DPQ Report: Surveying Power Quality Levels on U.S. Distribution Systems

Keywords:
Harmonic
Momentary Interruption
Report
Sag/Swell
Voltage Regulation

Introduction and Project Overview

The EPRI Distribution Power Quality Project is a two-year, ongoing assessment of power quality on the primary distribution systems of twenty-four utilities across the United States. This report includes a project overview including a discussion of the monitoring site selection process. Preliminary results are presented in this report, with data for a twelve month period from 223 monitoring sites. The results are in the form of statistical analysis for a composite of all sites. In particular, work has focused on rms voltage disturbances, voltage harmonic distortion, and steady-state voltage regulation. The fruit of this study will be a database of power quality statistics typical of U.S. distribution systems which can be used as a comparison base for power quality investigations in the future.

The EPRI research project, RP3098-1, An Assessment of Distribution Power Quality is an ongoing, multi-utility attempt to determine present levels of power quality on U.S. distribution feeders. It includes a two-year voltage and current monitoring program at 300 sites located on distribution circuits of the twenty-four different utilities across the United States shown in Figure 1. The chief goal of the project is to provide baseline statistics regarding quantities that fall under the general category of power quality, including:

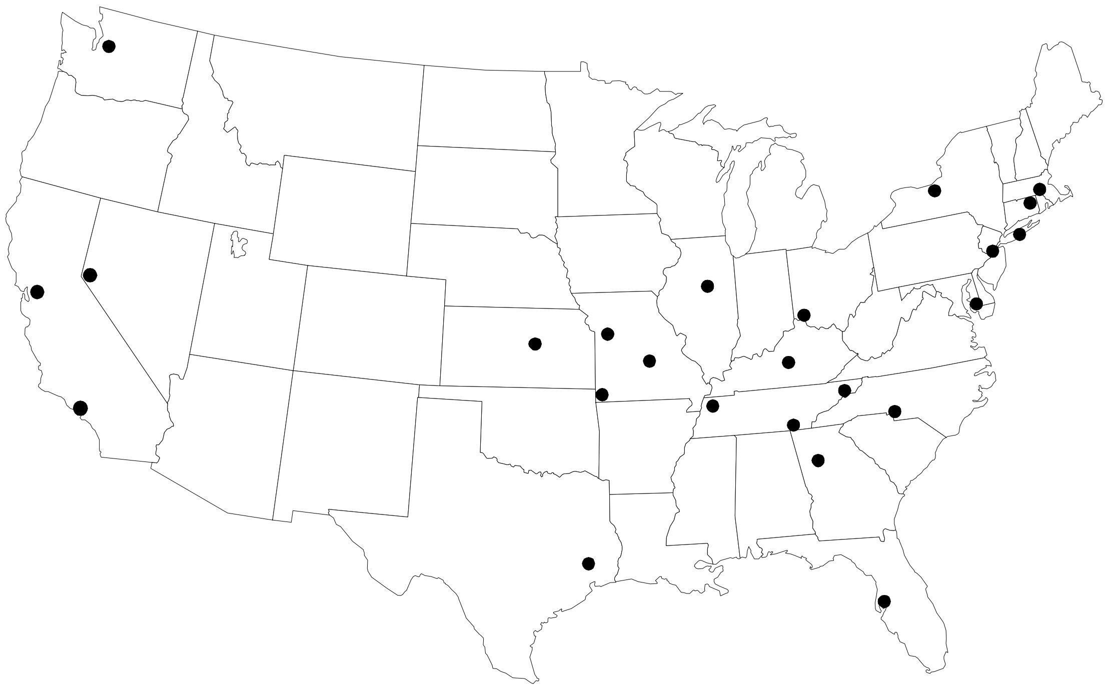

Figure 1: Location of Utilities Participating in the EPRI DPQ Project

I. Voltage Disturbances
   i. rms voltage variations
   ii. subcycle transients - impulsive and oscillatory

II. Steady-State Characteristics
   i. steady-state regulation
   ii. harmonic distortion
   iii. phase unbalance

Site Selection:

The utilities participating in the project were EPRI volunteers, representing a wide variety of geographic regions across the United States. The sites chosen for monitoring at these utilities were selected as part of both a systematic and a controlled random sampling process. This involved collecting site information from 1800 buses which was considered critical in characterizing any given feeder with regard to power quality. These characteristics, known as strata, included transformer MVA capacity, number of parallel feeders on the bus, feeder nominal kV, load type (urban, suburban, or mixed), and load density (residential, commercial, industrial, or mixed). These descriptors were used in a stratified, controlled selection of 100 buses from the 1800 in a manner that ensured both common and uncommon characteristics were represented in the study population. The feeder chosen to monitor on each bus was selected via random sampling.

It was decided to place monitors at three locations on each of the 100 feeders. The first monitor would be located at or near the substation. The other two were chosen by a random sampling process involving sectionalizing of the feeders into homogeneous lengths of power quality. The section lengths were determined by isolating large loads and important distribution equipment such as capacitors, reclosers, sectionalizers, and line branches. Each feeder was divided anywhere from three to twenty or more sections. Two sections were then selected using a random number table. The first section selected after the substation is often called the "feeder middle" and the second is called the "feeder end." Note that these terms are used loosely, since they only tell the location of the monitors relative to each other.

The purpose of the site selection process was to identify a population of monitoring locations which were a statistically valid representation of the types of distribution feeders present across the United States. We use the term "statistically valid" to refer to our ability to have developed an unbiased characterization of power quality for the set of participating utilities and in our capability to develop models and estimates of power quality that will be applicable nationally and for arbitrary system types that extend beyond those in the participating utilities. This is discussed further in [1].

Weighting factors need to be developed that will be used in these models extrapolating the results of the DPQ study to the national sample. This is accomplished by comparing the percentage of individual site characteristics in the DPQ population with those at the national level. Any results from the project which are presented without the weighting factors should be considered preliminary and exploratory. The statistical analysis presented in this paper, meant as an update on the ongoing data collection and initial results, is unweighted and therefore should be considered representative only of the sites monitored during the first twelve months of the project.

PQ Monitor:

The monitoring instrument used to gather data for the project was developed expressly for the project, the BMI 8010 PQNode. The PQNode is a user-configurable three-phase voltage and current measurement device. It can be triggered to record a disturbance record whenever the voltage of any of the three phases cross preset limits. It also samples both instantaneous and rms steady-state voltage and current, voltage harmonics up to the 100th, and current harmonics up to the 50th. Measurements are taken by four voltage and four current channels.

Statistical Data Analysis

Though monitoring began in 1991, it was not until June 1993 that the official data collection phase began. This will continue until September 1995, at which time about 5000 monitor·months of power quality data will have been collected. The data analysis presented in this report covers the first twelve months of the project. During that time period, 155 monitor·years of data were collected from 223 monitors that were in place recording data. The database in which the processed, or characterized, measurements are contained is 8.5 GB in size. Over 182,000 triggered events, or disturbances, were collectively recorded by the 223 monitors. In addition, more than 2.5 million one-cycle, three-phase, steady-state voltage and current "snapshot" measurement samples were taken.

RMS Voltage Disturbances:

Figure 2 presents an example of an rms voltage disturbance recorded by an EPRI DPQ power quality monitor. The instrument is triggered to record an "RMS Variation" disturbance whenever any of the three cycles has an rms value above or below user-specified limits for a user-specified number of cycles. For all of the DPQ monitors, the triggering thresholds are 95% and 105%, (0.95 and 1.05 per unit). The base of 100% voltage is not determined by using the feeder distribution voltage nominal, but rather by using the long-term average voltage measured by the three instruments on the feeder.

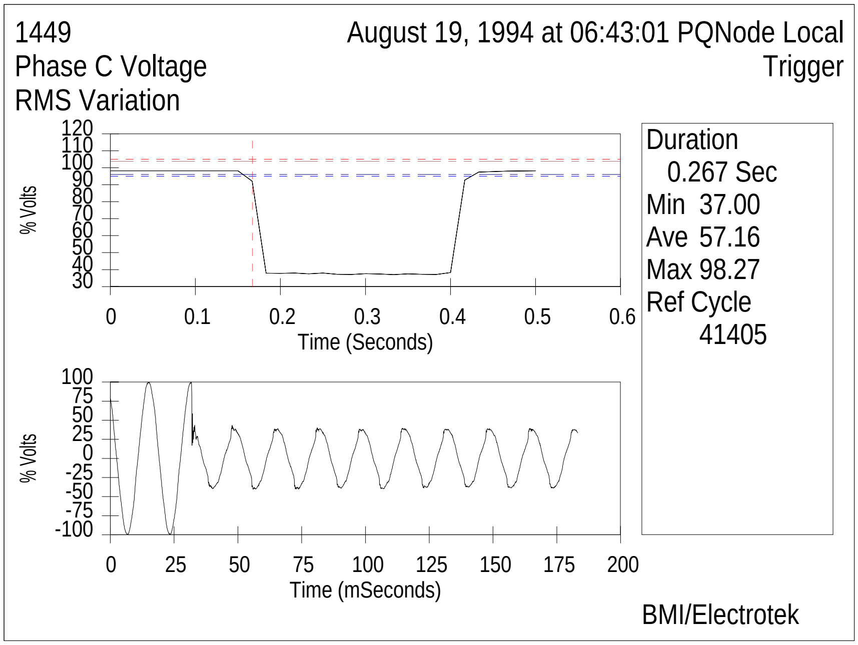

Figure 2: Example of a Voltage Disturbance Categorized as an RMS Variation

About 60,000 voltage disturbances were recorded by the 223 different monitors recording during the period for 1/6/93 to 1/6/94. For each, we determined event statistics similar to those shown in the Figure 2. For instance, this voltage event lasted 267 ms, and had a minimum rms voltage value of 37% of the monitoring location's long-term minimum voltage. Figure 3 is a histogram of the voltage magnitudes of all of the rms disturbances recorded by every monitor in the project which fell into specific ranges. The ranges are those proposed by the IEEE Working Group P1159 [4], namely:

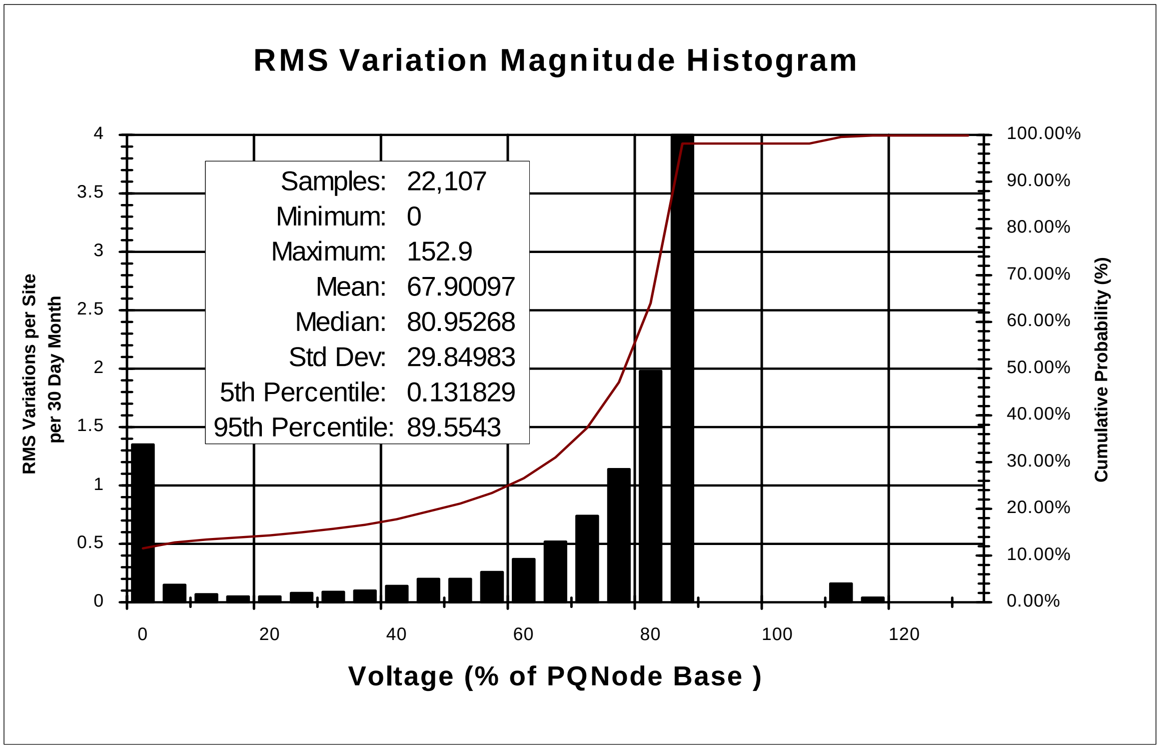

Figure 3: Histogram of the Voltage Magnitude of all RMS Variations

Sag: a decrease to between 10% and 90% (0.1 and 0.9 per unit) in rms voltage for durations of 0.5 cycles to one minute;
Swell: an increase to between 110% and 180% per unit in rms voltage or current for durations from 0.5 cycles to one minute;
Interruption: the complete loss of voltage (less than 10%) on one or more phase conductors for a time period. (P1159 further classifies interruptions based on their duration.)

The height of each column in Figure 3 denotes not a simple count of measurements which fell into the magnitude range represented by the column but rather a rate of occurrence of disturbances. It indicates that the magnitude of an rms disturbance appears to follow a normal distribution, skewed toward sag events, which outnumber swells 20 to 1. It also shows that interruptions, represented by the very last bar on the left of the histogram, do not follow the same distribution as sags. This is because a sag is the result of a fault or a motor start - a random event - while an interruption is a deliberate and controlled attempt by a distribution system device to clear faults upline from the monitor.

Figure 4 presents the same measurements as in Figure 3, except that it includes the duration of the disturbance as well as the magnitude. The figure indicates that the majority of rms voltage events have a magnitude between 70% and 90% of nominal and a duration of less than 10 cycles. Both Figure 3 and Figure 4 represent a raw count of disturbances. They include data from up to three monitors on each feeder and up to three phases from each event may appear on the same chart. In addition, the same power system event may have multiple records in the power quality database because of numerous crossings of the monitoring instruments' trigger thresholds, as would occur during a recloser sequence. Both figures present statistics on instrument measurements, rather than on customer or utility perception of the incidence of events.

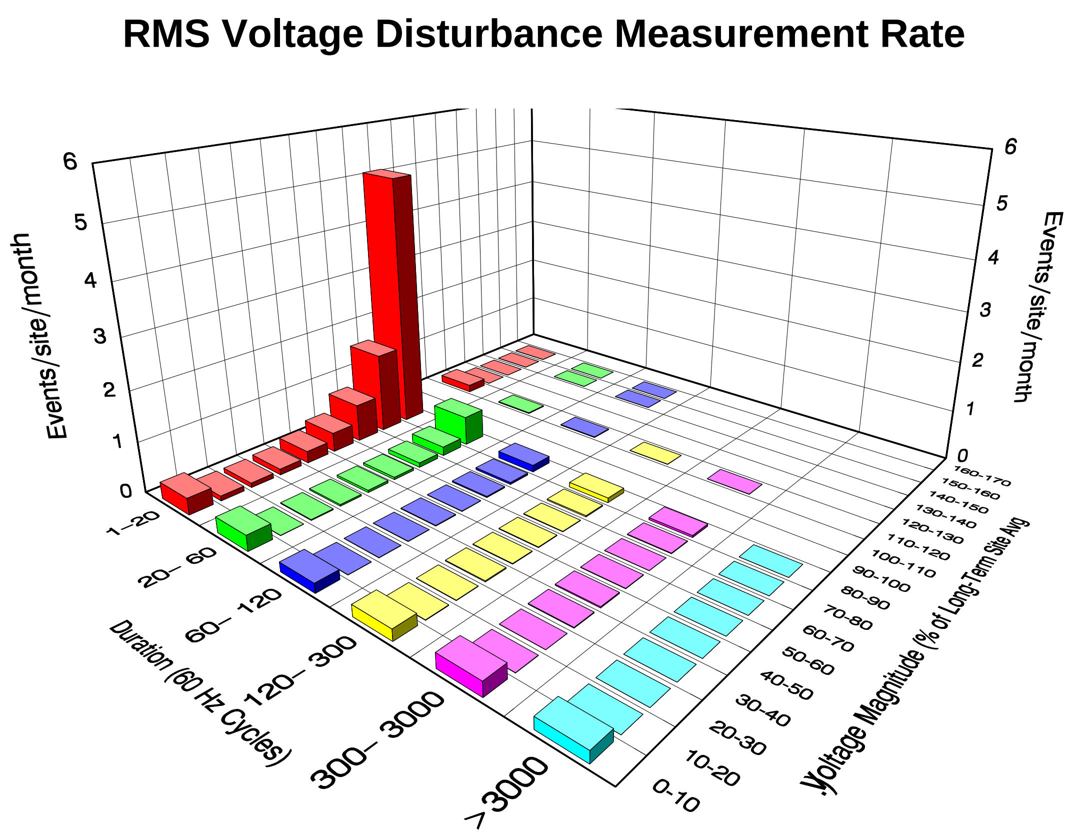

Figure 4: Two-variable Histogram of Voltage Magnitude and Duration of all RMS Variations

In order to obtain an event occurrence rate which may be more useful in assessing the impact of rms voltage disturbances, we have proposed the definition of a power quality "customer event," which attempts to group measurements related to the same fault or equipment operation sequence. We do this by grouping all of the measurements that were recorded per site in five-minute periods and then selecting that event which is the worst-case of that period. Determining which measurement of the five minute period to use depends upon the type of end-use equipment with which we are concerned. No one rule can be developed to identify the worst-case which considers the sensitivity of all types of distribution equipment and loads. For instance, a computer being fed by a switch-mode power supply reacts differently to a voltage sag than does an adjustable-speed drive, which in turns reacts differently to an induction motor. In this report, we consider the simplest method of determining a worst-case disturbance by identifying the minimum voltage seen on any phase during the five minutes.

For instance, consider the case where a two-fast, two-slow recloser sequence causes the monitoring instrument to record four rms voltage variations. These four measurements could have been recorded over a period of seconds, and would appear many times in the resulting power quality database. However, by the "customer event" method, we count only one disturbance with a 0% voltage magnitude.

Figure 5 presents the same 22,000 disturbances presented in Figure 3 but including only sags and interruptions. A separate histogram was developed for each feeder section(i.e., the feeder substation, feeder middle, and feeder end). This is to prevent double or triple-counting a disturbance which was recorded by more than one instrument on a feeder. In order to construct Figure 5, we combined the three plots together by averaging them and obtaining a feeder composite with respect to customer event voltage magnitudes. We interpret Figure 5 that there would be 2.5 customer events per site per month where the minimum voltage magnitude recorded would be between 85% to 90% of the site's long-term average voltage.

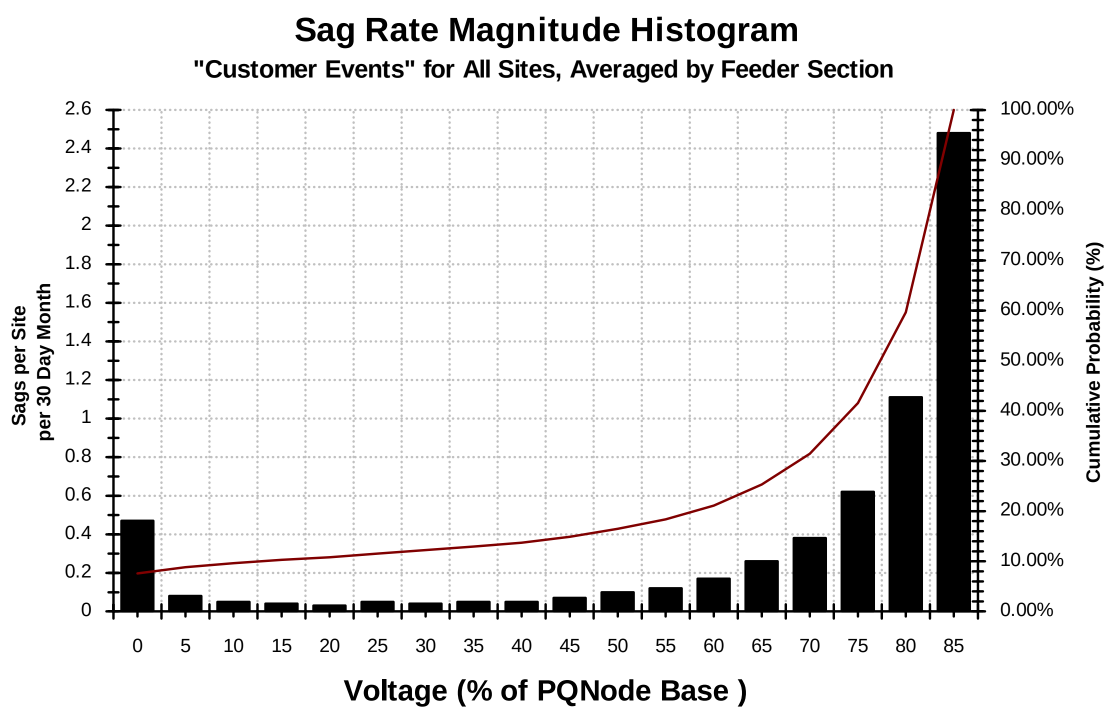

Figure 5: Histogram of the Voltage Magnitude of the "Customer Events" Derived from all RMS Variations

Table 1 presents a summary of the three histograms used to construct Figure 5, created by summing the heights of numerous columns. Note that there are nearly twice as many interruptions on average at the feeder sections identified by "feeder end" as there are at the feeder substations. This is mostly due to the operation of feeder reclosers. Another observation is that the average number of sags per month per site recorded by the monitors at the feeder substation, middle, and end do not vary significantly. This is once again due to the nature of faults and large motor starting, as they are random in magnitude, location, and occurrence. Thus we see no difference in long-term statistics no matter where the monitor is located.

	Feeder Substations	Feeder Middle	Feeder End	Feeder Mean
Interruptions (Voltage <=10%)	0.504	0.666	0.920	0.696
Sags (Voltage >10% and <=90%)	5.281	5.697	5.323	5.434
Sags and Interruptions	5.785	6.362	6.243	6.130

Table 1: Customer Events Summary by Section, in Events/Site/Month

Voltage Harmonics

Harmonic distortion is a topic which has received increased attention as of late because of the growing number of electronic loads on the power system which both cause distortion and are most affected by it. Possible problems due to distortion include transformer over heating, motor failures, capacitor fuse blowing, and misoperation of electronic loads. Harmonic currents are caused by devices or loads with nonlinear voltage/current characteristics which draw nonsinusoidal current when excited by a sinusoidal voltage. These devices include power electronic systems (adjustable-speed drives, uninterruptible power supply (UPS) systems, inverters, rectifiers), saturated transformers, arc furnaces, and fluorescent lighting.

Voltage distortion on the utility system is generally caused by distorted current being drawn through the system impedance. IEEE Standard 519 [3] sets a voltage total harmonic distortion (THD) limit to 5% for systems below 69 kV, which utilities have the responsibility of maintaining. Voltage THD is the ratio of the total harmonic rms voltage to the fundamental (60 Hz) component of rms voltage.

Figure 6 presents a plot of voltage THD versus time at a site typical of the EPRI DPQ population. Evident is the daily cyclical pattern which distortion often follows. The (mean) average value of THD for this particular month was 1.25%, which is well below the limit set by IEEE 519.

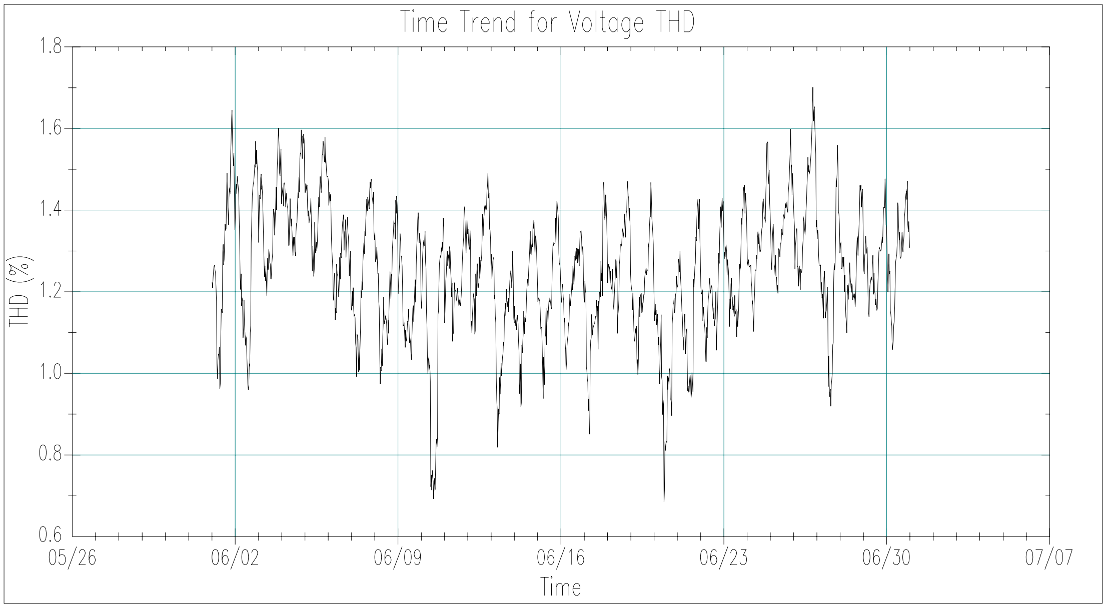

Figure 6: Trend of Voltage THD Versus Time for a One Month Period at a Typical Site

The average voltage THD values of each of the 223 monitoring sites are represented in Figure 7. This histogram can interpreted that 41 sites had a mean average value of voltage THD of 1.00% to 1.25% during the monitoring period. By using the cumulative probability line overlaid on the histogram, we see that 78% of the sites had an average distortion value less than 2% and that none had an average THD above 5%.

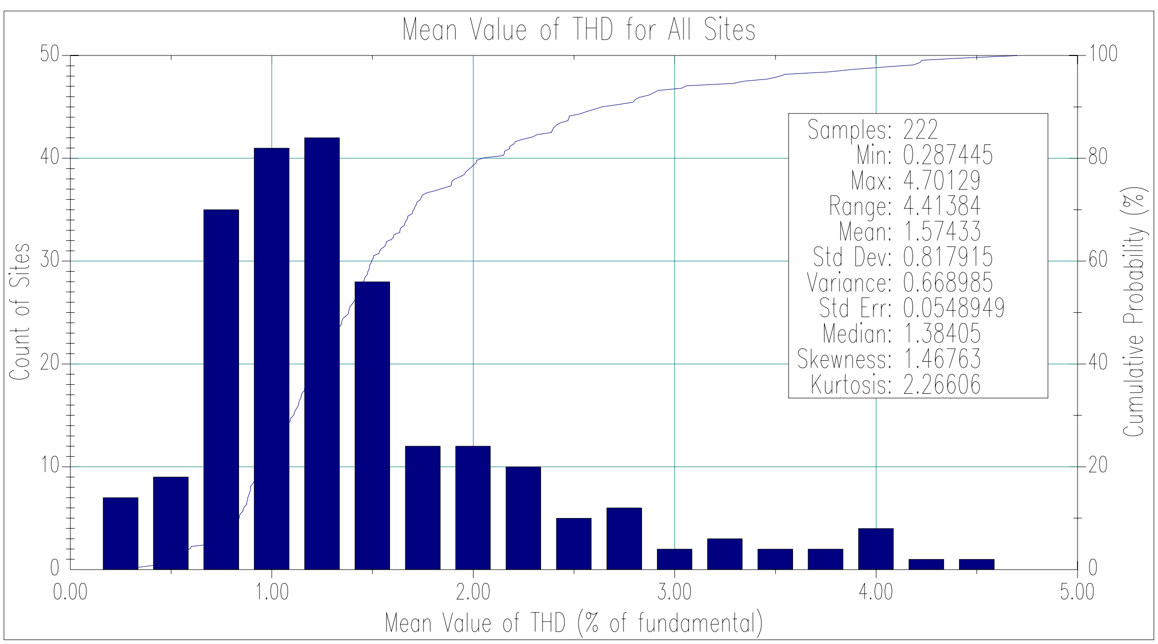

Figure 7: Distribution of Average Values of Voltage THD at 223 Sites of the EPRI DPQ Project

Figure 8 presents the 5th percentile, mean, and 95th percentile for THD and the first twelve harmonics at the 223 sites in the DPQ population during the twelve month period. The significance of each 95th percentile value is that 95% of the THD or harmonic measurements were below the value represented by the respective columns. (A harmonic is an integer multiple of the fundamental power frequency; i.e., the 3rd harmonic is equivalent to 180 Hz for a 60 Hz system.) Figure 8 indicates that the average value of THD was 1.57%; 5% of the measurements were below 1.05%; 95% were below 2.18%. We can also see that on average odd harmonics are far more common than even. This makes good sense, since even harmonics require a load with an impedance which differs on positive and negative current. The 3rd and 5th harmonics are the largest seen in the project composite, with an average 3rd harmonic value of 0.8%, and an average 5th harmonic value of 1.1%.

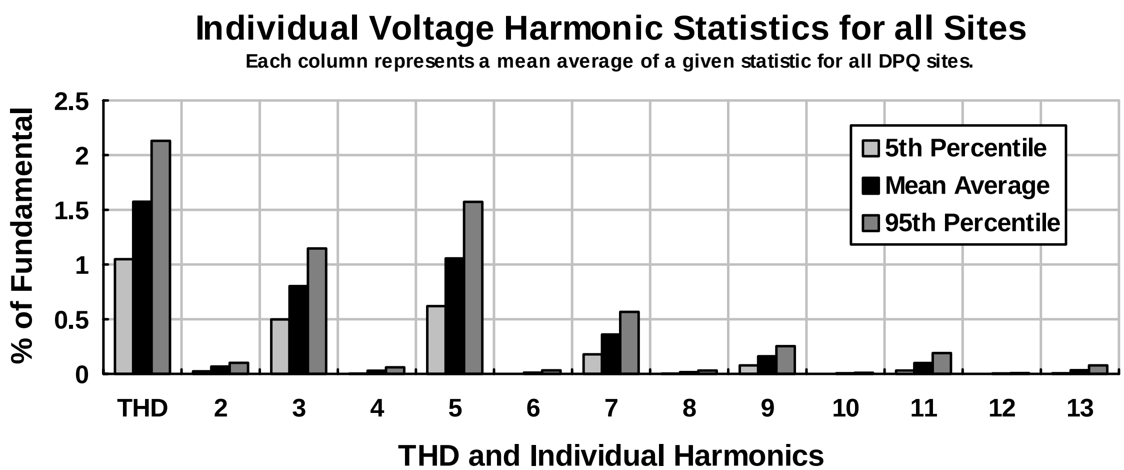

Figure 8: Average Values of Voltage THD and Harmonics at 223 Sites of the EPRI DPQ Project

Steady-State Voltage Regulation

Figure 9 presents a typical oscillographic measurement from a site in the DPQ Project. Its rms voltage value is 100.5%, or 1.005 per unit of the monitored feeder's nominal voltage rating of 4.16 kV. A three-phase, single-cycle voltage and current "snapshot" measurement was taken every half hour at this and the other 222 sites that were active over the monitoring period.

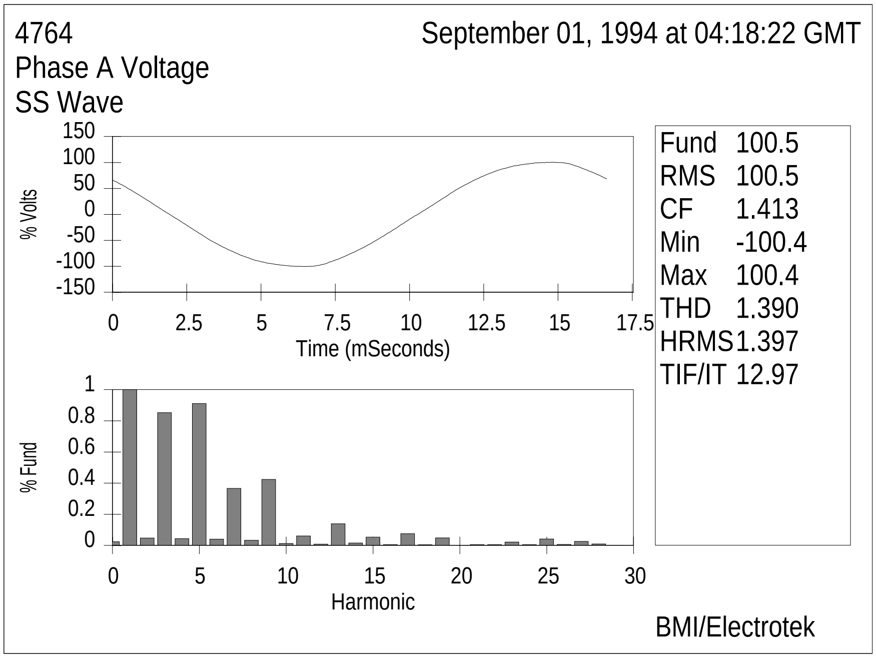

Figure 9: Steady-state Waveform "Snapshot" from an EPRI DPQ Project Monitoring Site

In Figure 10 we see an rms voltage trend taken for the same monitoring site over the monitoring period. Data reduction has taken place by calculating the maximum, average, and minimum value of steady-state voltage from the 144 measurements taken each day (3 phases, 48 snapshots). The top, middle, and bottom lines represent the maximum, average, and minimum snapshot values for rms voltage measured each day, respectively.

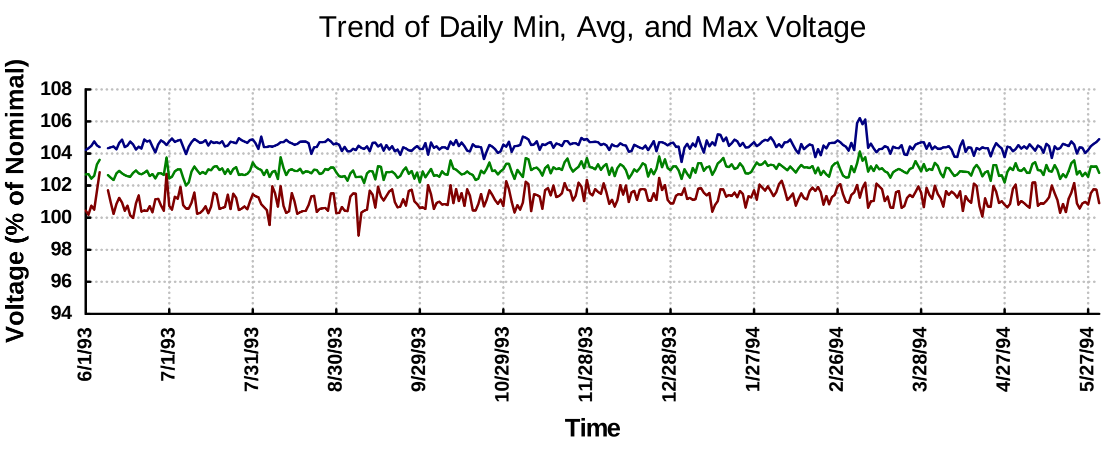

Figure 10: Trend of Daily Minimum, Average, and Maximum Voltage

We can average the three trends in Figure 10, thus calculating "statistics on statistics." These are the average daily maximum, average daily average, and the average daily minimum values. We can also calculate these three values for each site; the distribution of these quantities for all of the sites in the project appears in Figure 11, Figure 12, and Figure 13.

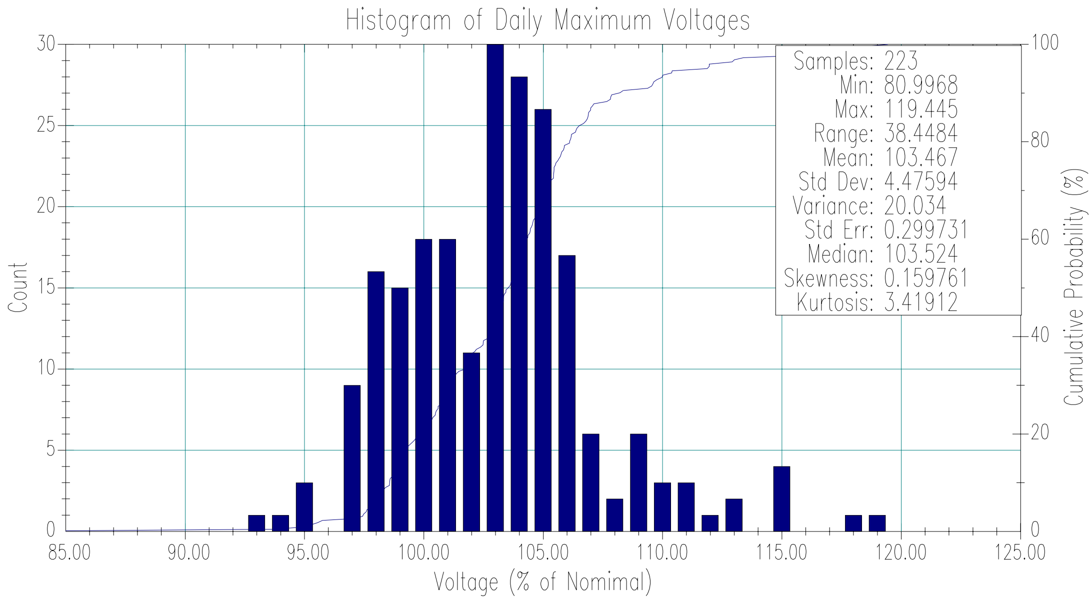

Figure 11: Histogram of Average Daily Maximum for 223 Sites

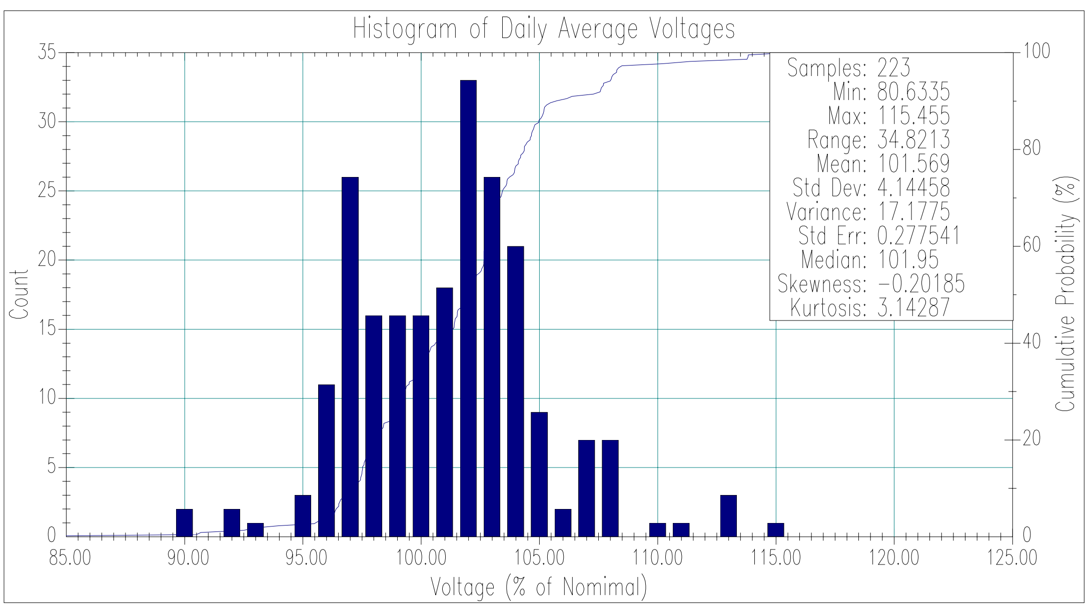

Figure 12: Histogram of Average Daily Average for 223 Sites

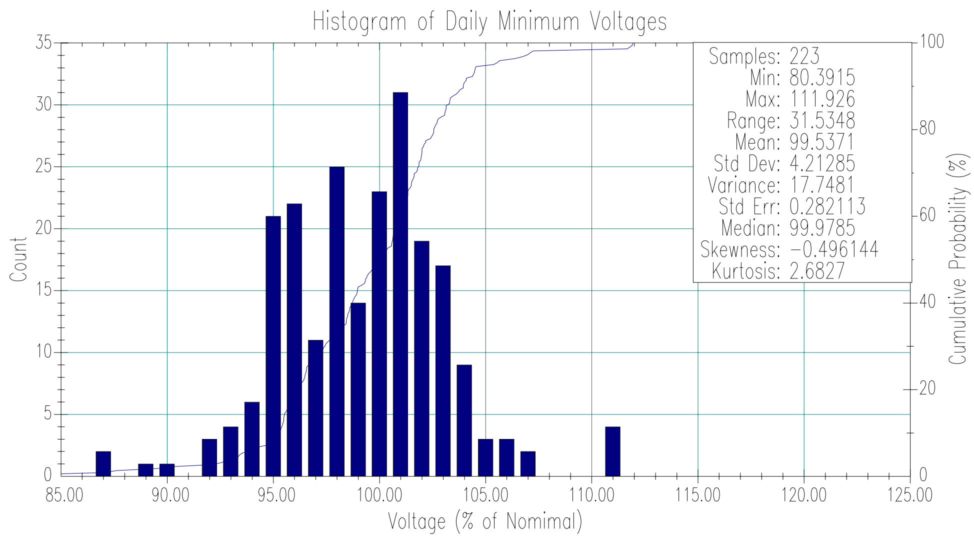

Figure 13: Histogram of Average Daily Minimum for 223 Sites

The manner to interpret these histograms is to understand that we have 223 samples representing the 223 sites measuring for the year. The height of each column tells us how many sites had an average daily maximum, average, or minimum value of rms voltage within the same voltage interval. For instance Figure 11 indicates that 30 sites had an average daily maximum value of 103% to 104% of nominal for the year. By making use of the overlaid cumulative probability lines, we note that 20% of the monitoring sites showed an average daily minimum voltage below 96% (0.96 pu) of nominal, and that 10% of the sites had an average maximum voltage above 108%. The median average daily voltage for all sites was 101.95% and the corresponding mean was 101.57%, indicating that the distribution voltage measured tended on average to be slightly higher than the circuits' nominal values. Six sites had an average daily average voltage above 105%, while eight had an average daily average below 95%.

Figure 14 presents an alternate method of examining the data presented in previous figures. Here we calculated the average voltage at each monitoring site and used that for normalization rather than the distribution nominal value. We again calculated the average daily minimum and average daily maximum voltage for each site, but normalized the data to the site average voltage for the year. Instead of plotting the results in two separate graphs similar to Figure 11 and Figure 13, we include them on the same bar chart, making a hybrid histogram. The bars in this chart more closely follow the bell-shape which one would expect with measurements as numerous as presented in this report. By examining the left-hand distribution in Figure 14, we can say that 80 (36% of the total 223) sites had an average daily minimum voltage that was 98.5% to 99.0% of the monitoring sites year-long average. The right-hand distribution indicates that 84 (38%) sites had an average daily maximum voltage that was 101.0% to 101.5% of the site average.

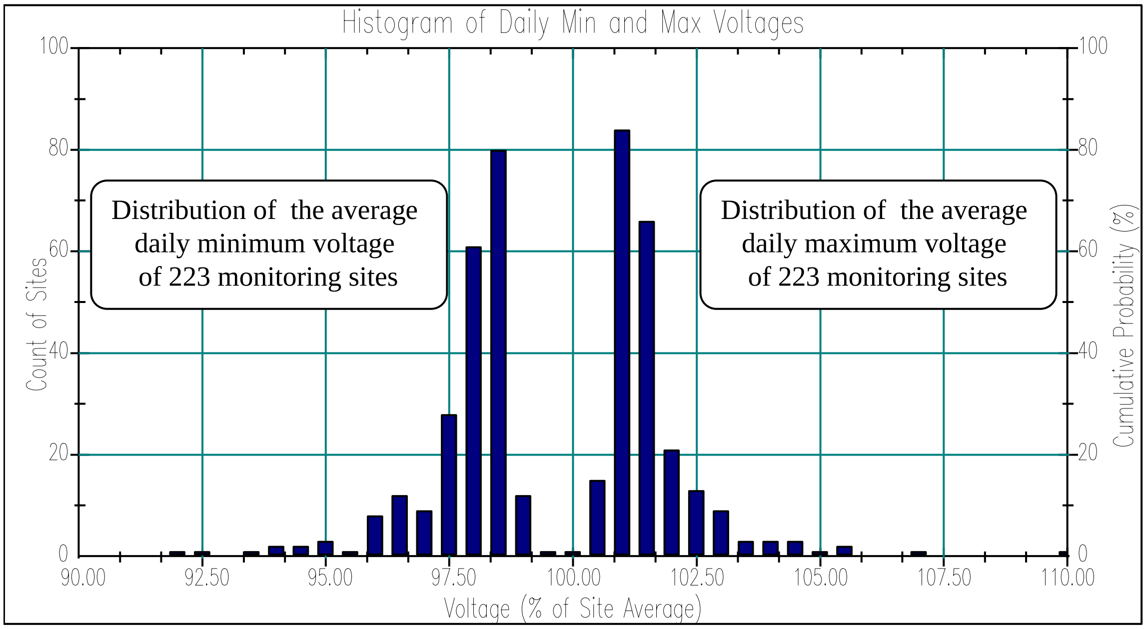

Figure 14: Histogram of Average Minimum and Maximum Values (Voltage in Percent of Each Site's Average)

Figure 15 is one final interpretation of the steady-state voltage measurements. We computed the average daily voltage range (average daily maximum minus the average daily minimum) and plotted them in a histogram. One piece of information from this plot is that 95% of the monitoring had an average daily voltage range below 4.5% of nominal, with a few showing an average range of over 10%.

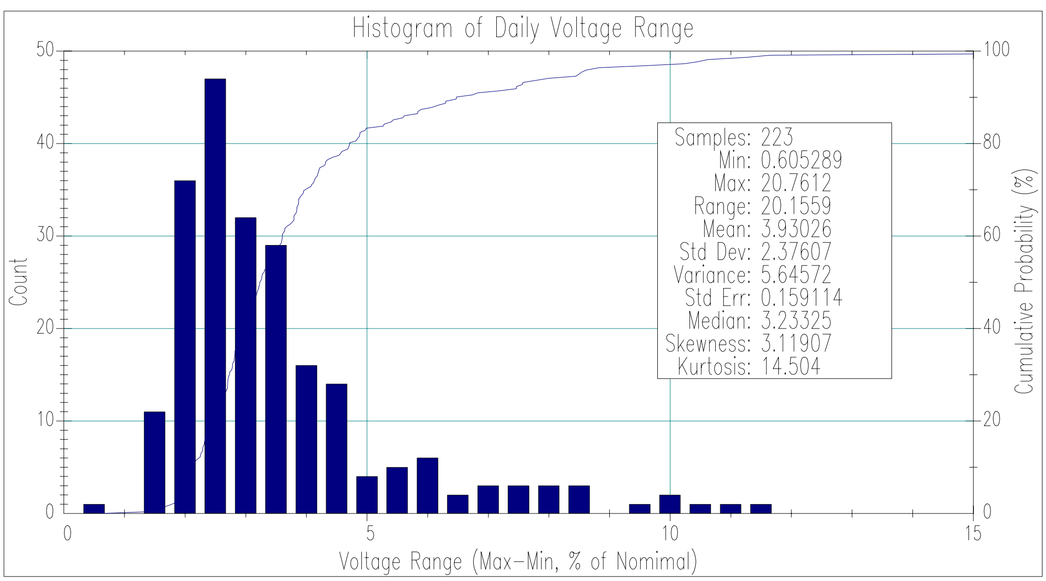

Figure 15: Histogram of the Average Daily Range (Voltage in Percent of Each Site's Nominal)

Conclusions
The EPRI Distribution Power Quality Project is beginning to yield valuable baseline statistics regarding power quality from a highly diverse set of monitoring sites across the United States. Monitoring will continue until September of 1995, with final characterized data becoming available in early 1996. The final report of this data will include weighting factor analysis, which will attempt an extrapolation of the results from the project's study sites to the national level.

References
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