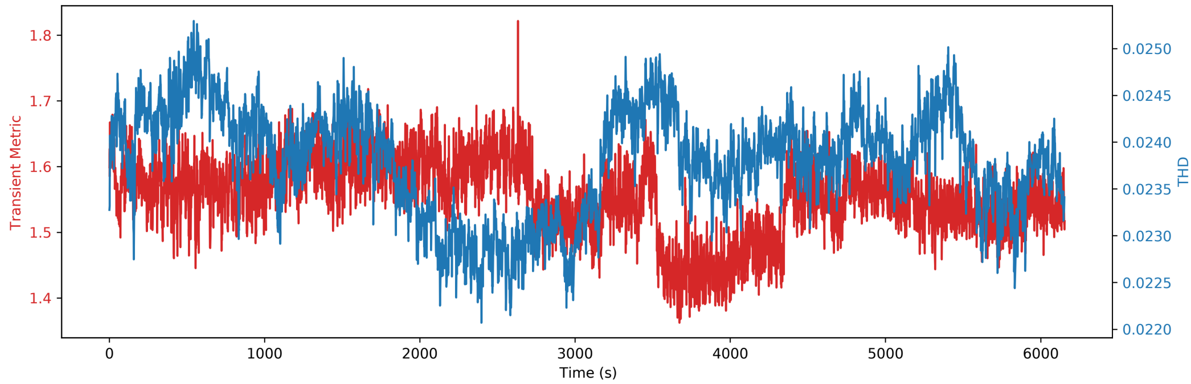


Figure 8. THD and Transient detection metric.

4.2.6. Manufacturing

Currently, there is no mechanism for mass production of OPQ Boxes, but all of the plans are available under an Open Source license, so interested organizations with some basic hardware engineering skills can build their own boxes.

Complete specifications for the OPQ Box hardware, firmware, and software are available [21]. As of the time of writing, a single OPQ Box can be manufactured for approximately $100 in parts. The cost drops significantly with scale, for example, 100 OPQ Boxes can be manufactured for a cost of approximately $75 in parts.

5. OPQ Makai

5.1. Overview

OPQ Box provides an inexpensive hardware device for collecting four important power quality measures with high fidelity, but realizing its potential requires an innovative approach involving two-way communication between OPQ Boxes and the OPQ cloud-based services. To see why, consider the IEEE 1159 standard for single location power quality monitoring [22]. For transient monitoring, IEEE 1159 suggests a sampling rate of at least 7680 samples/second, up to 1 Megasample/second. This implies that if the cloud service requires the high fidelity data from all OPQ Boxes, it would incur a very large bandwidth cost. At 20 Ksamples/second with 16bit samples, a single OPQ Box will generate 300Kb/second of network bandwidth. Several thousand devices would easily saturate a 1 GB network link. In addition, collecting and recording all of the raw waveform data from residential power quality meters could lead to security and privacy issues.

Network bandwidth saturation is a common problem for distributed sensor networks, and a common solution is called "self-triggering". In this approach, each monitoring device is configured with a threshold value for one or more measures of interest. When the threshold for a measure of interest is exceeded, then and only then is data sent over the network to cloud-based services for analysis.

The problem with the self-triggering approach is that grid-wide power quality events do not affect the entire grid in the same way. For example, due to the grid's hierarchical structure, a voltage sag on one sub-circuit can manifest as as a sag of a different magnitude or even a swell on another [23]. This may result in a situation where some of the monitoring devices will not consider a power quality anomaly as an event, because it did not surpass the metric threshold, and simply ignore it. From an analysis perspective, however, it can be useful to get raw data from all of the affected devices, not just the ones that were the affected to the point where the box was triggered. This additional information can be used to localize the disturbance, as well as better evaluate its impact.

Since sending all the data is infeasible, and since the self-triggering approach can potentially miss important forms of information, OPQ implements a novel, hybrid centralized/decentralized data acquisition scheme which involves two-way communication between the OPQ Boxes and a cloud service called OPQ Makai. In this scheme, OPQ Boxes use local processing resources to feature extract the incoming waveforms while storing them locally for an hour. Each OPQ Box sends its feature data to OPQ Makai once a second, which we called the "triggering stream". Feature data is very small, on the order of a few kilobytes, and so this approach allows the sensor network to scale to thousands of devices with acceptable network bandwidth requirements. OPQ Makai processes the incoming triggering stream and looks for anomalies. If an anomaly is present in only a single device, it is highly probable that the cause is local and not grid-level. On the other hand, if the triggering stream shows an anomaly temporally collocated across multiple devices, the entire network or a subset of the network may be queried for raw waveform data for a temporal region which corresponds to the disturbance in the triggering stream.

Our pilot study, discussed in Section 8 will provide examples of the novel analysis capabilities made possible by OPQ Box and OPQ Makai communication. In general, here are the main advantages of our hybrid centralized/decentralized approach over traditional self-triggering and the "naive" approach of sending all of the data:

Bandwidth usage is minimized. Instead of sending the entirety of raw data, only extracted features are sent. This results in a tiny fraction of the bandwidth requirement when compared to raw waveforms. Furthermore, the temporal window which encompasses a single feature can be adjusted in real time. Thus as soon as an anomalous behavior is observed in a subset of sensors, this window can be adjusted for a finer grained feature extraction.

Effects of latency are minimized. In this case, "latency" refers to the time required for OPQ Makai to process the incoming feature stream and decide whether or not to request high fidelity data from one or more OPQ Boxes. Even at 1M samples/second at 16 bits of resolution, the memory requirement to store 5 minutes of raw waveform without compression are on the order of 512MB, which is well within the realm of inexpensive single board computers such as Raspberry PI. With compression specifically suited to the signal of interest, the memory requirement can be reduced even further. In the case of the OPQ sensor network, OPQ Makai has an hour to process feature data and request high fidelity data from OPQ Boxes. During our pilot study, OPQ Makai always responded within a second or two, although the sensor network was very small with only 15 OPQ Boxes.

Cloud processing requirements are reduced. Since feature extraction is already performed at the device level, cloud computation requirements are reduced. With the advent of the Internet of Things, the computational capacity of edge devices is increasing.

Subthreshold data acquisition can improve understanding of grid-local anomalies. OPQ Makai makes the decision to acquire raw waveform from OPQ Boxes. This allows analysis of data from devices which were only mildly affected or even not affected at all by the disturbance. This creates new possibilities for investigation of disturbance propagation across the sensed area, as will be discussed in Section 8.

Temporal locality allows OPQ to provide improved insights into power quality anomalies over traditional triggering algorithms. By exploiting the idea of temporal locality, it is possible to ascertain the geographical extent of an anomaly with only coarse features. This allows for a simple robust algorithm which may be deployed at the sink node for anomaly detection.

5.2. Design

OPQ Makai is a distributed extensible microservice framework responsible for receiving the triggering stream from the OPQ Boxes, locating anomalous temporal regions and requesting raw waveform for the anomalous time ranges. As shown in Figure 9, Makai consists of four major components: Acquisition Broker, Triggering Broker, Event Service and the Acquisition Service.

The Triggering Broker is perhaps the simplest component of the OPQ Makai system. The triggering stream generated by the OPQ Boxes is encrypted to preserve user privacy. In order to

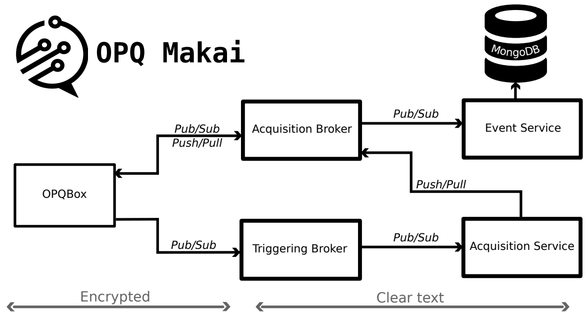


Figure 9. Makai component design

minimize the CPU time spent decrypting the data across multiple OPQ services, the Triggering Broker decrypts the data and sends clear text measurements to other OPQ cloud services. The Triggering Broker uses the ZeroMq subscribe socket to receive data from OPQ Boxes, and sends it via a publish socket to any connected client. Each publish message is published to a topic which corresponds to the ASCII representation of the originating OPQ Box ID. This allows services which utilize the Triggering Broker to select a subset of IDs to operate on. This is useful for load balancing the backend services, or dividing the OPQ network into separate regions with no electrical connections between them.

The Acquisition Broker manages the two-way communication between the OPQ Boxes and the rest of the cloud infrastructure. Unlike the triggering stream which originates from the OPQ Box, two way communication is always initiated by OPQ cloud services. Two way communication is realized via a command response interface, where the OPQ service initiates the communication by sending a clear text command to the Acquisition Broker, which then forwards it in encrypted form to the appropriate OPQ Boxes.

The Acquisition Service resides between the Triggering and Acquisition Brokers. The Acquisition Service is responsible for three tasks: (1) Computation of statistics of the incoming triggering stream; (2) Hosting plugins for triggering stream analysis; and (3) Generating data event requests for OPQ Boxes. The Acquisition Service accesses the triggering stream by connecting to the publish socket of the Triggering broker. Since the connection is managed through the ZeroMq publish-subscribe socket, several Acquisition Services can be connected to a single Triggering broker endpoint, each servicing a subset of OPQ Boxes by subscribing to only specific devices. The Acquisition Service does not include any analysis capabilities by default. Instead, analysis is performed by shared library loadable plugins. These plugins can be loaded and unloaded at runtime, thus allowing live upgrading and testing of new analysis methods.

The Event service is a microservice which stores raw data generated by OPQ Boxes in the MongoDB Database. On initialization, the Event service queries MongoDB database for the highest event number recorded so far, connects to the Acquisition Broker's publish port, and subscribes to all messages that start with the prefix "data". This allows the Event service to capture every response from OPQ Boxes generated from commands issued by the Acquisition service plugins. Once the Event service receives a data response with an identity containing an event token it hasn't seen before, it will increment the event number, and store it in an internal key value store.

6. OPQ Mauka

The previous sections discussed the design of OPQ Box, a custom hardware device for collecting four important measures of power quality, and OPQ Makai, a novel, hybrid centralized/decentralized data acquisition scheme which involves two-way communication between the OPQ Boxes. As a result of these two innovations, an OPQ sensor network has the ability to collect and analyze high fidelity, low level data about power quality anomalies in a cost-effective, scalable fashion.

There are remaining challenges to creating a useful power quality sensor network. First, the data provided by OPQ Boxes is low-level, "primitive" data consisting of either features (i.e. frequency,

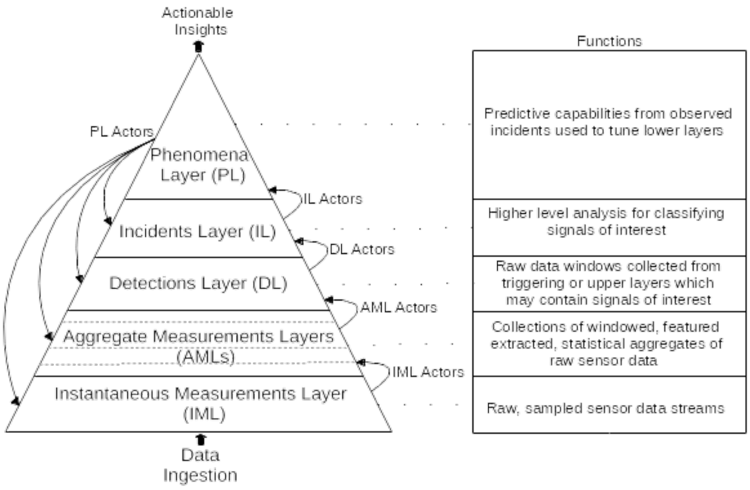


Figure 10. Mauka data model hierarchy

voltage, THD, and transients) or waveform data. But what we actually want is actionable insights into grid stability. For example, we might want to know if a given anomalous data value is actually detrimental, or we might wnat to be able to predict when a power quality event might occur in the future based upon the recognition of cyclical events in the historical data.

A second challenge involves the potentially high volume of data might accumulate in the cloud. Although OPQ Box and OPQ Makai provide a scalable mechanism for communicating power quality data to the cloud services, it is still the case that, over time, a substantial amount of data could accumulate. One strategy is to simply store all of the data sent to the cloud forever. This means that data storage requirements will increase monotonically over time, making the sensor network more costly to maintain the longer it is in place. An alternative strategy is to implement an algorithm to identify uninteresting (or no longer interesting) data and discard it. Ideally, such an algorithm would enable OPQ sensor network designers to calculate an upper bound on the total amount of cloud storage required as a function of the number of nodes (OPQ Boxes) in the network.

OPQ Mauka addresses both of these issues. First, OPQ Mauka provides a multi-leveled representation for structuring and processing DSN data. The structure and processing at each level is designed with the explicit goal of turning low-level data into actionable insights. Second, each level in the framework implements a "time-to-live" (TTL) strategy for data within the level. This strategy states that data must either progress upwards through the levels towards more abstract, useful representations within a fixed time window, or be discarded and lost forever. The TTL strategy is useful because when implemented, it allows DSN designers to make reasonable predictions of the upper bounds on data storage at each level of the framework, and making possible a "graceful degradation" of network performance if those bounds turn out to be exceeded.

Figure 10 illustrates the hierarchical data model for OPQ Mauka. This data model can be conceptualized as a multi-level hierarchy that adaptively optimizes data storage using a tiered TTL approach and provides a mechanism in which typed aggregated data is continually refined to the point of being of becoming actionable. The data model also includes software components called "actors" that both move data upward through the levels and apply optimizations downward through the levels. Actors are implemented through a plugin architecture, making it easy to experiment with the data model and improve it over time.

Anthony: Please review the following paragraphs for accuracy and quality.

In essence, the raw data sent to the cloud from OPQ Boxes is initially stored in the Instantaneous Measurements Layer (IML). IML Actors process this data to determine if additional data from OPQ Boxes are warranted, and request this data if necessary. This data, along with the instantaneous data, is then stored at the Aggregate Measurement Layer (AML). All data from the IML layer is discarded after one hour if it is not found to be interesting and thus promoted to the AML level. Once at the AML Layer, AML actors process the augmented data sets to determine if they constitute an actual power quality anomaly, and if multiple OPQ Boxes appear to be implicated in the anomaly. If so, all of the associated AML data is promoted to the Incident Layer (IL). AML data must be promoted within one day or else it is discarded. Finally, IL Actors are responsible for looking for ways to make Incidents actionable, and if successful, will promote the IL data to the Phenomena Layer (PL). For example, if the same boxes are generating the same Incidents on a periodic basis, then these Incidents could be promoted to a Phenomena that can predict when the next occurrence of this Incident might occur.

While IML, AML, DL, and IL Actors all promote data upward, the Phenomena Actor actually works in the opposite direction, using its knowledge to configure lower levels. For example, if a periodic Phenomena has been created, then a PL Actor might alter the behavior at the AML, gathering more raw data from Boxes around the time of the next predicted Incident.

6.1. OPQ Mauka Actors

The current capabilities of OPQ Mauka can be summarized in terms of its Actors, which are implemented as plugins.

BasePlugin. All Actor plugins derive from the BasePlugin, which provides primitives for running plugins as separate processes, serialization and deserialization of type safe messages, communication over ZeroMQ, metrics collection, MongoDB communication, debugging, and plugin health.

MakaiEventPlugin. The MakaiEventPlugin Actor is responsible for reading Events newly created by OPQ Makai into OPQ Mauka. It performs feature extraction on the raw Event data streams and forwards those features (or the raw data) to subscribing plugins. This allows OPQ Mauka to perform feature extraction once, and reuse those features in multiple plugins.

FrequencyVariationPlugin. The FrequencyVariationPlugin is used to classify generic frequency sags, swells, and interruptions as defined by the IEEE 1159 standard. Both duration and deviation from nominal are used to perform these classifications. Duration classifications include frequency deviations that last for less than 50 ns, between 50 ns to 1 ms, and 1 ms to 50 ms. Classifications for deviations from nominal are performed for values that are up to 40% deviation from nominal. The plugin is able to classify frequency swells, frequency interruptions, and frequency sags. When a new frequency variation is detected, a frequency Incident is created.

IEEE1159VoltagePlugin. The IEEE1159VoltagePlugin is used to classify voltage Incidents in accordance with the IEEE 1159 standard[29]. In general, this standard classifies voltage disturbances by duration and by magnitude. Voltage durations are classified from 0.5 to 30 cycles, 30 cycles to 3 seconds, 3 seconds to a minute, and greater than 1 minute. Voltage deviations are classified in both the sag and swell directions as a percentage from nominal. Sags are generally classified between 10% and 90% of nominal while swells are generally classified from 110% to 180% of nominal. This plugin is capable of classifying voltage sags, swells, and interruptions as defined by the standard. The plugin works by identifying sags, swells, and interruptions and determining the duration of those Events. If the duration or delta is large enough, a voltage Incident is created.

BoxOptimizationPlugin. The BoxOptimizationPlugin is responsible for sending and receiving typed messages to and from OPQ Boxes from OPQ Mauka. This plugin is capable of requesting the state of each OPQ Box (e.g. uptime, Measurement rate, security keys, etc). This plugin is also capable of adjusting the state of individual OPQ Boxes by changing things such as the Measurement and Trend rate or the sampling rate that the Box is sampling at.

FuturePhenomenaPlugin. The FuturePhenomenaPlugin is responsible for creating Future or Predictive Phenomena. These Phenomena are used to predict Events and Incidents that may occur in the future. This plugin does not subscribe to any messages, but instead utilizes timers to perform its work. By default, this plugin runs every 10 minutes.

When the plugin runs, it loads any active Periodic Phenomena found in the database. If Periodic Phenomena are found, this plugin extrapolates possible Events and Incidents by first examining the timestamps of previous periods and then extrapolating into the future using the mean period and the standard deviation. For each timestamp in the periodic phenomena, the mean period is added. If the resulting timestamp is in the future, a Future Phenomena is created using the time range of the future timestamp plus or minus the standard deviation of the Periodic Phenomena.

When a Future Phenomena is created, timers are started in a separate thread signifying the start and end timestamps of the Future Phenomena. When the first timer runs, messages are sent to the BoxOptimizationPlugin and the ThresholdOptimizationPlugin instructing Event thresholds to be set lower and Box Measurement rates to be set higher. This increases the chance of seeing an Event over the predicted time window. When the second timer runs, these values are reset to their default values. Thus, the plugin increases fidelity and decreases thresholds over the period of a Future Phenomena.

ITICPlugin. The ITICPlugin analyzes Vrms to determine where it falls within the ITIC curve [24]. The ITIC curve is a power acceptability curve that plots time on the x-axis and Vrms on the y-axis. The purpose of the curve is to provide a tolerance envelope for single-phase 120V equipment. The curve defines three regions. The first region is "No Interruption" and generally includes all voltages with very short sustained durations. All events within this region have no noticeable effect on power equipment. The second region, the "No Damage Region", occurs during voltage sags for extended periods of time. Power Events in this region may cause equipment interruptions, but it will not damage the equipment. The final region, the "Prohibited" region, is caused by sustained voltage swells and may cause damage to power equipment. This plugin determines if an event falls within the "No Damage" or "Prohibited" regions and if so, creates an Incident to record this.

SemiF47Plugin. The SemiF47 plugin is another plugin like the IticPlugin that plots voltage and duration against a power acceptability curve. In this case, the standard used is the SemiF47 standard [25]. Rather than using a point-in-polygon approach, this plugin reads the VRMS features sequentially and uses a state machine to keep track of the current classification. This plugin only classifies values as a "violation" or as "nominal".

TransientPlugin.] The "TransientPlugin" is responsible for classifying frequency transients in power waveforms. The plugin subscribes to messages from the "RawVoltage" topic which contains a calibrated power waveform payload. The TransientPlugin is capable of classifying impulsive, arcing, oscillatory, and periodic notching transients. A decision tree is utilized to select the most likely transient type and then further analysis is used to perform the actual classification of transients. Dickens et al [26] provides more details on the transient classification system.

PeriodicityPlugin. *The "Periodicity Plugin" is responsible for detecting periodic signals in power data. This plugin does not subscribe to any messages, but instead runs off of a configurable timer. The plugin is set to run by default once an hour and every hour it scrapes the last 24 hours worth of data and attempts to find periods in the Measurements over that duration.*

For each feature in the Measurement and Trend data (e.g. frequency, voltage, and THD), the Periodicity plugin first removes the DC offset from the data by subtracting the mean. Next, the plugin filters the signal using a 4th order high-pass filter to filter out noise. The plugin then performs autocorrelation on the signal followed by finding the peaks of the autocorrelation. The mean distance between the peaks of the autocorrelation provides the period of the signal.

The plugin only classifies data as periodic if at least 3 peaks were found and the standard deviation of the period is less than 600 seconds (10 minutes). Once a positive identification has been made, peak detection is performed on the original signal. Once the plugin has the timestamps and deviations from nominal of the periodic signal of interest, the plugin can group Measurements, Trends, Events, and Incidents that were created during the periodic signals together as part of the Periodic Phenomena.

7. OPQ View

OPQ View.

8. Results from the Pilot Deployment

Pilot study.

9. Conclusions and Future Directions

Conclusions.

10. Misc. Literature Quotes

In February 2014 on the Big Island, the utility reports that 10% of its circuits hit unstable levels [1].

Photovoltaics affect power quality by introducing harmonics [27]. The power feed-in of PV generation in rural low-voltage grids can influence power quality (PQ) as well as facility operation and reliability [28].

Models, not actual installations [27,29–31]. Or data taken for only one week [32].

"across all business sectors, the U.S. economy is losing between $104 billion and $164 billion a year to outages and another $15 billion to $24 billion to PQ phenomena" [33] India lost more than $9.6 billion in 2008 due to power quality, and Europe lost $150 billion per year [34].

A study of the island of Porto Santo in Portugal found that intermittent nature of installed photovoltaic and wind energy could result in a potential drop in frequency of 12 Hz, lasting as long as 7 seconds [35].

Reduced input voltage can cause excessive power supply heat dissipation, resulting in reduced mean time between failures (MTBF). In addition, rectifiers and DC-to-DC converter switching transistors draw high-peak currents, which raise their junction temperatures. These temperature excursions take a toll on semiconductor longevity. High input voltage can also puncture a power supply's rectifier and switching transistor junctions, causing MTBF reduction and eventual breakdown. High-voltage transients lasting microseconds can permanently wreck the power supply and its electronic equipment load. [36].

Solar panels connected to low voltage networks will result in over-voltages, the switching frequency of the converters in wind turbines causes high-frequency signals flowing into the grid, and harmonics are generated by EV chargers. [37]

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