Open Power Quality Pilot Program

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Abstract

The face of power distribution has changed rapidly over the last several decades. Modern grids had to adapt to the distributed power generation, and highly variable loads. Furthermore as the devices we use every day become more electronically complex, they become increasingly more sensitive to power quality problems. A distributed power quality monitoring systems have been shown to provide real-time insight on the status of the power grid and even pinpoint the origin of the power disturbance. Island of Oahu presents a fantastic test bed for such a system. The small power grid combined with high penetration of distributed renewable energy generators create perfect conditions for a grid study. Over the last three months we have been collecting power quality data from several locations of the island as a pilot study for a larger deployment. This papers describes our methodology, hardware design and presents a preliminary analysis of the data we collected so far. Lastly this paper lays out the plan for the next iteration of deployment.

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1 Introduction

The face of a modern power grid has changed dramatically over the last few decades. A few centralized power generators, gave way to a composite architecture, where distributed renewable sources work in synergy with the municipal power plants. This trend is accelerating as the renewable energy generators, such as PV and wind turbine becomes cheaper and more efficient. Unfortunately renewable sources are not able to provide a consistent power output. This has an adverse effect on the grid stability as has been demonstrated by .....

Oahu power grid makes an ideal testbed for power monitoring study. Its a small isolated system with high penetration of renewable power generators. Furthermore Oahu power grid has been been slow to adjust to the distributed generation. New PV and wind generators now undergo careful scrutiny by the utility, in an attempts minimize the adverse effects on the grid. A grid study could evaluate quality of the power generated on the island, and attempt to correlate it to environmental factors could gain insight into the problems that the Oahu grid is facing.

Over thee last three months Open Power Quality group has been collecting V_{rms} and $f_{utility}$ data across three different locations as part of a pilot study for a larger scale deployment. This paper describes the prototype system, shows initial analysis of the collected data, and finally presents a roadmap for further deployment. First however, we must describe the metrics and background of power quality measurements.

1.1 Power grids and power quality

Modern power grid provide a fixed AC frequency at a set voltage. For United States this amounts to a $60Hz$, and $120V_{rms}$. A power quality on the voltage side is the measure of the frequency composition and RMS of the voltage across several grid cycle. An ontology of power quality events has been presented across several publications.... For the purpose of this study we focus on rudimentary metrics for power quality:

1. Voltage fluctuations(V_{rms}).
2. Utility frequency($f_{utility}$).

Root mean square of a voltage is a useful tool, for analyzing voltage time series. It is a measures the equivalent DC voltage for a time varying signal.

RMS Voltage in the discrete domain can be defined as:

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{0}^{n} V_n^2} \tag{1}$$

Variations in the RMS can lead to conditions known as sags/brownouts and swells. A voltage sag, is a 10%-80% drop in the power line voltage ranging in duration from half of a grid cycle to one minute. A brownout is a sag lasting longer then a minute.

Another useful metric for studying power quality is the utility frequency($f_{utility}$). Utility frequency is the fundamental frequency of AC power distribution. Small deviations from the norm can cause catastrophic results. Sufficient increase in utility frequency can cause the turbine generators to malfunction, while a drop in frequency can cause damage to grid connected electric motors. There are several methods of measuring the utility frequency from discrete voltage waveform. Phase Locked Loops can be employed to compare the utility frequency to a frequency of a stable oscillator, and extract the difference in real time. A Fourier transform may be used to transform the voltage signal to a frequency domain, where fitting of the maxima, can be used to extract the fundamental frequency. Finally the waveform can be fitted to a sinusoid to extract the phase, amplitude, and utility frequency.

1.2 Measuring Grid Health on a Residential Scale

Utility companies monitor the state of the grid they service down to the substation level. This means that they generally have no situational awareness of power quality at the level of homes and businesses. Furthermore do not report any information on power quality of their grid. The lowest granularity event they are required to disclose is a power outage lasting longer then 3 minutes. In order to gain insight into the health of the power grid at the residential level, a distributed real-time power quality monitoring system needs to be developed. Such a system would monitor the line voltage and frequency bellow the substation level and combine this data to produce a meaningful picture of the grid health. In order for a power quality monitoring system to be useful it must fulfill several criteria:

- **Synchronization.** Temporal synchronization is required to separate individual events from single widespread one. Generally synchronization down to a single grid cycle, ie 8ms is adequate. In the case if a power quality event occurs in several location during the same grid cycle, can be attributed to the same source.

- **Availability.** Power grids operate without interruption, and so must the monitoring system. Furthermore most applications, beyond academic ones, require live grid status. This implies that each monitoring device must be able to transmit the power quality data in real-time.

- **Filtering.** In order to measure the power quality on the hardware level, one must sample the waveform of the voltage across the mains, and neutral terminals. High end commercial systems for example sample 256 data point for every grid cycle, using 16bit resolution. This results in the raw data rate of 400kb/s. Given that an residential cable subscription provides upload speeds the order of 1Mbps, this will substantially degrade the quality of their Internet service. Furthermore just 100 devices would produce the aggregate bandwidth of 400Mbps. This limits the scalability of such a system. Finally most of the data generated by the power quality monitors would not be interesting, since it would show healthy grid operation. In order to overcome these problems, voltage waveforms must be processed on the power quality meter. This way interesting events such as transients can be sent over to the operator in their raw state state. The rest of the data can be reduced to a few fundamental values, such as $f_{utility}$ and V_{rms} over a sliding window greatly reducing the required bandwidth.

- **Dencity.** Ideally a power quality monitoring system would have several meters for every group of consumer connected to a distinct substation. This is because at the consumer level power quality can be affected by a multitude of factors unrelated to the grid health. For example we demonstrated that a heating coil, such as a water heater or even an electric kettle, can cause a voltage sag while powered. On the other hand large inductive loads, such as air conditioners can cause a large transient due to the inrush currents of the electromagnet. By having several units connected under the same substation it is possible to filter the noise generated by the regular activities of a consumer, and evaluate the grid status instead.

Devices used to measure power quality, aka power quality meters, are ubiquitous. Unfortunately they generally fall into two distinct categories:

- Professional grade such as National Instruments®862001. These devices are generally used by the utility companies, and power engineers. They combine high accuracy measurement electronics, with fast digital signal processors in order to provide detection and classification of power quality events, and real time grid status.These devices allow for unparalleled connectivity from WIFI, to CAN bus, and power line communications. Unfortunately the cost of these meters prohibits their use in a distributed grid study where several dozen, or even hundreds of devices are required.

- Consumer grade such as AC Scout®. These devices are simple voltage line monitors. They provide adequate power quality measurements to give home-owners insight into the state of their electrical wiring and the health of the grid as a whole. Unfortunately these devices leave much to be desired when it comes to connectivity. Generally they use offer no connectivity beyond external storage. This makes them unattractive for a distributed real-time monitoring systems.

2 OPQ Cloud: cloud based power quality monitoring network.

Over thee last three months Open Power Quality group has been collecting V_{rms} and $f_{utility}$ data across three different locations as part of a pilot study for a larger scale deployment. We developed an in-house prototype power quality meter(OPQBox) with wifi/ethernet connectivity, cheap enought for widescale deployment. Furthermore we developed a cloud based aggregation system(OPQHUB), capable of displaying grid status in real time.

2.1 OPQBox: Prototype Power Quality Monitor.

OPQBox is an in-house developed power quality monitor, specifically designed for distributed use. It is capable of continuous 4Ksps 16Bit measurement of the line voltage, along with on-board filtering and processing. The block diagram for this device is shown below:

At the heart of the device is the MSP430AFE integrated circuit by Texas Instruments ®. This innovative device combines a 24bit $\Sigma\Delta$ analog to digital converter(ADC), along with an MSP430 CPU core. MSP430 cpu core controls the hard real-time acquisition tasks, however with the peak of 8 MIPS, 512 bytes of RAM and no floating point unit, this device is not capable to analyze the data it is gathering on its own. The soft real-time analysis is performed on a raspberry PI single board computer(SBC). Raspberry Pi is readily available SBC based on an 800Mhz ARM11 SOC by broadcom. It features a high variety of digital peripherals, fast CPU with FPU and 512MB of memory. Furthermore this SBC is well supported

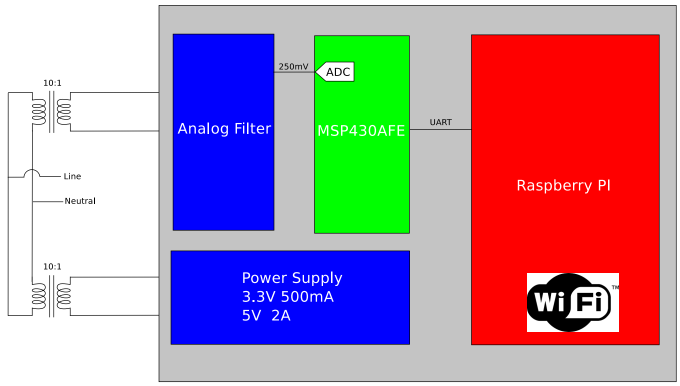

Figure 1: OPQBox Block Diagram

by the Linux kernel and userland, with most drivers being open source and highly stable. The SBC reads and accumulates the ADC values generated by the MSP430 via a serial link. Once 4000 samples, or 1 second worth of data have been gathered SBC performs rudimentary analysis and send interesting events, and overall statistics to the cloud via WIFI. Synchronization between devices is accomplished via disciplining the local clock with NTP.

2.2 Acquisition design.

In order to measure the line voltage, it must first be scaled down to the ADC input range. This is performed in two stages. First a 10:1 transformer which isloates the circuit from the mains , as well as steps down the $120V_{rms}$ to $12V_{rms}$. Next a passive network further scales the $12V_{rms}$ input to $200mV_{pp}$. Finally MSP430AFE digitizes the signal via a 24bit $\Sigma\Delta$ ADC. The 1bit ADC samples at 1Msps with the oversampling rate of 256 to achieve the 24bit resolution and 4kHz sampling rate. The state machine for the MSP430 CPU core is shown below. At startup MSP430 sets up the ADC, internal clocking and UART interfaces. Once the setup is finished it enters the IDLE state where the main CPU is in the low power mode. It remains in this mode untill one of the three conditions are met:

1. **Reset line is pulled low.** In this case the CPU will reconfigure all of the peripherals, and enter the IDLE state once more.
2. **ADC interrupt fires.** This signifies that a new ADC sample is ready.
3. **WR Flag is pulled low.** This asserts that the Raspberry PI is ready to receive voltage samples.

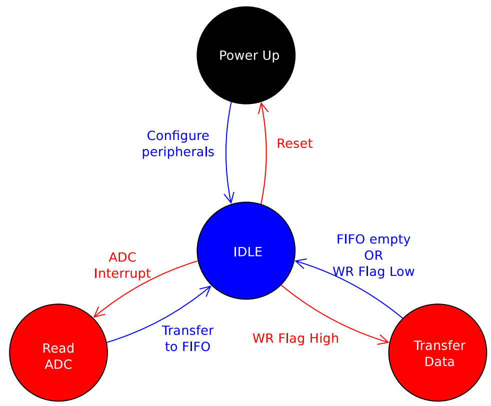

Figure 2: MSP430 State Machine

ADC is operating in the free-running mode, meaning, that the conversion timing is controlled via hardware. Once the conversion is complete a system interrupt notifies the CPU. In order to remove the hard real-time constraint for the Raspberry PI, MSP430 CPU stores the ADC readings in an 85 sample FIFO. This FIFO, implemented as a circular buffer, allows the Raspberry PI to receive data at non-regular intervals. This is important since Raspberry PI is running a non real-time operating system. If the FIFO is full, the oldest sample is dropped from FIFO. Unfortunately there is no mechanism to inform the Raspberry PI of an overflow in OPQBox. This is remedied in the next iteration of the meter. See section 4 for more details on the future device revisions.

Communication between the Raspberry PI and the MSP430AFE is performed via UART with an addition of a WR line. When the WR line is pulled low, a level triggered interrupt notifies the MSP430 CPU that the PI is ready for more data. The data is transfered via UART running at 230400bps.

2.3 Data filtering and analysis

Raspberry PI is responsible for selecting events which deviate from the steady state condition. In our case steady state is a sinusoid with a set frequency and amplitude. Acquisition and processing is performed in five steps:

1. Acquisition.
2. FFT/Peak fitting.

3. RMS calculation.

4. Event Filter.

5. Communication.

Acquisition step accumulates a 4000 sample window, and passes it on for processing. In order align the data during aggregation a millisecond timestamps is generated for each window. Next the fundamental frequency of the waveform is computed. In order to do that a Fourier transform of the sample window is performed. Six points surrounding the largest FFT peak are selected, and fitted with a Gaussian in order to extract the true utility frequency.

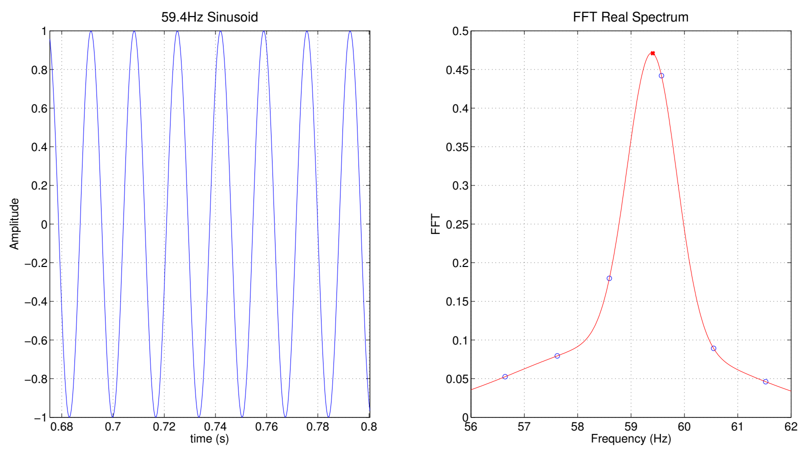

Figure 3: Calculating the fundamental frequency using FFT and peak fitting.
Left: 59.4Hz sinusoid. *Right:* Gaussian fit to the 6 point stradeling the peak. Extracted maximum is $59.39Hz$.

Next OPQBox calculates the RMS voltage. Only complete half-periods are included in this calculation, and the leading and trailing samples are pruned. The calculation is performed according to equation 1

Every window recorded passes through the first three steps in OPQBox analysis system. However if the frequency and voltage are within tolerance, there is no reason to send it to the aggregation service. In order to monitor the voltage and frequency trends however every 15th window is sent to the aggregation service regardless. If the utility frequency or rms voltage fall out of bounds the whole window is sent to the aggregation service as well. Filter task check the computed values against the tolerances and selects events to send to the cloud. We defined our tolerances to be:

- $\pm 0.5Hz$ deviation from the $60Hz$ norm.
- $\pm 7V_{rms}$ deviation from the $120V_{rms}$ norm.

Finally a window is ready to be sent to the aggregation service. Raspberry PI maintains a connection to the service via a WIFI dongle. If a window is selected to be sent to the aggregation, it is serialized into JSON, along with the appropriate metadata, and sent over a websocket connection.

2.4 Aggregation Infrastructure

Open Power Quality aggregation software, titled OPQHub, is responsible for communicating with the OPQBox devices, and serving user side content. It is written in Java using the Play framework.

Figure 4: OPQHub public interface.

OPQHub provides a rich visualization suit as shown in Figure 2.4, along with a data querying API for developers. Unfortunately description of the internal function of such a feature rich, scalable architecture is beyond the scope of this paper. A white paper on this topic has been previously published by OPQ. Cite anthony!

3 Results

In this section we discuss the preliminary results of OPQBox deployment. First we present the daily trends seen by our network. Next we correlate the voltage trends to the output of a PV installation. Finally we take a look at an event recorder on two geographical separated devices.

3.1 Daily Trends

Using our power quality sensor network, we are able to monitor daily trends throughout the grid. Figure 10 shows a typical daily trend for three devices. This data was collected over Oct 26. The CSDL device was located in the Collaborative Software Development Lab at the University of Hawaii. Justin device was located in the high-rise apartment, near downtown Honolulu. Finally Philip devise is located in a residential house, with a rooftop PV installation in Manoa valley.

The frequency measurements track each other throughout the day. This is to be expected since the grid frequency is set by a few central generators. Voltage data recorded by the CSDL and Justin, show the same behavior throughout the day, however local voltage disturbances dominate the short term trends. In case of device Philip however a daily voltage fluctuation of $10V_{rms}$ was present daily. We attempt to explain this phenomenon by correlating the voltage reading to the PV activity in the section 3.2.

3.2 Grid Voltage and Grid Tied Photovoltaic Installations

Top graph in figure 6 shows the rms voltage recorded from August 1 to August 8 for a single device in a residential home in Kailua, Oahu. The bottom plot shows the power produced by a grid tied PV installation, located on the roof of the same house.

The correlations between the power produced and the voltage are clearly shown in figure 6. Some of the more fine-scale correlations are also visible. For example large drop in PV output on August 4 13:00pm is correlated to a drop in the utility voltage. This leads us to believe that solar panels contribute to the variation of the line voltage of the house they are supplying. This begs the question: how do photovoltaics influence the grid voltage as a whole?

Figure 3.2 shows the same to graphs as figure 6 for October 15 to October 18. This time however OPQBox device and the Photovoltaics unit are separated by 20 miles. The house containing the device did not have a grid

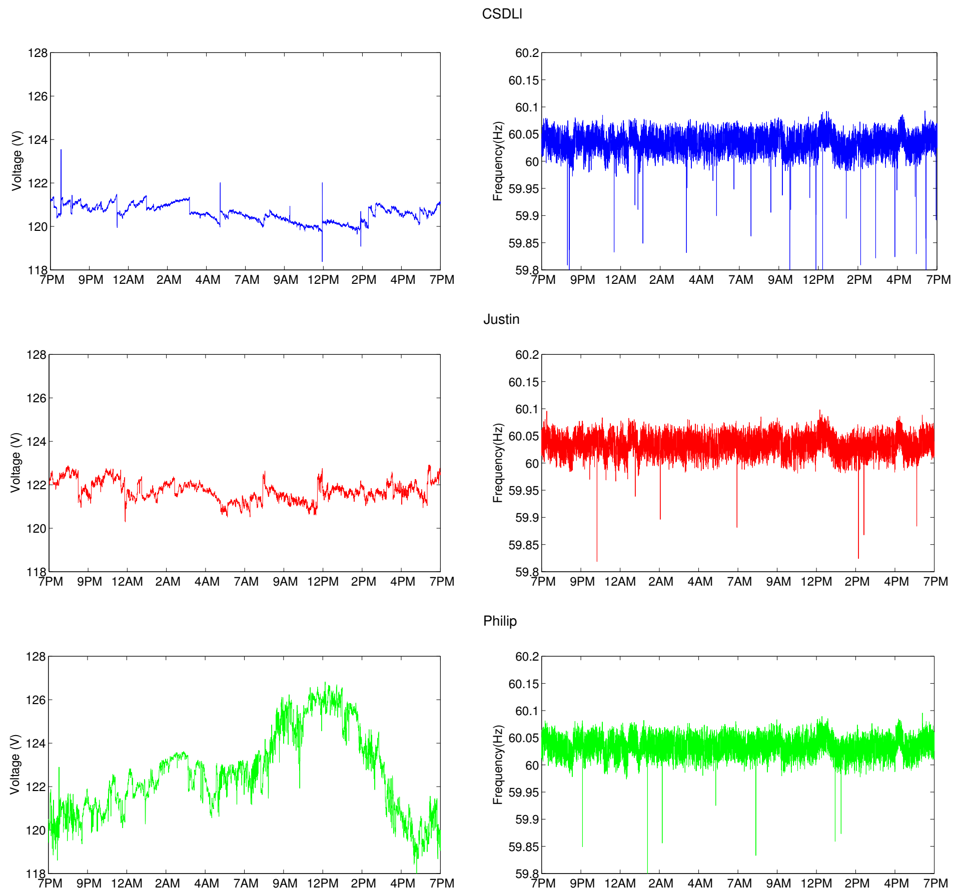

Figure 5: Voltage and frequency readings for three devices over Oct 26.

tied PV system. Correlations are present nonetheless, line voltage measured by the device is proportional to the power generated by the PV installation. A possible explanation for this effect is that PV installations affect the line voltage across the whole grid. Oct 15-17 were clear days with minimal cloud cover, which implied that PV installations were generating power across the island, perhaps affecting the grid voltage while doing so. One way to answer this question is examine the line voltage trend while the PV installations across the island are idle.

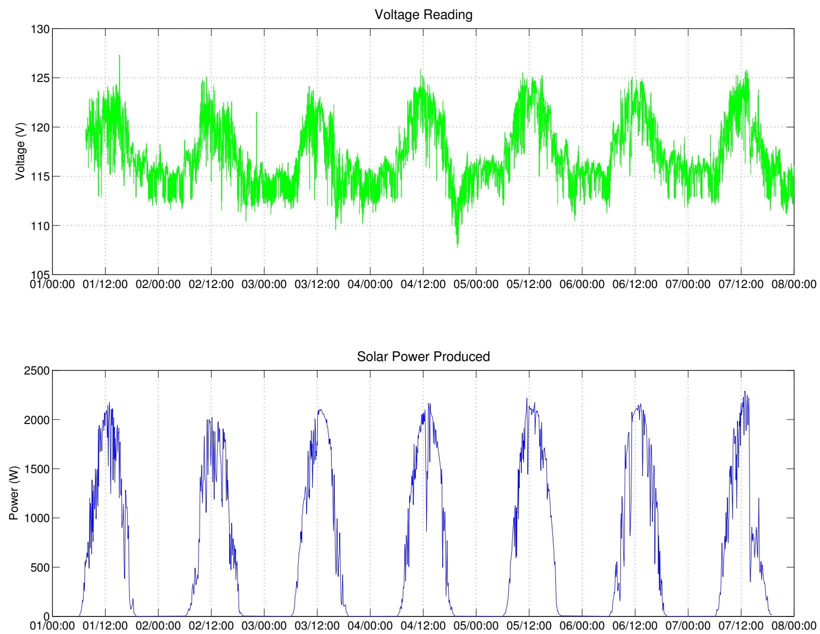

Figure 6: Grid voltage and solar power produced. Device and PV located in the same house.

On the days of October 17 through October 19 hurricane ANA passed within 100 miles of the island of Oahu. Its passing brought heavy clouds which enveloped the entire island. Clouds began to form late afternoon Friday, October 18, as demonstrated by the power generation drop in figure along with the line voltage drop recorded by the device. Voltage and Power reading for October 18 through October 20 are shown in figure 8.

As shown in figure 7, during peak hours, the PV installation was generating 2kW of power, yet during the storm on October 18 and 19 it was generating 550W and 100W respectively. Furthermore the line voltage did not exhibit the same variations we saw in figure 6 and figure 7. While more research is required, data we collected over the last several months shows that the high penetration of PV installations on Oahu is affecting the grid voltage. The extent of this effect remains to be shown.

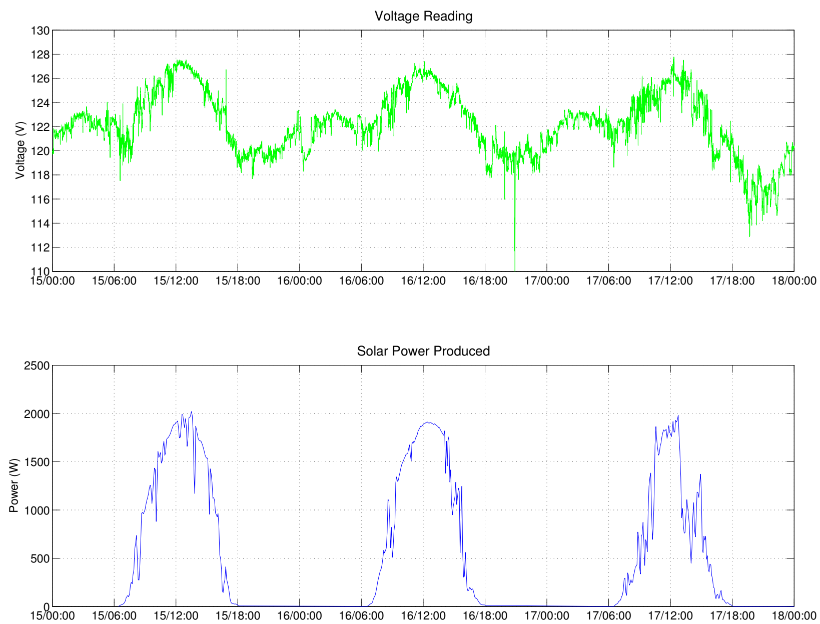

Figure 7: Grid voltage and solar power produced. Device and PV located are separated by 20 miles.

3.3 Grid Wide Events

As described in subsection 2.3, our system is able record both long term trends, and short term transients. Unfortunately only several of such transients have been confirmed to be grid wide. The best example of such an event is shown in figure 3.4.

An event above is two voltage sags lasting 6 cycles, separated by 700ms. It was seen by two devices, one located at University of Hawaii at Manoa, and the other 10 miles away in a high rise apartment building. The timestamp between two waveforms differed by 18ms, or approximately one grid cycle. Using the data we collected we are able to examine the the voltage and frequency trend around the event time as shown in figure 10.

Figure 10 shows that while the voltage dip quickly recovered, frequency variations continued for several minutes. While the cause of this particular disruption will likely remain unknown, events such as this prove both the feasibility and the need for deployment of a power quality monitoring system

Figure 8: Grid voltage and solar power produced during hurricane Ana. Device and PV located are separated by 20 miles.

such as OPQBox and OPQHub.

4 Further Study

During the initial deployment of the OPQBox1 and OPQHub several problems have been discovered. In order to overcome these changes the next iteration of OPQbox is in active development. The list of proposed changes is shown Table 1.

On board processing for OPQBox1 was performed by the Raspberry PI SBC. Raspberry PI was an attractive option, due to the wide range of interfaces, ample processing power and small footprint. However due to the limitations imposed by the non-realtime nature of Linux, it became impossible to grantee consistent timing between devices. Even with perfectly syncronized clocks, the rms jitter of up to 50ms was observed between window samples. Next generation of the device is based around a dedicated 32bit

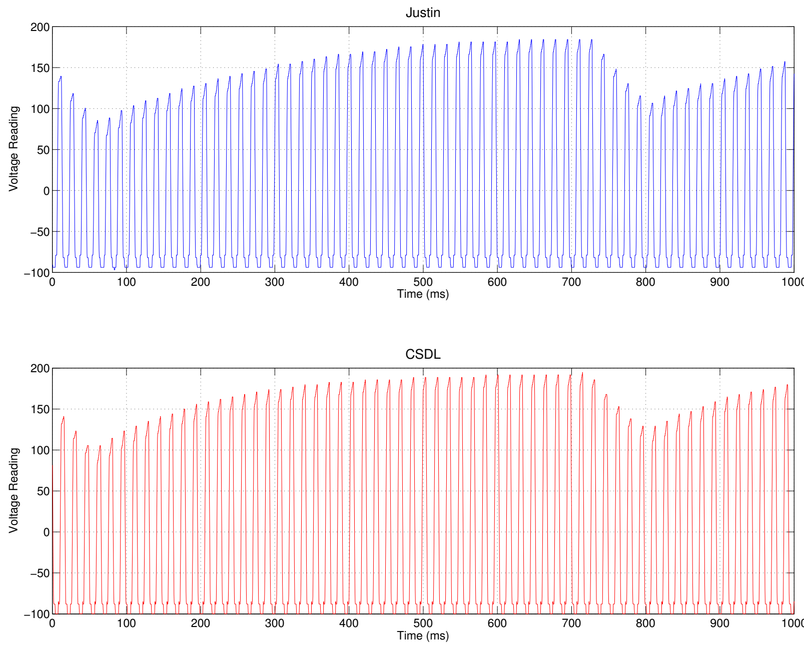

Figure 9: Grid-wide event recorded by two devices on 13:46 on Sept 30. Devices are 10 miles apart.

Table 1: Comparison of OPQBox1 and OPQBox2

Feature	**OPQBox1**	**OPQBox2**
Synchronization	NTP/Software sampling	NTP/Hardware sampling
Sampling rate	4kSps	Up to 50kSps Nominal 15.36kSps
Voltage sensing method	Wall Wart transformer	Resistor Divider
Power Fault Handling	NONE	FRAM waveform storage
Communication Capabiliy	UART	UART/SPI/USB/I^2C
On board processing	NONE	ARM CPU with FPU

ARM MCU. This MCU is responsible for controlling the sampling rate of the device, and since this process is interrupt driven, the scheduler jitter will be eliminated. Furthermore the MCU is responsible implementing running a phase locked loop such that a first and last sample of a grid cycle fall on the zero crossing. This will simplify the analysis and improve synchronization between devices.

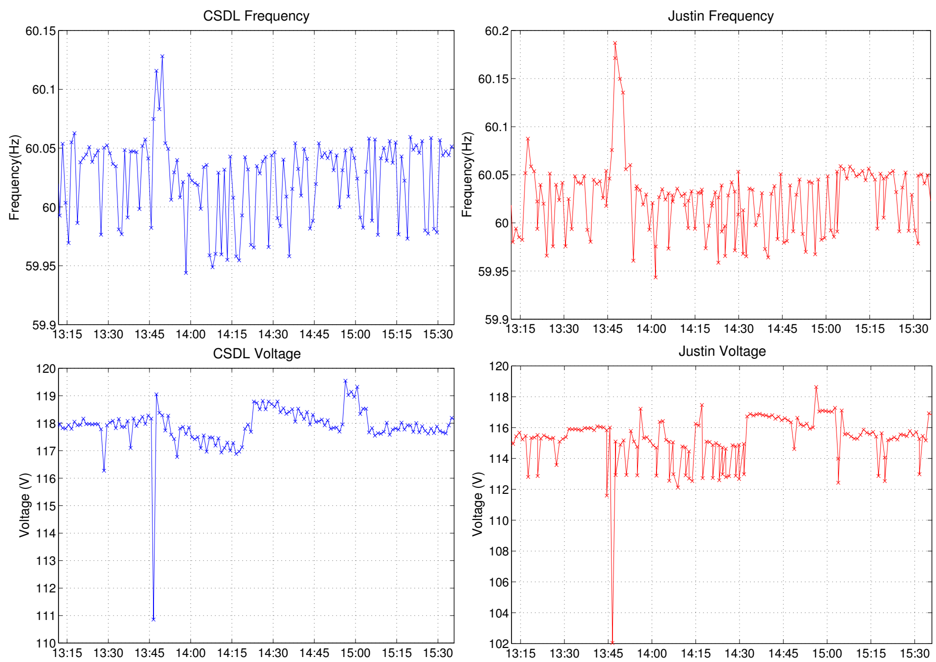

Figure 10: Voltage and frequency trend for the event shown in Figure 9.

Due to the window size used in OPQbox1 made it almost impossible to detect short lived transients. In order to improve transient detection, OPQBox2 will analyze the input one grid cycle at a time, thereby shrinking the window from 1s to 16ms. This will require a new algorithm for frequency extraction, however since OPQBox2 includes a dedicated CPU/FPU this analysis will be performed by the realtime controller. Fitting is being considered as an algorithm of choice, since it will provide phase, amplitude and fundamental frequency information.

Sampling rate increase in OPQBox2 is dictated by the IEEE Std 1159. This standard recommends the minimum 256 points per grid cycle, or a sampling rate of 15.36kSps. In order to accomplish this the MSP430AFE is replaced by a dedicated 50kSps ADC. However during our calibration of the OPQBox1 we found that the wall-wart transformers used in sampling had on average 3kHz of bandwidth. In order to catch short lived transients and justify the high sampling rate, the transformer was removed from the OPQBox2 design. Instead voltage scening is performed via a simple resistor divider, and an isolation amplifier. OPQBox2 leaves a large margin of conversion rate for future applications, and sampling rate of 800 samples per grid cycle can be achieved if required.

During development of OPQBox1 we focused on UART as primary method of communication with the outside world. Raspberry Pi provided all the processing and WIFI for communication. OPQBox2 on the other hand provides several possible interfaces, and since the processing is performed on the device, any communication controller compatible with the SPI UART or I^2C can be employed. This allows us to tailor OPQBox2 to operate independent of the communication interface, thus allowing us to monitor power quality in locations inaccessible to WIFI.

Power outages have not been considered in the design of OPQBox1. Since data leading up to the power outage can provide insight into the nature and the cause of the fault OPQBox2 was designed to handle outages. Battery and supercapacitor have been considered during the design stage, however they added bulk and did not necessarily preserve the data during a long term power failure. Instead OPQBox2 design uses ferromagnetic RAM to buffer most 30 grid cycles of high resolution waveforms. Since FRAM maintains it state during a power interruption, OPQBox2 is able to provide 500ms worth of high resolution voltage waveforms leading up to the outage.

5 Conclusions

A Gen 1 Schematics