# Fancy That: Measuring Electricity Grid Voltage Using a Phone and a Fan

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## ABSTRACT

We describe the design, development, and characterization of a system that uses only a commodity smartphone and a consumer fan to measure the voltage of an electricity grid. This system represents the first known example of a system for measuring power quality of an electricity grid without specialized equipment, and can enable those with electricity access who live in "weak grid" environments to determine the current state of their electricity system, especially whether it is safe to plug in appliances. Our work leverages the microphone of the phone to measure the disturbance created on a pure sinusoidal tone into a running fan. The distance between adjacent harmonics in this disturbance is a direct proxy for the electricity grid voltage. We build a system to exploit this phenomenon and show that it is robust to a variety of fan types, phone types, and background audio environments, consistently producing voltage estimations within +/- 2%. We also show that our method works for smartphones as well as feature phones, making it applicable in a wide range of settings.

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## 1 INTRODUCTION

Improvements in technology in electricity generation, sensors, and communication technologies coupled with redoubled efforts from governments, donors, private companies, and NGOs have led to enormous gains in electricity access. Despite recent improvements in systems for distributed electrification, most of the billions who have access are via traditional electricity grids, even in developing regions. However, the reliability and quality of this electricity is not consistent among those connected; away from cities, power quality still bedevils the few that are lucky enough to have an electricity connection. In particular, power quality is a poorly-studied problem because the instruments to collect better data and expose the problem are simply not cheap or widespread enough to be deployed in the environments where power quality is a challenge. Consumers on these "weak grids" are typically more rural and poorer than average, and suffer from a justified fear of damaging appliances, which are of high relative value. Nonetheless, these "weak grids" cause substantial losses in ruined appliances and leave unrealized improvements in income and quality-of-life among these consumers. While it is possible to build more durable appliances to serve "weak grid" consumers [2], part of this challenge stems from an inability to monitor the nature of power quality at scale.

In this work, we design, develop, and characterize a unique system for measuring power quality on an electricity grid that uses only a fan and a smartphone. As specialized equipment for measurement of power quality is seldom available in developing settings, our system leveraging only commodity equipment can lower the barrier to collecting broad-scale power quality data via crowdsourcing. Our system works by exploiting the observation that the speed of the induction motor that controls the rotational speed of a fan directly relates to the AC supply voltage of the grid. To measure the rotational speed of the fan, we develop a signal processing method that is able to interpret recorded audio of a fan coupled with a constant-frequency tone. We focus on fans in this work because they are widespread and reasonably robust to under- and over-voltage events, but any spinning appliance (e.g., motors) could also likely work for our system.

We begin by presenting measurement of power quality on "weak" electricity grids and examine related work. We then describe the scientific phenomenon that our system exploits, our test setup and methodology, and our signal processing algorithm. We discuss the training procedure for our system, and continue by documenting how we select a range of important design parameters. We then evaluate the usage conditions for our measurement system, showing that it is robust to a diversity of fans and phones used for measurement. We also consider the problem of measurement using only a feature phone rather than a smartphone and conclude by describing future directions.

## 2 BACKGROUND AND RELATED WORK

### 2.1 Measuring Power Quality

Power quality is seldom considered when measuring global access to electricity. For example, the World Bank has recently developed its Multi-Tier Framework (MTF) [16], a global scorecard for measuring energy access. While the MTF makes important improvements in measuring electrification by considering a diversity of connection types beyond only centralized grids, the measure fails to quantify power quality, classifying communities with low-quality yet reliable power (i.e., mostly useless for productive purposes) equivalently


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to those communities with no interruptions and an entirely stable power supply.

What drives this omission of power quality? First and foremost, there is limited power quality measurement. While standard utility practices the world over entail installing and operating sensors for measuring power quality throughout electricity networks, limited infrastructure budgets in developing economies preclude installation of power quality sensors, let alone those sensors that can log or communicate data.

How is power quality measured? It can primarily be assessed using two quantities: grid frequency (measured in Hertz) and grid voltage (measured in Volts). Frequency is especially adept at measuring aggregate imbalance of electricity supply and demand on the grid. Operators attempt to maintain a nominal grid frequency – typically, 60 Hz in the Americas and 50 Hz across most of the rest of the world – by ensuring that the amount of electricity supply on the grid always matches the amount of electricity demand. While there are low-cost, readily-available meters for measuring grid frequency, these are not widespread in developing economies. As an alternative, there is potential to automatically measure grid frequency using smartphones [6]. However, grid frequency is generally a poor measure of power quality because it varies continuously, making estimation of the current state of the grid using only frequency measurements challenging [4].

Power quality is more appropriately measured using grid voltage. Typically, grid operators aim to maintain a system voltage within 5% of a nominal voltage (typically 120V in the Americas, Japan, and Korea and 230V elsewhere). Under-voltage events, also known as brownouts, are typically either an indicator of undersupply of power or some type of partial disruption in the grid. Persistently operating appliances and other electrical loads at low voltages can burn out motors that are forced to work too hard to maintain their nominal frequency. On the other hand, over-voltage events can be caused by sudden changes in demand or faulty equipment on the grid – an over-voltage event can damage and possibly destroy appliances by overloading protection circuits or simply burning out components. At present, we know of no scalable way to cheaply and accurately measure electricity grid voltage.

Typically, rural areas have brittle electricity grids and face more issues with under-voltage and over-voltage events; however, these are precisely the locations that are under-monitored, making power quality problems relatively less visible. As an example of the conditions that rural grids might face, we obtained data from the Energy Supply Monitoring Initiative [1], an effort to deploy specialized power quality monitoring hardware, primarily in India but also in other developing regions. We retrieved data for the electricity voltage in two different locations in India over 15 days in February, 2018, as can be seen in Figure 1, which shows a classification of the voltage levels experienced each day at the two locations as well as a time series of voltage readings with one-minute resolution. From these figures, we can see that there may be substantial variation in voltages experienced in these locations, both within days and among days. This variation makes it especially difficult to avoid under-voltage and over-voltage events, making rural denizens especially susceptible to power quality issues. While we highlight India here, we have seen similar data from Zambia [9], Tanzania [12], and elsewhere in the developing world. Further, fans are an ideal appliance for our system to work with, as they are common even among low-income households. For example, as of 2010, 60% of rural households and 90% of urban households in India own a fan [11].

## 2.2 Related Work

A wide range of multimeters and other electrical testers are available for measuring low-voltage AC grids. Though this technology is widespread and relatively low cost, it is purpose-specific and generally not freely available in "weak grid" areas. Further, most multimeters are non-communicating devices, so data collection and communication are separate tasks.

There are also a number of consumer-grade [10, 15] and research-grade [3, 5] plug meters that measure power quality. Current Transformers (CTs) can also be used for measuring power quality. These devices represent a range of costs, accuracies, and communication capabilities. However, they are all specialized equipment, limiting their deployment in developing regions. While this will change in the future as power quality monitoring becomes ubiquitous and cheap, we presently do not know of any power quality measurement system that is widely used in the developing world. The sole example that we could find of a system that approaches this goal is the Energy Supply Monitoring Initiative (ESMI), run by the Prayas Group [1]. This system currently consists of 428 power monitors, residing primarily across 22 states in India, but also in four other developing countries. The ESMI device is a purpose-built power monitor intended to measure and report power reliability and power quality issues. Each device costs roughly $150 and measures and communicates a range of power parameters every minute. We aim to complement the high-resolution data produced by a system like ESMI with low-resolution data originating from a larger number of endpoints.

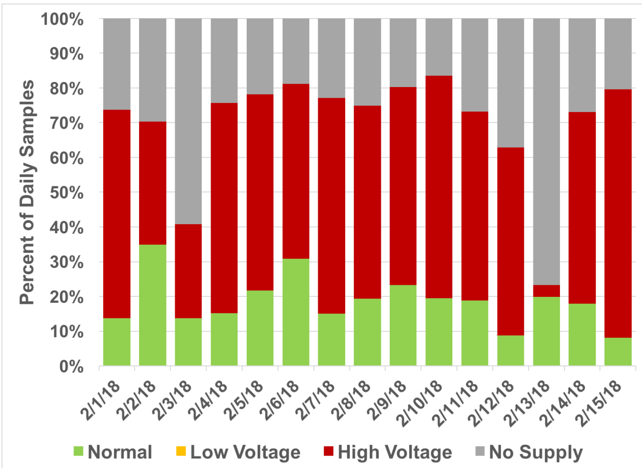
## 2.3 Crowdsourced Infrastructure Measurement via Smartphones

The improvement in quality of sensors and the broad deployment of smartphones has enabled a groundswell in crowdsourcing applications for measuring the condition of infrastructure systems. These include Waze for traffic measurement [14], GridWatch for electricity grid outage measurement [6], the Living Roads Project for assessing road quality [13], NextDrop for measuring drinking water delivery [7], and many more. Many of the projects mentioned are focused in developing contexts, where a lack of measurement in the infrastructure enables mobile phones to uniquely provide monitoring capabilities. We aim to leverage the successes of these efforts to ultimately build a widespread system for measuring power quality in developing regions.

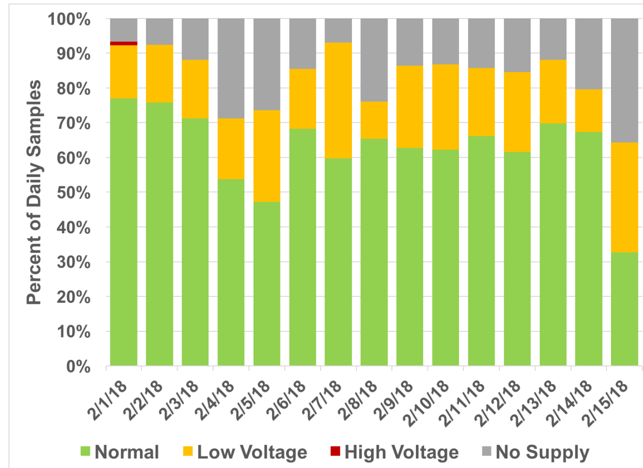
# 3 SYSTEM DESIGN

## 3.1 Design Goals

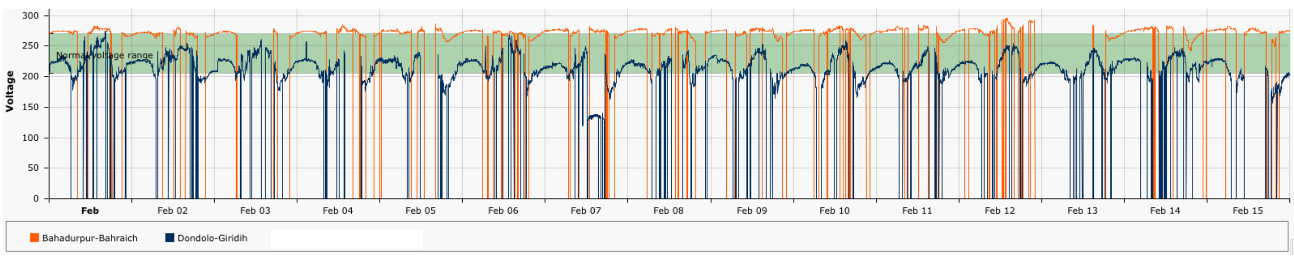
Our work stems from an observation made during field research in a rural area: at various times of day, the fan in a household would noticeably slow down. We reasoned that this was a direct reflection of the lower AC voltage on that local grid affecting the speed of the induction motor found in the fan. Thus, the fan presents an opportunity for unexpected insight into the power quality status




(a) Daily Power Quality in Bahadurpur, Bahraich, Uttar Pradesh, India.




(b) Daily Power Quality in Dondolo, Giridih, Jharkhand, India.




(c) Voltage timeseries, 2/1/2018 – 2/15/2018.

**Figure 1: Power quality statistics at two sites in India for 2/1/2018 – 2/15/2018. Data are from the ESMI project from Prayas.**

of the local grid: characterizing the speed of the fan could present some indication of the grid voltage. Figure 2 characterizes the strong linear relationship between fan speed and AC voltage supplied[1]

Thus, we set a goal of measuring electricity grid voltage without specialized equipment, mostly autonomously, and with minimal challenge to the person taking the measurement. To investigate this possibility, we considered different methods for measuring fan speed with a smartphone: using magnetic field, optical, or audio methods. Magnetic fields were easily dismissed because of the relatively small magnitude fields induced by current in a fan wire, as well as the balanced magnetic field of two conductors with equal and opposite currents.

There are a number of different apps for using the camera flash on the phone at a high-frequency strobe in order to visually ascertain the rotational speed of a fan. While it may be possible to build a video processing algorithm for figuring out the rotational speed of a fan, the high framerate requirements needed of a video camera are likely beyond the capabilities of the low-cost smartphones that predominate in developing economies. While this may change as better camera hardware proliferates, at present, optical sensing is likely not feasible for our context. Further, this optical sensing technique requires a relatively dark room to get enough contrast with the flash, encumbering the user experience of this method.

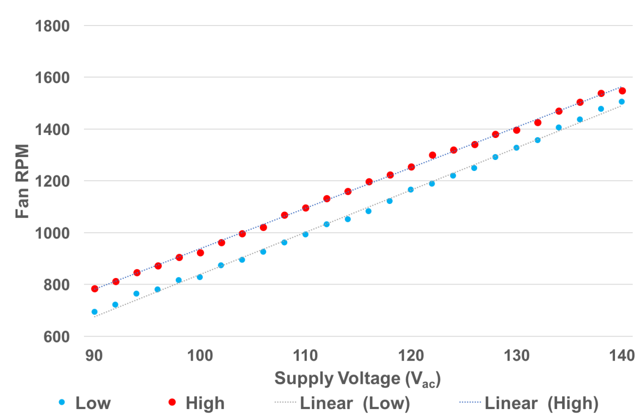



**Figure 2: Measurement of fan speed versus supply voltage for two fan settings. A line of best fit with very high correlation is also plotted for each fan setting ($R^2 > 0.997$ in both settings).**

[1] Fan speed was manually collected using the StrobeLight app from the iTunes app store [8].

Thus, we created a method that is able to measure audio recordings to determine fan speed. The key benefit of audio is its universal applicability – all phones have a microphone. An important observation is that a fan by itself produces a broad range of uninterpretable noise across the frequency spectrum. To understand the effects of the fan, we exploited the phenomenon of the harmonics created when a tone is played into an operating fan. This tone is reflected from the fan's blades, creating a series of harmonics that can be individually identified. Additionally, while the bulk of our experiments use a smartphone, we even had limited success implementing our approach on a feature phone – we discuss this further in Section 4.2.

However, for our system to work, there are a number of challenges of diversity to consider:

- the broad range of smartphones and their associated signal processing components;
- the array of fan sizes, designs, ages, and efficiencies; and
- the conditions of sensing environments.

Faced with this diversity, we aim to build a system that produces high consistency of measurement, requires limited ground truth, is easy-to-use, and works in a range of different settings with different measurement equipment. The remainder of this section describes how we designed and built our system, and Section 4 shows the sensitivity of our system to different conditions.

## 3.2 Test Setup

To determine the best parameters for our system and test the robustness of sensing methods, the fan was tested using a laptop to supply a pure sinusoidal tone played into the front of the fan and a mobile phone held directly in front of the fan recording the audio signal. In the future, we will move both tone generation and recording to the phone itself. A diagram of our test setup is provided in Figure 3.

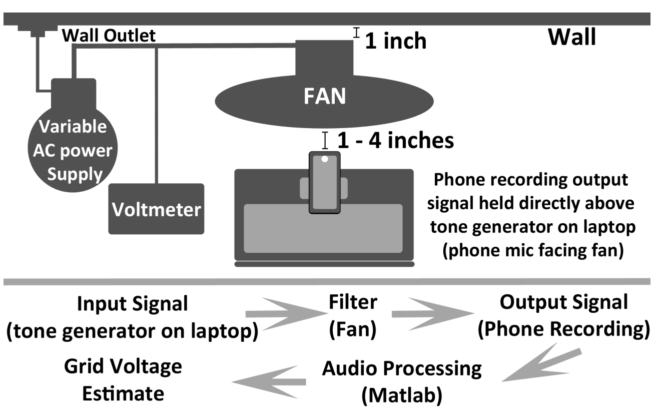



**Figure 3: Diagram of test setup and information flow in our system from tone generator on laptop to final voltage estimate.**

For consistency across experiments, a standard testing setup - shown in Figure 3 was established using the parameters discovered in the experiments documented herein. Each parameter was independently varied and tested to determine acceptable values as described in Section 3.4. In each case, parameters were chosen to maximize observation of our phenomenon, the Inter-Harmonic Distance of the collected audio sample. While all of our testing was conducted in a grid with a nominal 120 Volt supply, we do not believe the system will perform any differently on a grid with a nominal 230 V supply.

## 3.3 Audio Signal Processing

Our technique uses the Fast Fourier Transform to inspect the frequency-domain behavior of the fan's effect on the sinusoidal wave. An example of this behavior is presented in Figure 4, which shows the frequency response of an audio clip of a 15 $kHz$ tone played into a fan running on its high setting. We can see that the sinusoidal tone is spread across a wider range than would be typical; this spreading creates a series of harmonics, and our algorithm captures the peaks of these harmonics. We discovered that the distance between adjacent peaks, herein referred to as the "Inter-Harmonic Distance" (IHD) varies directly with the speed of the fan. Thus, the IHD can be used to measure the speed of the fan, which correlates directly to the supplied AC voltage.

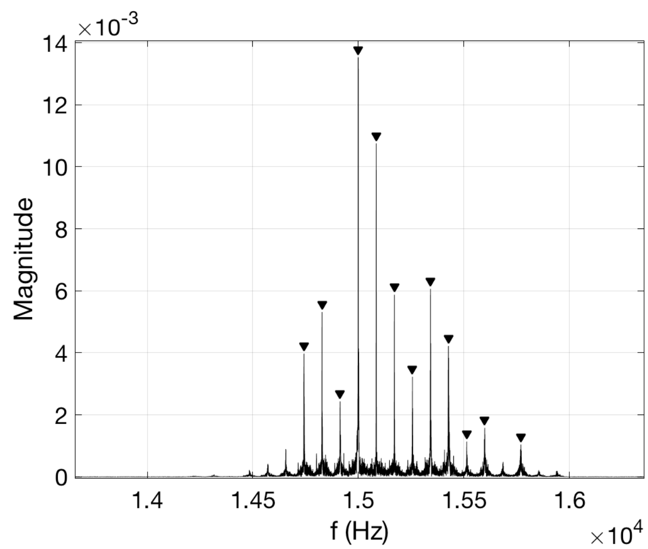



**Figure 4: Fast Fourier Transform for a recording of a 15 $KHz$ tone played into a fan. A peak identification algorithm has been run to identify harmonics of the signal. Note the equal spacing between harmonics.**

It was shown that higher fan speeds as a result of higher voltages supplied to the fan would result in a larger distance between the reflection harmonics in the FFT. For the most isolated and easily measured harmonic peaks, the highest setting on the selected fan was used for all experiments unless explicitly stated otherwise.

We also found that the individual harmonics formed more obviously isolated peaks, making for easier peak discovery, when the microphone was situated as close as possible to the rotating fan blades with the microphone aimed directly into the fan. A standard of 1 inch between microphone and fan blades was chosen for best results. We further examine the effect of this parameter in Section 3.4.

During early tests of fan-microphone alignment we discovered that the harmonic peaks were noticeably more narrow and isolated when the tone generator was situated directly in front of the fan with the phone held directly behind the fan, 180 degrees from the tone generator. This allowed the phone to record the tone after it passes through the blades of the fan.

We place the fan perpendicular and roughly an inch from the wall. From our experience, this provided similarly isolated harmonics. We believe this is due to the the wall reflecting any signal to the rear of the fan back to the phone microphone in front of the fan. Additionally, we place the phone 1-4 inches away from the fan grill (or blades, if no grill is present). While we were also able to recreate the effect with the fan and phone placed in many orientations and away from walls as would be expected in deployed settings, we performed all of the tests in this work in a single configuration unless otherwise noted to ensure consistency of comparisons – we leave a more complete investigation of the effects of fan and phone placement to future work.

To consistently determine the IHD, a sequence of array sorting and operations were carried out using a few select variable parameters. First, peaks in the FFT output frequency array were identified as any value greater than both their left and right neighbors. These values were placed in a two-column matrix with their corresponding Hertz to later reproduce their natural neighboring order. Threshold parameters of minimum height and minimum inter-peak distance for peak discovery were introduced to minimize the discovery of non-harmonic noise peaks (the selection of these parameters follows a common pattern and could easily be automated in future works). The matrix of magnitude and frequency pairs was then sorted in descending order of magnitude, placing the largest magnitudes at the front of the array. This was done as the harmonics of largest magnitude were often all adjacent harmonics and centered around the fundamental tone, for example the 9 largest peaks in Figure 4. A variable number $X$ peaks were polled off the top of this array to determine the $X$ peaks with highest magnitude under the assumption that these $X$ peaks would all be adjacent harmonics. Making this assumption significantly reduced the amount of computation necessary for peak detection. These $X$ largest peaks were placed in a new array with their corresponding frequency values which was then sorted in ascending order of frequency at which they occur to attain their natural neighboring relationships. Finally, the mode of the differences between adjacent frequencies reveals the IHD for the recording. In most trials, polling the 6 largest peaks from the matrix resulted in a majority of those 6 being adjacent and useful for measuring IHD. In the ideal case, harmonic peaks in FFT form an obvious bell curve, monotonically increasing in magnitude until the fundamental, or some global maximum, and then monotonically decreasing until the end of the frequency spectrum. In some exceptional cases a harmonic close to the fundamental tone or between two of the X polled maximum peaks may be substantially shorter causing the final list of maximum peaks to not include this substantially shorter peak resulting in the final array of IHD to contain a value that is exactly double the expected value. The final mode operation should handle this, but in cases where none of the maximum detected peaks are adjacent, the parameters of poll number, minimum height, and minimum distance may be tuned for specific recordings or fans.

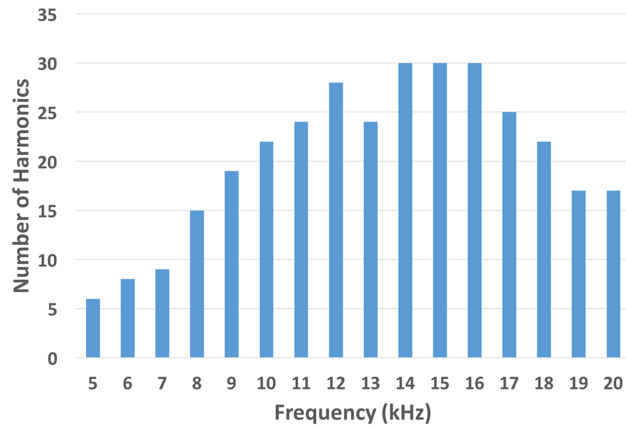



**Figure 5: Number of harmonics counted for different frequency tones played into a fan. A larger number of harmonics ensures a signal that is more accurate and robust to interference. For our system, we have chosen a tone frequency of 15 $kHz$.**

## 3.4 Choosing Parameters

This section examines the parameters that are critical to the design of our system.

*3.4.1 Signal Processing Parameters.* Our signal processing algorithm contains a few parameters for identifying peaks. With minimal tuning of these parameters, our method was able to distinguish the inter-harmonic distance of 54 trials using a small black desk fan (herein, Fan 1) and 81 trials with a medium-sized black desk fan (herein, Fan 2), with only 1 and 3 incorrect outputs, respectively. However, when the script was run without tuning on 81 recordings of the large white box fan (herein, Fan 3), which produced noticeably larger noise peaks, there were 25 incorrect outputs. Another test of Fan 3 where parameters were tuned shows an obvious linear trend in data. We leave it to future work to automatically tune these parameters as needed for each fan.

*3.4.2 Tone Frequency.* What is the optimal tone to be played into a fan to measure IHD? In general, higher frequencies were shown to correlate to a larger amount of present reflection harmonics. Therefore, the highest possible tone allows for the most harmonics, which increases the probability of clearly distinct harmonics and an accurate measurement. The mobile phone used to record the tones (an iPhone 7 for most of our testing) was able to record tones of up to 15 $kHz$ without worry of rolling off any upper reflection harmonics, so this frequency was chosen as a standard for all experiments other than those independently varying frequency or experiments with external frequency restrictions such as remote usage.

As further evidence towards this conclusion, frequencies ranging from 1 $kHz$ to 20 $kHz$ were played into the fan with the speaker and microphone placed 1 inch away from the center of the spinning blades of the fan; the results of this experiment are shown in Figure 5. The fan was placed 1 inch from a wall directly behind it and set on its highest setting. For frequencies below 5 $kHz$, any reflection harmonics produced were close to indistinguishable from noise

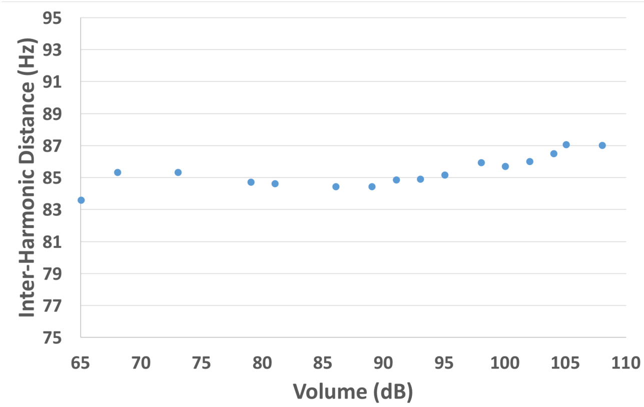



**Figure 6: Inter-harmonic distance across a range of tone volume levels generated by a MacBook Pro 2015. 16 volume measured in dBZ, an unweighted measurement on dB, to reflect the 16 volume ticks on the laptop. The inter-harmonic distance, which is a proxy measurement for fan speed and AC voltage, remains steady, indicating that this measurement is robust across volume levels.**

peaks around the fundamental tone being played. Consistently at 5 $kHz$ harmonics become distinguishable from noise and the amount of distinguishable harmonics steadily increased, reaching maximum at a 14 $kHz$ - 16 $kHz$ range. We believe the number of distinguishable harmonics begins to decrease due to the restrictive sample rate of the microphone on our test mobile phone.

*3.4.3 Tone Length.* How long of a tone is needed to ensure accurate results? Length of tone was tested using a practical testing method or recording a tone played into fan in as short of recordings as the voice recording application used allowed. Robustness to tone length was shown in that recordings as short as 0.72 seconds (the shortest tone we could record) maintained similar results to the usual 6-second recordings. Thus, our system is robust to tone length at least down to sub-second measurements.

*3.4.4 Tone Volume.* How loud does the tone need to be for an accurate measurement? Tone length was tested using variation of the 16 speaker volume measurements on our testing laptop, a MacBook Pro 2015. We again used our standard testing environment, with the fan set on high with rear of fan facing wall 1 inch away, the laptop supplying a tone of 15 $kHz$ 1 inch away aimed directly at spinning fan blades. Figure 6 shows the consistency of this measurement; the measurement of IHD differs by +/- 2% across all volume levels, as measured in unweighted dBZ (the range is 38-86 dBA, the most common acoustic weighting). Thus, our system is robust to volume level. This also provides confidence that the tone played from a phone's speaker will be sufficient for our measurement.

*3.4.5 Distance of Phone to Fan.* How close to the fan does the phone need to be? Figure 7 shows the percent error of IHD at varying distances between phone and fan. The error jumps from near 0 to well above 50 percent between distances of 4 and 5 inches between phone and fan. The farther the phone is from the fan

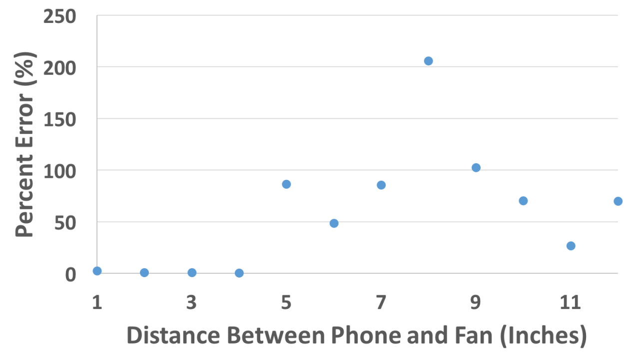



**Figure 7: Percent error in measurement of number of harmonics as the phone is moved further from the fan. For most accurate results, the measurement phone should be four inches from the fan or closer.**

blades, the less obvious the harmonics present in the FFT of the the recording. At 1 inch away the harmonics are the most heavily centered around one specific tonal value of Hertz. As the distance between the phone and the fan increases the harmonics become wider and more triangular in shape. The harmonic peaks quickly become indistinguishable from surrounding noise peaks and the harmonic itself is no longer represented by a single value in Hertz, but a wider range of values around the harmonics true tonal center. At 5 inches away from the fan the harmonic peaks are no longer obvious enough for the algorithm to detect. For our system to work with high accuracy, the phone should always be held at 4 inches away from the fan or closer. In practice, the phone should be placed as close to the fan's spinning blades as possible.

## 3.5 Encountering New Fans

We recognize that in practice, we will not have the ability to immediately characterize a newly-encountered fan across a range of voltages. In this section, we describe a technique for incrementally characterizing that fan over a series of measurements while still providing voltage estimates along the way. Over time, we will build a larger library of fan data to improve the accuracy of this method.

When a user desires to measure the voltage of a fan, he or she will need to identify the fan to our system; though make and model can possibly improve the estimate, simply knowing that this is a fan previously encountered is sufficient. In the future, this identification step can be automated by using default settings, computer vision techniques, location information, or other methods. Knowing the identity of the fan helps to associate new samples with previous samples from the same fan. Upon a first encounter with a new fan, the system initiates a training process. The system requests the user to take samples at each of the speed settings of the fan; this provides a series of ($Voltage, IHD$) pairs. For this explanation, we will assume three fan settings. While the voltage is not initially known, we assume that this reading is taken at the nominal voltage, 120V or 230V depending on the locale; this will be corrected with more samples. Looking at the response curve of a fan in Figure 9(b),

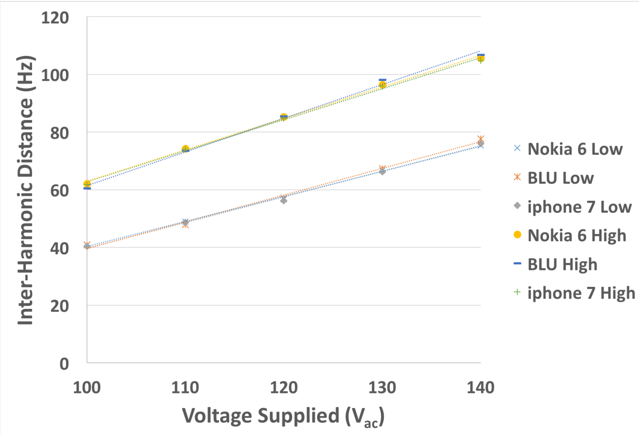



**Figure 8: Inter-harmonic distance across a range of voltages for three different smartphones. The trend lines remain similar across all three devices, indicating that this technique works regardless of phone used.**

these initial three points represent a column of readings at the nominal voltage.

We use these initial points as guidance for building our initial IHD response function. If we seek to map the response function for each of the speed settings, as seen in Figure 9(b), we first choose response functions from a fan in our library that had similar initial readings; this provides us with initial guesses for the response function of IHD for this particular fan at each setting.

On subsequent readings from the same fan, the system requests the user to again take samples at each of the speed settings. Estimates of voltage can be provided using the current response functions. Then, linear interpolation of these new points combined with previous points can be used to update the response functions. As more points are captured, the system builds a better understanding of the response function. The guess for nominal voltage can be updated using a density-based approach; if a particular set of $(Voltage, IHD)$ pairs shows up repeatedly, the system can shift its estimate of the nominal voltage. This approach assumes that the nominal voltage is the most common – for future work, we will evaluate this assumption using real-world power quality data, as seen in Figure 1 [1]. Once more samples from a particular fan are collected, the system can determine that only one setting of the fan is needed to provide an accurate voltage estimate, easing the process for the user.

A key benefit of this approach is that a larger library will help to improve the initial estimate for IHD response functions, providing a more accurate voltage estimate. This technique is enabled by the consistency of our method, providing a similar IHD response given the same fan at the same voltage. Degradation of the fan components, dust, or other factors may have an effect on this; we leave this investigation to future work.

# 4 EVALUATION

In this section, we evaluate the robustness of our system to a range of orientations, positions, types of phone, and types of fans. Then, we discuss the potential and challenges of using only a feature phone, rather than a smartphone.

## 4.1 Robustness Checks

*4.1.1 Repeatability.* As a simple check of repeatability of our system, we conducted 20 tests of the same 15 $kHz$ tone and identical test environment to show minimal variation in IHD. From the 20 tests a mean of 86.266 $Hz$ between each harmonic was found with a minimum of 84.907 $Hz$ and a maximum of 87.649 $Hz$, leading to a maximum variation of 1.383 $Hz$ and a standard deviation of 0.763 $Hz$. The testing method and algorithm for harmonic peak detection were shown to be repeatable with minimal variation in trials.

*4.1.2 Orientation of Phone.* Orientation of phone was experimentally shown to yield best results when the microphone was held directly straight on towards the spinning fan blades and as close to the blades as possible. Tests were done at 45 and 90 degrees, both left and right of the fan blades axis of rotation. While harmonics were often less obvious and more spread apart from their harmonic tonal center when recordings were taken at an angle, the algorithm often worked similarly to when the recordings were taken head on. However, recordings at an angle are significantly less robust to distance between phone and fan. The ideal position of the phone while recording is straight on, aimed into the fan at as short a distance as possible.

*4.1.3 Phone Hardware and Software Diversity.* There are a wide range of phones representing a wide range of microphone hardware and software. To show that our system is robust to a variety of devices, we tested it with three different phones: a Nokia 6 model TA-1025, an Apple iPhone 7, and a BLU R1 HD (ranging in retail price from roughly $100 USD to $700 USD). The applications used for recording were, for Android - Easy Voice Recorder by Digipom, and for iPhone - Voice Memos by Apple. Note that Apple's Voice Memos samples at a rate high enough to record up to a maximum frequency of 22.05 $kHz$ (in practice the outputs capped at about 17 $kHz$), whereas Easy Voice Recorder maxes out at 8 $kHz$. Taking this into account, a fundamental of 7 $kHz$ was used for the Android phones, maximizing number of potentially discoverable harmonics while leaving a large buffer between the fundamental tone and the frequency cap. The usual 15 $kHz$ fundamental was used for the iPhone tests.

Each phone was tested at a range of 100 to 140 volts with the standard test set up using the 2 setting black fan at both high and low settings. The results of these tests are shown in Figure 8. The tests revealed this technique is sufficiently robust to phone variation with calibration to accommodate hardware and software restrictions on sample rate.

*4.1.4 Effect of Interfering Noise.* Sensing environments will seldom be bereft of other noises. To test the robustness of our system to external noise, tests were performed using a tone being played from a laptop which was simultaneously playing white noise and music - specifically Anton Webern's Rondo in F Major. Other tests were performed with standard conversations ongoing. In all cases, noise interference was shown to have no effect on the Hertz measured between harmonics or the peak discovery algorithm's ability to determine the harmonics. This matches our intuition, as noise within the typical audible range does not interfere with the frequency of the 15 *kHz* test tone or its nearby harmonics. Further, noises originating from further away from the microphone appear to have minimal effects on the system's measurements.

*4.1.5 Fan Diversity.* There are also a wide range of fans available. As stated previously, we tested three fans. The results of testing these fans across a range of voltages are shown in Figure 9. These tests show near-linear responses for each fan in each setting, with $R^2$ values at all settings for all fans above 0.97. For Fans 1 and 2, multiple trials were conducted. While there may be benefit from altering the fit for various fans at various settings, a linear fit provides an accurate estimate of the fan's response to varying voltage.

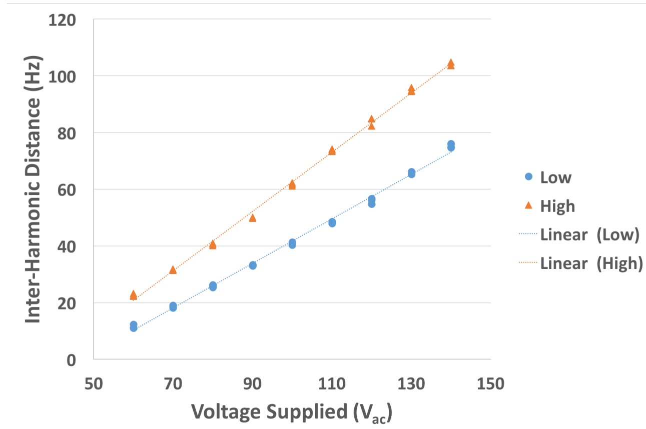
Additionally, fans with and without grills were both tested and in both cases the voltage supplied versus IHD showed similar results. We believe the grill has minimal effect on IHD as the tone must reach the oscillating fan blades to produce harmonics and the grills do not interfere with that as the signal propagates in a wide range around the speakers.

## 4.2 Remote Usage

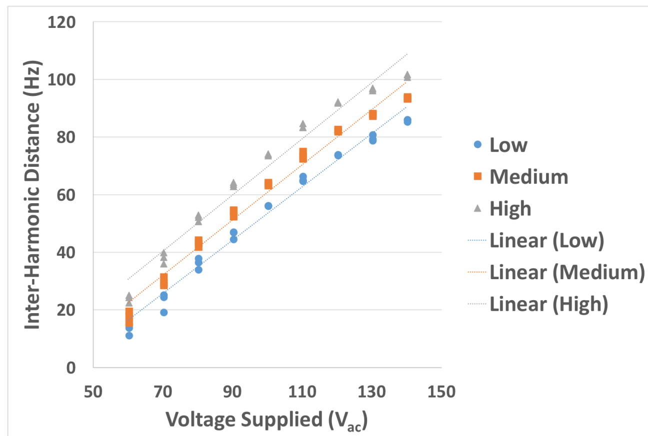
Smartphones are not available in all of the environments that would benefit from using our system. In this section, we examine the potential to use a feature phone instead via remote usage. Remote usage of this voltage measurement technique consists of a user connecting with a remote phone service that provides a pure tone generator and records the response of the caller phone as it is held, on speaker phone, directly in front of the fan. In practice, to reduce the cost to the user, this phone call could be connected via an SMS or missed call request. The operation of the audio processing algorithm is exactly the same as for when the recording generated by a phone both recording and supplying the tone. However, the fundamental tone used must be within the standard operating range of telecommunication which lies - in most cases - at 3 *kHz* or below. As seen in Figure 5 the number of harmonics is generally indistinguishable below 5 *kHz* and fundamental frequencies below 5 *kHz* are considered less desirable as they produce fewer harmonics for the algorithm to run as desired.

We tested remote usage with one smartphone model and one feature phone model by placing the test phone directly in front of Fan 1. We then called the test phone from a laptop using Google Voice in another room outside of ear-shot of the test phone and fan. The audio return from the call in Google Voice was virtually routed to a recording software to ensure isolation response from Google Voice from a tone generator running in a separate application. The tone was propagated out of the computer speakers, received by the computer microphone, and sent through Google Voice to the test phone placed in front of the fan. The test phone, on its speakerphone setting, projected the received tone directly into the fan and sent the return signal via its microphone back to Google Voice on the laptop. The signal was recorded and processed as usual.

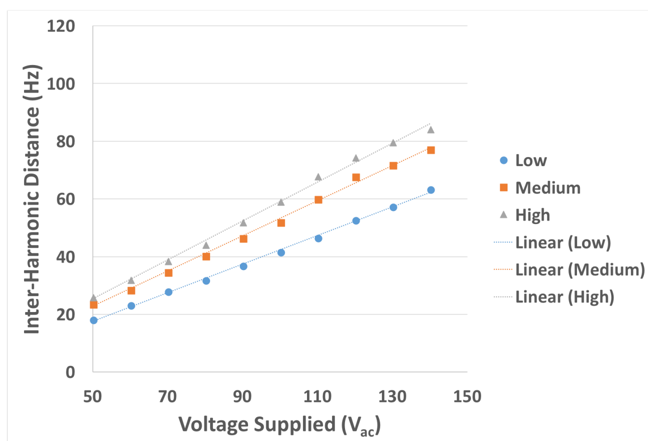
In testing this remote usage method, a 3 *kHz* fundamental produced exactly 1 harmonic with an IHD of approximately 85 *Hz* in all trials. This information (two peaks – one peak from the fundamental and one from the harmonic) provides sufficient information about the speed of the fan and therefore voltage so long as the peak detection algorithm can properly identify that single harmonic as




(a) Fan 1 (Small Black)




(b) Fan 2 (Medium Black)




(c) Fan 3 (White Box)

**Figure 9: Characterization of response of inter-harmonic distance for three different fans. For each fan, trials were run across a range of supply voltages and at each of the fan's speed settings. Responses show a linear relationship across the entire range of supply voltages tested, with very high correlations ($R^2 > 0.97$ in all cases).**

isolated from noise. In successful remote usage trials of the system, the single harmonic was clearly distinguishable. While our system was not successful in all remote usage trials, we believe it will be possible with further system development for our system to consistently support feature phone-based voltage measurements via remote usage. Further, field trials will be needed to ensure robustness to poor quality cellular connections and a larger variety of phone equipment.

## 5 FUTURE WORK AND CONCLUSION

Our results show a system for measuring power quality that uses only commodity smartphones and fans. The system is robust to a range of fans and phones; optimized to work at different tone frequencies, durations, and volumes; and is potentially capable of even working with only feature phones. In the future, we intend to improve the accuracy of our system by building a larger library of fans and inter-harmonic distance response functions, better characterizing learning rates of our system for individual fans, automatically optimizing algorithm tuning parameters, and detecting poorly-placed phones or fans. We also plan to enable the broad distribution of our system, creating a smartphone app that does tone generation, data collection, and signal processing directly on the phone. To study the effectiveness of our system in developing contexts, it will also be necessary to perform a human interaction study and refine the system design as needed. We also seek to further improve distribution by creating and building a system to accept recordings from feature phones. Though this work is only a small step towards widely-available and accurate power quality measurements generated in the places where "weak grids" abound, we believe it puts us a little closer to improving access to reliable and plentiful power for all.

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