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 which must accomodate distributed, intermittent generation. This transition also means that the formerly sharp distinction between energy producers (i.e. utility companies) and consumers (residences, businesses, etc) are blurring: residences can now both produce and consume energy, making energy policy more complex. The Open Power Quality (OPQ) project began in 2013 with the goal of designing and implementing a low cost, distributed power quality sensor network in order to provide make useful information about electrical grids available to producers, consumers, and policy makers. Since then, we have designed low cost hardware devices that monitor power quality and low-cost cloud-based software services that can economically analyze the data and detect a variety of anomalies. 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.

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1. Introduction

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 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 public concern and interest. First, there is a global need to shift to renewable energy sources. Second, modern consumer electronics place more stringent demands on power quality. Third, effective policy making in this modern context requires better public access to power quality data.

We need more renewable energy. There is now 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 can be 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, in Hawaii on the island of Oahu, the public demand for rooftop solar exceeds Hawaiian Electric Company's ability to utilize it and maintain adequate power quality. As a result, in many neighborhoods, new rooftop solar installation is prohibited because Hawaiian Electric fears its impact on not only local power quality but global grid stability [**?**].

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.

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 required to make a "best effort" to provide non-harmful voltage and frequency values, but are only required to publicly report on power outages of more than 3 minutes. There is no requirement for utilities to report potentially harmful forms of voltage, frequency, THD, or transients. Indeed, in Hawaii, there is not yet infrastructure in place that would enable utilities to collect that information, even if they were asked to report on it. For more details, see Hawaiian Electric Tariff Rule No. 2 Character of Service and Hawaiian Electric Tariff Rule No. 16 Interruption of Service.

OPQ intends to provide an unbiased, independent, third party source of accurate power quality data. This can be used by consumers to better understand the performance of their public utilities, by researchers to devise improvements to grid control, and by public policy makers responsible for designing and implementing regulatory frameworks for electrical utilities. The OPQ Project has produced a suite of innovations that can help address each of these issues.

OPQ Box. First, our 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 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. Second, our architecture is "cloud native", which means that OPQ Boxes are not designed for "stand alone", autonomous use. 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 analyzed. This creates the ability to control individual OPQ Boxes based upon the global state of all OPQ Boxes. It means our 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.

Extensibility. Third, all OPQ software subsystems 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. We are also developing API endpoints for interoperation with other software systems. 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.
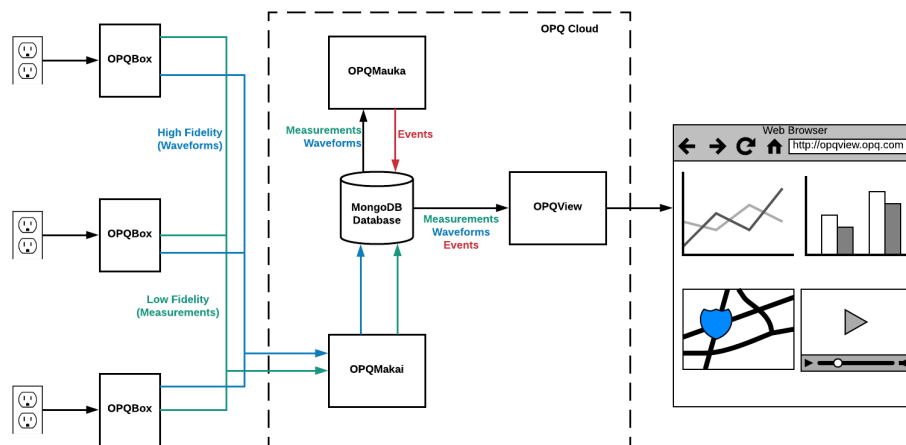
Figure 1. High level architecture of the OPQ System

Finally, while we believe OPQ offers a compelling combination of capabilities, we want to be clear that all 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 power monitoring may be most appropriate. Our goal in this paper is to describe OPQ well enough for organizations to make a thoughtful decision about the use of our technology.

2. System Architecture

At its most basic, the OPQ system architecture is extremely simple: 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.
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 data, creates "events" when it detects anomolies, and can tell OPQ Makai to request high fidelity data from one or more OPQ Boxes to facilitate analysis.
4. OPQ View is a 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 OPQMakai. 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.

3. 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. It is a five layer architecture in which data in the form of Measurements collected by an OPQ Box can eventually yield insights in the form of Phenomena. (The Incident and Phenomena levels are currently in development.)

Table 1 provides an overview of the five layers from lowest level (Box) to highest level (Phenomena). "TTL", to Time To Live, indicates how long entities at each level are stored before they are automatically deleted.

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	Approximately once a second, each box sends a Measurement to OPQ Cloud. Measurements provides "low fidelity" summary statistics regarding four power measurements (Frequency, Voltage, THD, Transients). Measurements give OPQ Cloud basic situational awareness of the grid without the overhead of transmitting and storing wave form data. Measurements exist for one day, though a daily roll-up of Measurement summary statistics called "Trends" persists much longer.
Event	1 month	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 written over in the Box.
Incident	6 months	Not every non-nominal power data value is significant, i.e. actually meaningful for gaining insight into the grid. Over the years, electrical engineers have 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.
Phenomena	1 year	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."