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Impacts of Electric Vehicle Charging on Electric Power Distribution Systems

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FINAL REPORT

Impacts of Electric Vehicle Charging on Electric Power Distribution Systems

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IMPACTS OF ELECTRIC VEHICLE CHARGING ON ELECTRIC POWER DISTRIBUTION SYSTEMS

FINAL

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16. Abstract

Electric Avenue, located on the PSU campus along SW Montgomery Street, is a joint project between Portland General Electric, Portland State University (PSU) and the City of Portland. Launched in August 2011, Electric Avenue is intended as a research platform for understanding the impact electric vehicles have within the larger context of the city. For this research, we used Electric Avenue to investigate the impacts electric vehicles (EVs) may have on electric power distribution systems. Nonlinear loads, such as EV chargers, will often introduce power quality (PQ) issues within distribution circuits, which can have detrimental effects on system components. PQ encompasses several specific concepts such as harmonic distortion, DC offset, phase imbalance, and voltage deviations, among others, and these are quantified in myriad ways. For this study, we focus on harmonic currents since these have the potential to affect the lifetime of magnetic assets such as distribution transformers and instrument transformers. Utilities plan asset management by anticipating the nature of loads and selecting assets designed to handle those loads. A deeper understanding of these matters specific to EVs will aid utilities in the design of distribution systems and provide guidance for asset planning. A load's PQ affects magnetic assets because of the potential for insulation failure and core saturation. Understanding the PQ of nonlinear loads assists distribution engineers with the selection of k-factor ratings for distribution transformers, selection of CTs and VTs, protection settings and decisions regarding conductor ampacity. For this study, we measured the PQ of EV chargers, paying specific attention to total harmonic distortion (THD) of individual EV chargers and total demand distortion (TDD) of the Electric Avenue service. We also noted phase imbalance, phantom loading and other PQ issues observed during the course of our study. Our objective is to expand the electric utility industry's understanding that EVs have on these issues.

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EXECUTIVE SUMMARY

Electric Avenue, located on the Portland State University (PSU) campus along SW Montgomery Street., is a joint project between Portland General Electric (PGE), PSU and the City of Portland.[1] Launched in August 2011, Electric Avenue is intended as a research platform for understanding the impact electric vehicles (EVs) have within the larger context of the city. For this research, we used Electric Avenue to investigate the impacts EVs may have on electric power distribution systems.

Nonlinear loads, such as EV chargers, will often introduce power quality (PQ) issues within distribution circuits, which can have detrimental effects on system components. PQ encompasses several specific concepts such as harmonic distortion, DC offset, phase imbalance, and voltage deviations, among others, and these are quantified in myriad ways. For this study, we focus on harmonic currents since these have the potential to affect the lifetime of magnetic assets such as distribution transformers and instrument transformers.

Utilities plan asset management by anticipating the nature of loads and selecting assets designed to handle those loads. A deeper understanding of these matters specific to EVs will aid utilities in the design of distribution systems and provide guidance for asset planning. A load's PQ affects magnetic assets because of the potential for insulation failure and core saturation. Understanding the PQ of nonlinear loads assists distribution engineers with the selection of k-factor[2] ratings for distribution transformers, selection of CTs[3] and VTs[4], protection settings and decisions regarding conductor ampacity.

For this study, we measured the PQ of EV chargers, paying specific attention to total harmonic distortion (THD) of individual EV chargers and total demand distortion (TDD) of the Electric Avenue service. We also noted phase imbalance, phantom loading and other PQ issues observed during the course of our study. Our objective is to expand the electric utility industry's understanding that EVs have on these issues.

The OTREC Small Starts grant is intended to provide seed funding that results in further research. We are pleased to report that this objective has been met. PGE is now funding a follow-up study to this project, for which we will use our Electric Avenue PQ data to derive nonlinear models of various EV charge controllers. These models can be used within a simulation environment, such as MATLAB/Simulink, to inform distribution engineers as they plan for EV growth within their service territories. The modeling tool can be used to determine the number of EV charging stations that can be added to an existing feeder, or to plan feeder upgrades and new feeders that accommodate high EV penetration. Specifically, distribution engineers will be able

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[1] Electric Avenue website: www.pdx.edu/electricavenue
[2] Specified in ANSI/IEEE C57.110, k-factor denotes a transformer's ability to serve nonlinear loads without exceeding temperature limits.
[3] Current transformers.
[4] Voltage transformers.

use these models to select appropriate conductor sizing, protection settings and transformer ratings that meet the challenges imposed by the nonlinear nature of EV loads.

1.0   DISTRIBUTION SYSTEM IMPACTS

Power quality (PQ) is a measure of the fitness of electrical power from the utility to the electrical customer. Low PQ is of concern because it can cause variations in voltage magnitude, issues with continuity of service from utilities, and transient voltages and currents (Hunter, 2001). Harmonic distortion is a primary culprit in the causation of reduced power quality.

Our research is focused on investigating three hypotheses. One, we hypothesized that, because EV charge controllers are nonlinear loads and because EVs demand a large amount of power, the PQ issues presented by EV charging could have an impact on distribution feeders. Two, we also hypothesized that the total harmonic distortion (THD) of the current drawn by an EV charge controller would change as a function of time as the charge controller moved through various phases of the charging cycle. And third, we hypothesized that the *cumulative* effects of multiple charge controllers on the same feeder would result in distortion greater than that of any one charge controller, thereby setting an upper bound on the maximum number of EV charging stations that could be connected to a single feeder. As specified by IEEE 519.1992, that impact is a function of the size of the distribution feeder, as measured by the ratio of the short circuit current available at the point of common connection to the maximum fundamental load current, and quantified by the quantity total demand distortion (TDD).

Our intention was not to measure the TDD at Electric Avenue, which is very well sized for the EV loads currently connected to it. Rather, we used Electric Avenue as a means to gather data characterizing real-world EV charge controller PQ, measured as THD, for those individual chargers. We then used that THD information to project what the TDD consequences could be in distribution feeders as a function of the feeder size and design and as a function of the number and type of charge controllers connected to the branches of the feeder.

The concepts describing harmonic distortion within electric power distribution systems are discussed below.

1.1   HARMONIC DISTORTION

Harmonic distortion is a deviation of the current or voltage waveform from a perfect sinusoidal shape. In the case of nonlinear loads, such as EV charge controllers, current distortion is very common due to the need for using power electronics switches to convert power from an AC to a DC form. Introduction of these distorted currents into the distribution system can distort the utility supply voltage and overload expensive electrical distribution equipment. In order to prevent harmonics from negatively affecting the utility supply, the IEEE Standard 519-1992 was established with the goal of developing, "recommended practices and requirements for harmonic control in electrical power systems" (IEEE Std 519-1993). This standard describes the problems that unmitigated harmonic current distortion can cause within electrical systems as well as the degree to which harmonics can be tolerated by a given system. The standard recognizes the

responsibility of an electrical user to not degrade the voltage of the utility by drawing heavy nonlinear or distorted currents (Hoevenaars, LeDoux and Colosino, 2003).

1.1.1 Total Harmonic Distortion

EVs employ power electronics within the charge controllers that interface the vehicle's electric power system with the grid. For Level I and Level II chargers, vehicle charging is done by an on-board AC-DC controlled rectifier that couples with the electric service via a single-phase connector. For Level III charges, aka DC Fast Chargers, the charging is controlled by electronics within the charge controller (Putrus et al., 2009). In either case, the harmonic distortion introduced into the distribution system by these charge controllers can be measured in terms of THD. However, it should be noted that the THD of a charger changes throughout the charging cycle as the firing angles of the power electronics switches changes in response to the various phases of the charging cycle. Further, the THD on a utility feeder is compounded when multiple EVs are connected to the same service. Equation 1-1 illustrates how the THD for each charger is calculated.

$$I_{THD} = \frac{\sqrt{\sum_{n=2} I_n^2}}{I_1} * 100\% \tag{1-1}$$

1.1.1.1 Power Resolution Tree

The current harmonics in three-phase nonsinusoidal situations can be evaluated using the IEEE Standard 1459-2010 (IEEE Std 1459-2012). This standard quantifies the active and reactive powers in a three-phase unbalanced system, as seen in Figure 1.1, based on the effective apparent power for the system, S_e. The standard goes further to break down the powers into their fundamental and nonfundamental components S_{e1} and S_{eN}, respectively; positive sequence components (S_1^+, P_1^+ and Q_1^+); and system unbalance as quantified by fundamental unbalance power S_{1u}. Finally, harmonic active (S_{eH}, P_{eH} and D_{eH}) and distortion (D_{eI} and D_{eV}) powers are described using the standard.
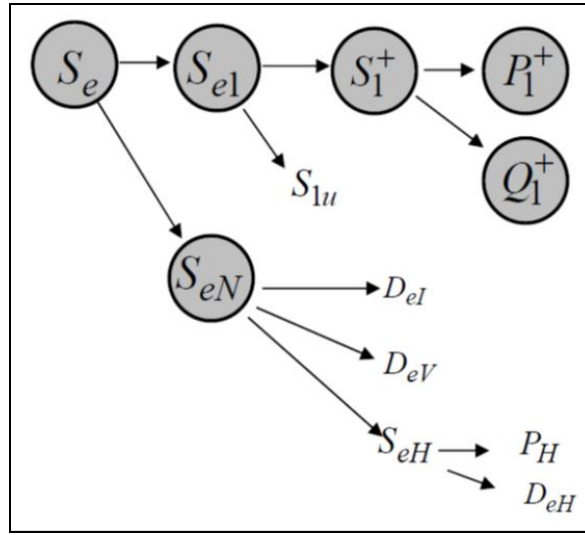
Figure 1.1: The power resolution tree for three-phase nonsinusoidal conditions (Emanuel, 2012).

1.1.2 Total Demand Distortion

TDD is the harmonic current distortion of a system in percent of maximum demand load current. (IEEE Std 519-1992). The maximum allowable TDD is determined by the ratio of the short circuit current at the point of common coupling to the to the average maximum demand load current for the system for the previous 12 months (Hoevenaars, LeDoux and Colosino, 2003). Ideally, the harmonic distortion caused by a single consumer should be limited to an acceptable level at any point in the system; however, the prescribed levels for TDD establish the maximum allowable current distortion for a given system (IEEE Std 519-1992). Equation 1-2 outlines how the TDD for a system is calculated.

$$I_{TDD} = \frac{\sqrt{\sum_{n=2} I_n^2}}{I_L} * 100\% \qquad \text{(1-2)}$$

1.2 EFFECTS OF HARMONICS ON DISTRIBUTION ASSETS

IEEE 519.1992 discusses the impacts that harmonic distortion can have on distribution assets, particularly transformers, power cables, capacitors, metering, relaying and switch gear. Harmonic distortion also affects nearby loads, particularly power electronics devices and motors. Below, we discuss impacts on some of these assets; we refer the reader to IEEE 519.1992 Chapter 6 for further detail.

1.2.1 Transformers

Current harmonics can be especially troublesome for power transformers. One example of the losses caused by high harmonic content in the system is I^2R losses. These losses are due to higher-order currents within the transformer windings. If the root mean square value of the load current is increased due to a harmonic component, the I^2R losses increase accordingly (Said and Nor, 2008). Consequently, the transformer will consume more real power than anticipated, making its efficiency of conveying power to customers lower.

Another concern in the presence of increased harmonics are eddy current losses in the core of the transformer. These currents create an abnormal temperature rise in the windings of the device. This increased temperature accelerates the loss of insulation within the transformer, and can ultimately lead to a shortened life span for the equipment (Elmoudi, Lehtonen and Nordman, 2006). Eddy current and core losses are frequency-dependent, so higher-order harmonics are particularly problematic for transformers.

Other losses due to increased harmonic content are stray flux losses. These can occur in the core, clamps, tank and other iron components of the transformer. These stray losses may increase the oil temperature and thus hot spot temperatures within the transformer. This can also contribute to the premature degradation of the transformer insulation and oil, leading to eventual catastrophic failure of the equipment.

1.2.2 Power Cables

The primary effect of harmonics on power cables is the additional heating due to an increase in the I^2R losses. This can be attributed to the two phenomena known as skin effect and proximity effect, both of which vary as a function of frequency as well as conductor size and spacing. Also, cables involved in system resonance may be subjected to voltage stress and corona, which can lead to dielectric (insulation) failure (IEEE Std 519- 1992).

1.2.3 Relays, Switch Gear and Metering Equipment

Protective relaying equipment, switch gear and metering equipment may also be negatively impacted by the presence of harmonic currents. Relaying equipment may operate more slowly because of higher pick-up values than settings would otherwise dictate, resulting in unexpected operation. Fuses may experience premature operation due to I^2R heating by harmonics. And as with power transformers, harmonic currents can increase heating in CTs and VTs due to I^2R, eddy currents and core saturation, leading to shortened asset lifetimes. Within switchgear, the presence of harmonics contributes to I^2R heating, reduces steady-state ampacity, and shortens lifetimes of insulating components.

1.2.4 Capacitors

Harmonics introduced by a nonlinear load may interact with nearby capacitors if the harmonic frequency is in resonance with a LC time constant. The inherent positive reactance of distribution cabling, transformers and loads can couple with the negative reactance of capacitor

banks, resulting in very high voltages and currents at resonant frequencies. The unexpected increased voltage stress and I^2R heating within resonating capacitors can result in a shortened asset lifetime or catastrophic failure.

1.3   SYSTEM IMBALANCE

Nonlinear loads create imbalance in three-phase systems. When system imbalance occurs, the current and voltage in one phase differs from that in another. This produces what is referred to as zero-sequence components. These zero-sequence components are comprised of the non-even multiples of triplen harmonics (Dahono, Widjaya, Syafrudin and Qamaruzzaman,1997). Examples of these are the 3rd, 9th and 15th harmonics. Zero-sequence components are troublesome because they add up in the neutral line of a wye configured system or circulate in the case of a delta wired system. When these zero-sequence currents superpose in the neutral line, they can cause excessive currents and can lead to conductor heating (Hiranandani, 2005).

2.0   MEASUREMENT & EVALUATION PROCEDURE

In order to analyze the impacts that EVs have on the local distribution system, the team gathered and analyzed two data sets that were collected at Electric Avenue. Located on the PSU campus on SW Montgomery Street between 6th and Broadway, the site has five Level 2 chargers and two Level 3 chargers, all of which were donated by six different manufacturers.[5] A drawing of the site, including key terms for this section, can be seen in Figure 2.1 The Level 2 units are single-phase machines that, when attached to an EV manufactured with a SAE J1772 charging receptacle, replenish the EV's battery with a 4-20kW input at 208 volts (V) of alternating current (Bohn and Chaudhry, 2012). Depending on the vehicle type, it can take 1-4 hours to fully replenish a depleted set of batteries (Yilmaz and Krein, 2012). The power electronics that control the flow for the Level 2 chargers are located onboard the vehicles themselves. However, in contrast, the Level 3 charging units are three-phase designs that deliver power through a CHAdeMO-style receptacle ranging from 20-50kW at 208V direct current and can recharge a set of EV batteries in as little as 30 minutes (Yilmaz and Krein, 2012). The power electronics that control the power flow for the Level 3 chargers are located at the site in the charging unit itself.
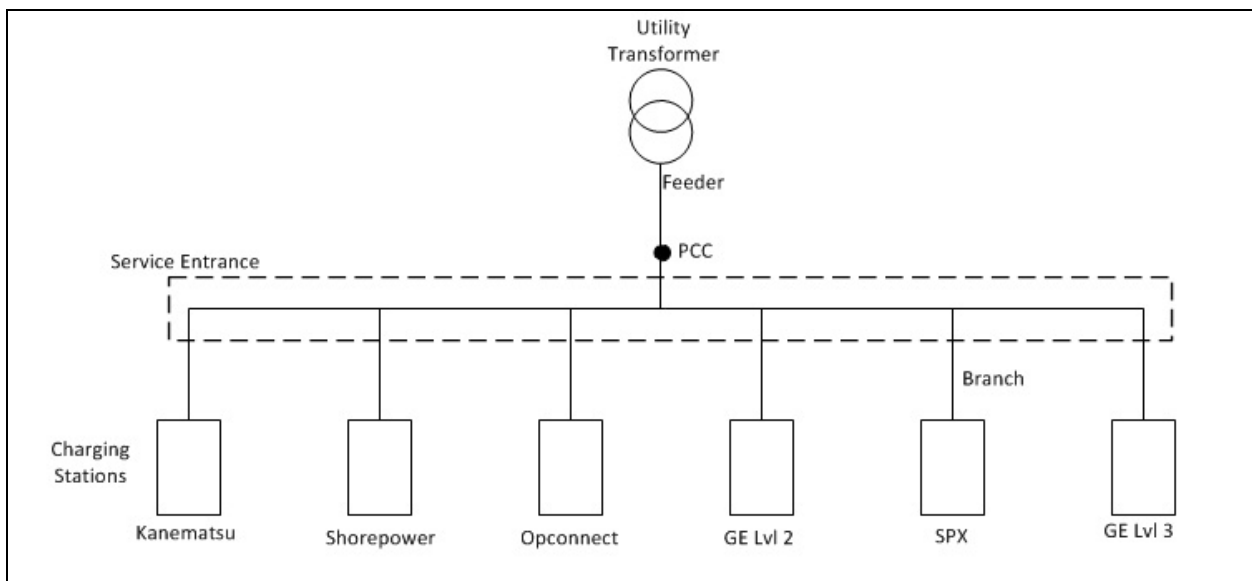
Figure 2.1: A drawing of Electric Avenue from the utility transformer to the chargers.

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[5] EATON, GE, Kanematsu, OpConnect, Shorepower and SPX.

2.1   ELECTRIC VEHICLES AT ELECTRIC AVENUE

During the initial data collection period in 2012, students from OTREC[6], under the direction of John MacArthur, performed a week-long survey of usage at Electric Avenue. The students monitored EV use along the avenue and performed driver surveys. From this survey, we know that a wide array of EVs use the site. During the data collection period in 2013, when individual charging circuits were being monitored, there were no representatives at the site tracking which types of EVs were plugged in during each charging event. Makes and models that often charge up at Electric Avenue include the Chevy Volt, Ford Focus Electric, Nissan LEAF, Toyota Prius Plug-In Hybrid, Honda Fit EV, Mitsubishi i-MiEV, Tesla Model S, Smart Electric Drive and THINK City.

2.2   MEASUREMENT PROCEDURE
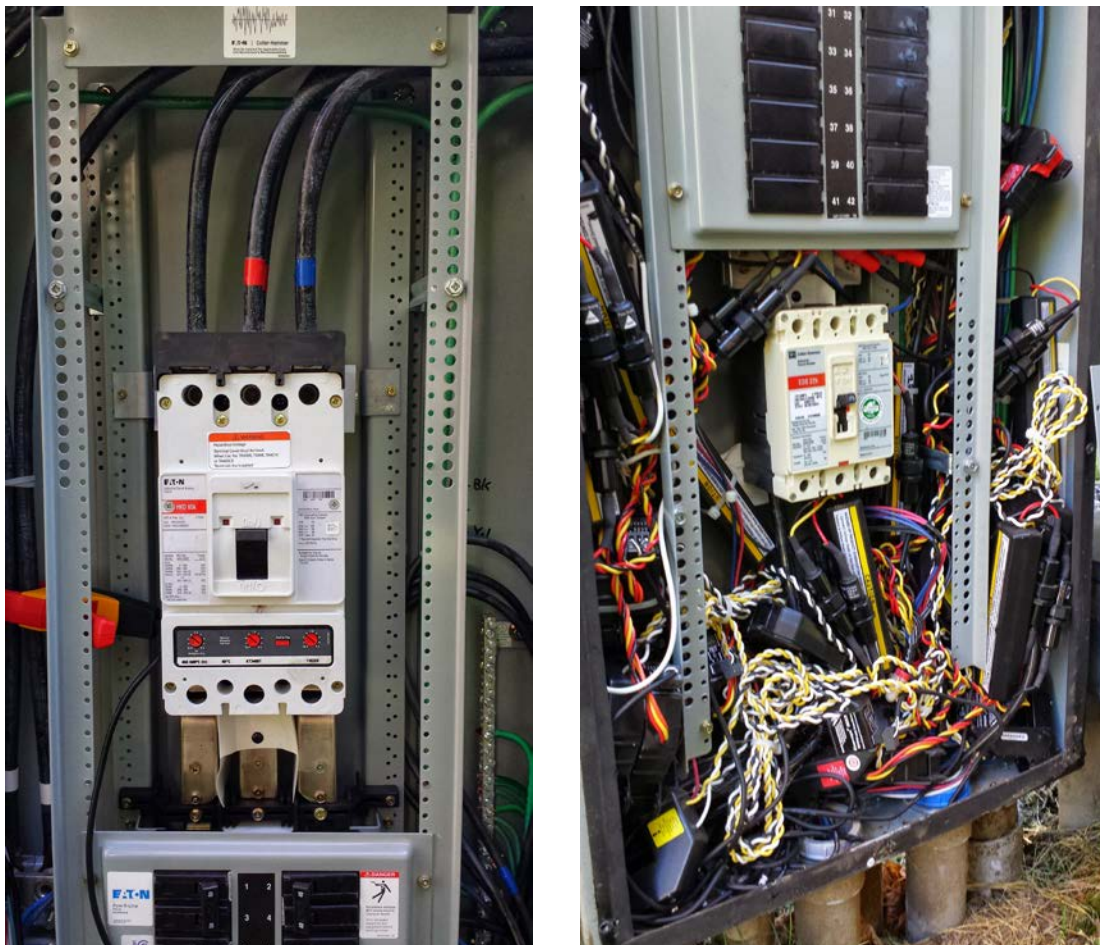
Figure 2.2: The service entrance at Electric Avenue with a red and yellow CT installed for data collection can be seen on the left. On the right, CTs and PTs permanently installed at the site.

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[6] Oregon Transportation Research & Education Consortium.

From October 22-29, 2012, Jack Siebel, a PQ engineer from PGE, installed a PQ meter on the main service at the Electric Avenue site. Jack oversaw the collection of voltage and current readings by the meter during the week. The data that he passed on to our research group included the voltage and current readings indicated as well as data derived from those readings by the PQ meter that included information about phase harmonics, real and reactive power, and power factor. All of the data was time and date stamped showing the average and maximum readings for each associated five-minute interval. The information proved very useful to begin to investigate how the system functioned as a whole; however, it was limited by the fact that individual charging circuits could not be identified when they were in use. In order to quantify the effects that a single charger has on the system, data was needed that isolated one charger at a time.

During the months of July and August 2013, Dale L. Garcia, a PGE electrical project manager, assisted with the installation of a Fluke 1750 PQ meter. The meter was connected to each of the individual charging circuits located at the site for one week. The equipment has the capability of monitoring up to three phases of voltage and current readings at a time. This enabled the team to collect data on more than one charging unit at a time during the data collection period. At the end of each week, the current and voltage transformers that were used to acquire the data were moved from one circuit to the next. At that time the week's data was downloaded in 24-hour periods from the Fluke to an SD card and taken back to be stored on PSU's servers.

2.3   DATA ANALYSIS PROCEDURE

The data was stored by the equipment in a .odn file type that can be opened with the Fluke Power Analyze software. The software displays the data sets in various types of graphs that illustrate voltage and current wave forms, harmonic spectra, THD, and power and energy. The user interface of the proprietary software allowed us to observe the overall harmonics for the entire collection period of each download; however, we were unable to analyze the system harmonics as a function of time. This is to say that we could see the harmonics of the entire charging cycle as a set of singleton values, but were unable to observe the variation in the harmonics from one part of the charging cycle to the next.

In order to evaluate the harmonics at various points in the charging cycle, we exported 70 millisecond-long sets of current points to Excel from multiple points throughout the charging event. These data sets were at a resolution of 256 points per 60 Hz cycle. With 65 microseconds between data points, we had a resolution that enabled us to utilize MATLAB software to perform a Fast Fourier Transform (FFT) on each of the selected periods throughout the charging cycle. An FFT is an optimized algorithm which allows the user to input a signal, in our case the current waveforms, and outputs the associated magnitudes and angles at various frequencies. The original signal is converted from the time domain to the frequency domain. This conversion allows the user to look at the frequency components that make up a signal, the harmonic spectrum.

From this harmonic spectrum the THD for each charger was calculated using the MATLAB software. Graphics of the original signals, paired with visual representations of the frequency spectrum, were created as well as tables containing the 3rd, 5th, 7th and 9th harmonics and THD

for each charger. A graph that illustrates the TDD for the entire system was also constructed utilizing the MATLAB graphics package.

3.0   RESULTS

In this section, we present the results from measuring the THD of a single-phase (Level I/II) charge controller and a three-phase (Level III, aka DC Faster Chargers) charge controller. We measured THD for a large number of charging events, but for this section we present only these two examples in order to illustrate the behavior of THD as a function of charge cycle. Additional data sets are presented in Appendix A-1.

As hypothesized, we found that THD varies during the course of a charge cycle, with THD typically starting out low during the beginning of the cycle but deviating towards the end of the cycle. The charge cycle typically starts with a large current that decreases as the cycle proceeds, as shown in Figure 3.1. Though THD may increase during the charging cycle, the magnitude of that distorted current is actually decreasing. The metric of THD may be somewhat misleading, implying the harmonic content within a branch is getting worse, when really what is happening is that harmonic content within a smaller current is increasing. Hence, THD is not a suitable metric for expressing the impact that harmonics have on a branch or feeder circuit. Rather, TDD is the preferred metric.
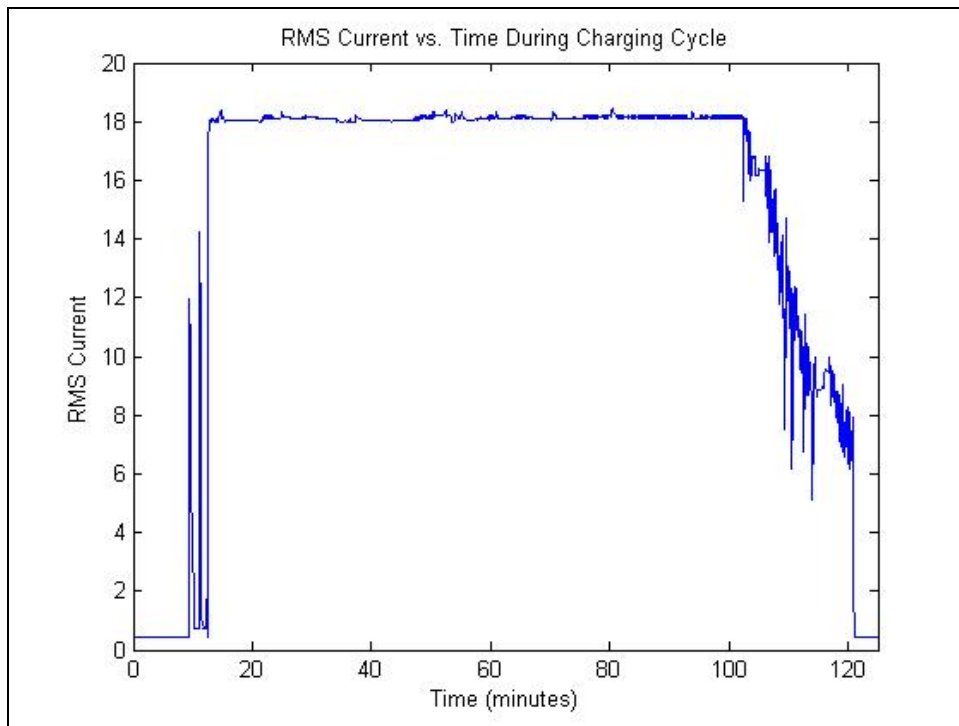
Figure 3.1: The RMS current of a charger during a charging cycle.

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3.1 TOTAL HARMONIC DISTORTION FOR A THREE-PHASE CHARGER

In this section, we analyze the THD of a single-phase (Level I/II) charger at two points of a charging cycle. Figures 3.2 and 3.3 each show two subfigures. The upper subfigures show roughly two periods of the current versus time, while the lower subfigures show a spectral plot, harmonic magnitude versus frequency, derived from the upper plots.

At the beginning of the charging cycle the current waveform is nearly sinusoidal, as shown in the upper portion of Figure 3.2. This indicates that the contribution of harmonic components to the current waveform is very small. These harmonic components can be seen in the bottom half of Figure 3.2. The fundamental is the largest peak, located at 60 Hz on the x-axis. Very small harmonic components can be seen at 180 Hz, 300 Hz and 420 Hz. These components are integer multiples of the fundamental frequency, 60Hz, and therefore correspond to the 3rd, 5th and 7th harmonics. (Note, even harmonics only appear in waveforms that have asymmetric shaping above and below the x-axis).
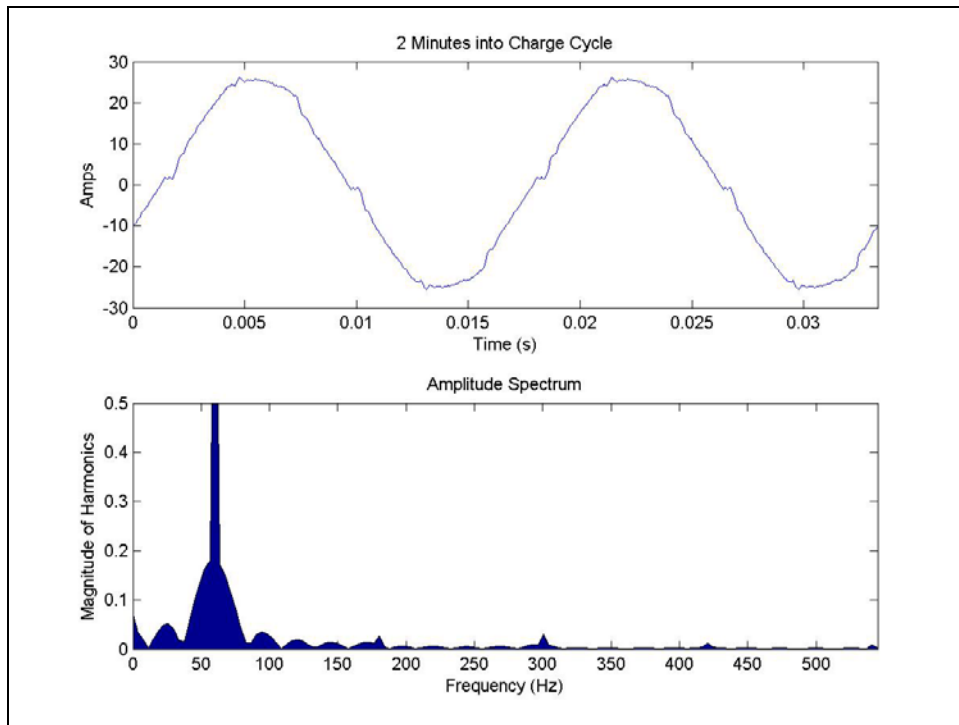
Figure 3.2: The temporal waveform, top, and its harmonic spectrum, bottom, for a single-phase charger near the beginning of a charging cycle. Note the waveform is nearly sinusoidal, corresponding to a spectrum consisting of only a fundamental component, and represented by a low THD of less than 4%.

As the EV's batteries reach their charge capacity the power electronics within the charge controller cause the current to decrease, entering a ``trickle charge'' mode best suited for topping off the last fraction of the battery capacity. This reduction in the current is accompanied by greater distortion in the current waveform, as clearly seen in the upper portion of Figure 3.3.

This distortion is also recognized by the larger magnitudes of the harmonics components in the lower portion of Figure 3.3. The 3rd, 5th, 7th and 9th harmonics can be seen at their corresponding frequencies, with magnitudes that are now much more pronounced. This means that they have a greater impact on the shape of the waveform, and that the THD of the current waveform is greater.
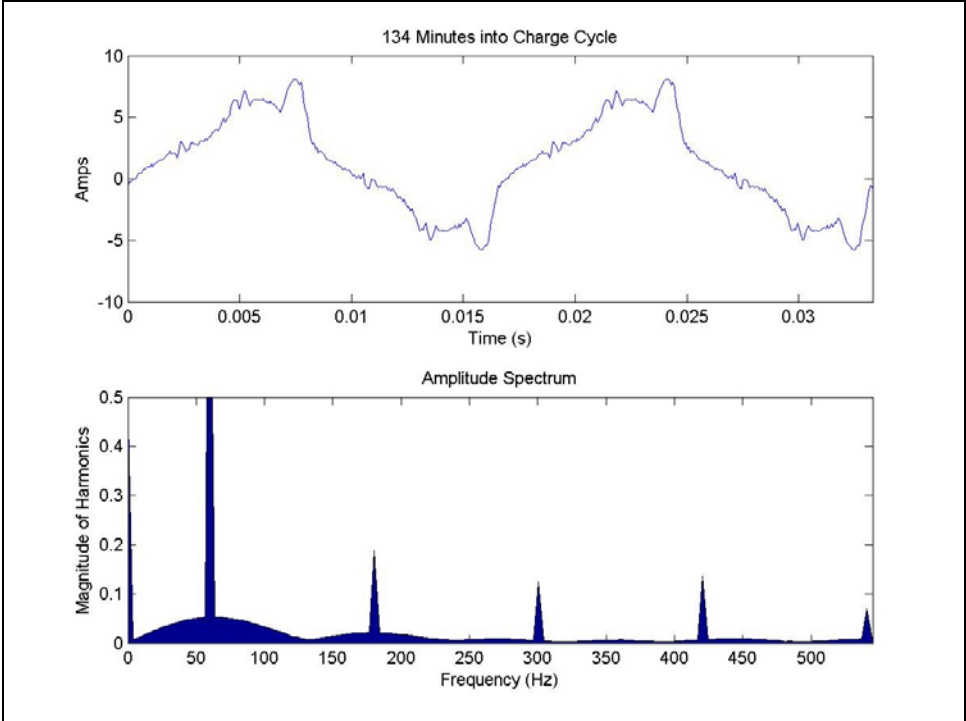
Figure 3.3: The temporal waveform, top, and its harmonic spectrum, bottom, for a single-phase charger near the end of a charging cycle. Note the higher order harmonic components, but lower current magnitude compared with Figure 3.2. The THD is now around 16%.

Table 3.1 lists the 3rd, 5th, 7th and 9th harmonics and THD at various points throughout the charging cycle, expressed as percentages of the fundamental current magnitude. Note THD changes during the course of the charging cycle, increasing toward the end of the cycle.

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		Time in Charging Cycle (minutes)						
		2	33	63	92	110	128	142
Harmonic (%)	3rd	0.1 < -63.1°	3.14 < 19.8°	0.21 < 40.7°	0.25 < 17.5°	0.34 < -52.5°	0.34 < 43.4°	0.73 < -61°
	5th	0.16 < -47.5°	3.4 < -88.1°	0.09 < -1.3°	0.1 < 13.6°	0.16 < -55.9°	0.18 < 74.8°	0.2 < 48.6°
	7th	0.06 < 74.9°	1.22 < 59.4°	0.08 < 65.7°	0.04 < -34.1°	0.13 < -78.7°	0.09 < -38.6°	0.27 < 82°
	9th	0.09 < -66.9°	0.85 < -19.4°	0.05 < 14.1°	0.04 < -23.9°	0.08 < -88.8°	0.05 < -83.8°	0.24 < -76.3°
THD (%)		3.7	5.6	4.1	6.2	7.2	6.3	16.0

Table 3.1 – THD of Level I/II charger: The 3rd through 9th harmonics, including both percent magnitude and phase angle, and the THD for a single-phase charger (Level II) at seven different points across a charging cycle.

3.2   TOTAL HARMONIC DISTORTION FOR A THREE-PHASE CHARGER

The waveforms and THD spectrum for a three-phase (Level III, aka DC Fast Charger) charger near the beginning of its charging cycle are shown in Figure 3.4. Again, it can be seen that there is very little distortion in the current waveform; the harmonic spectrum of this waveform is dominated by the fundamental component. Note, too, that the three phases are balanced; that is, they are 120° out of phase with one another, so there is no current flowing in the neutral line.
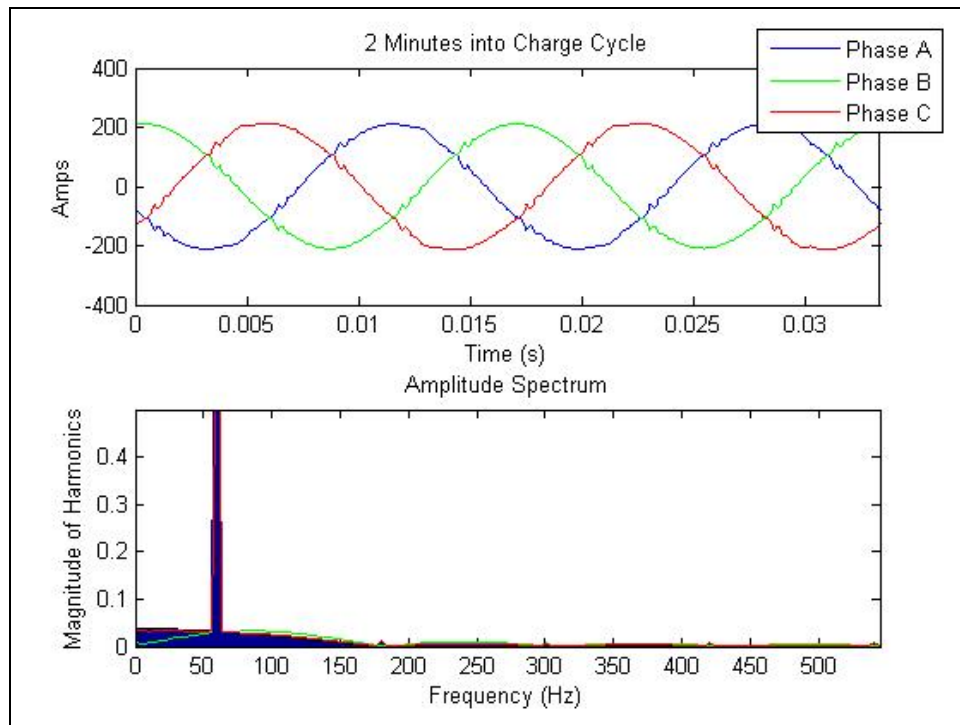
Figure 3.4: The temporal waveform, top, and its harmonic spectrum, bottom, for a three-phase charger near the beginning of a charging cycle. Note the three waveforms are nearly sinusoidal, corresponding to a spectrum consisting of only a fundamental component. The THD at this point in time is around 2%.

Later in the charging cycle, large frequency components can be seen at the 3rd, 5th, 7th and 9th harmonics in Figure 3.5. Also, the FFT spectrum shows that the harmonics for each phase varies. This is confirmed by the numerical data in Table 3.2. This implies that there is system imbalance that may contribute to neutral currents.
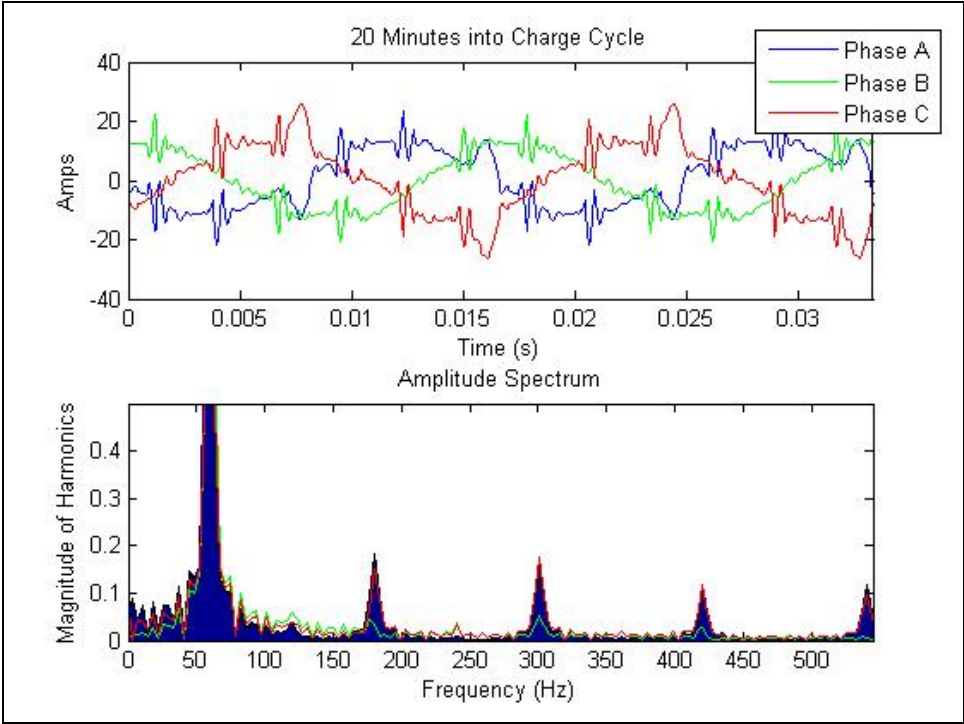

Figure 3.5: The temporal waveform, top, and its harmonic spectrum, bottom, for a three-phase charger near the end of a charging cycle. Note the higher-order harmonic components, but lower current magnitude compared with Figure 3.4 THD is now greater than 16% for all three phases.

The individual current distortion limits as described in IEEE Std. 519 are limited to 7% for a given odd harmonic less than 11 and limited to 25% of that value for even harmonics in that range (IEEE Std 519-1992).

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Phase A		Time in Charging Cycle (minutes)					
		2	7	10	17	23	29
Harmonic (%)	3rd	0.26 < 51.7°	2.84 < -75.6°	0.25 < 2.7°	6.61 < -73.1°	0.21 < -59°	0.87 < -56.6°
	5th	0.15 < 52.4°	2.96 < -27.1°	0.07 < 3.7°	6.27 < -16.9°	0.29 < 58.2°	0.38 < -47°
	7th	0.06 < 38.7°	1.81 < -83.6°	0.1 < -36.8°	4.75 < 84.9°	0.28 < -59.5°	0.58 < 0.9°
	9th	0.06 < 58.6°	2.28 < -31.7°	0.13 < 12.1°	4.65 < -29.5°	0.06 < -42.4°	0.36 < -46.3°
THD (%)		2.2	7.1	6.8	15.9	18.9	31.2
Phase B							
Harmonic (%)	3rd	0.62 < 74.1°	2.84 < -75.6°	0.25 < 2.7°	6.61 < -73.1°	0.21 < -59°	2.17 < 33.3°
	5th	0.36 < 68.7°	2.96 < -27.1°	0.07 < 3.7°	6.27 < -16.9°	0.29 < 58.2°	0.92 < -27.5°
	7th	0.22 < 53.4°	1.81 < -83.6°	0.1 < -36.8°	4.75 < 84.9°	0.28 < -59.5°	0.64 < 36.4°
	9th	0.19 < 52.3°	2.28 < -31.7°	0.13 < 12.1°	4.65 < -29.5°	0.06 < -42.4°	0.62 < -66.5°
THD (%)		2.1	7.1	6.8	15.9	18.9	20.3
Phase C							
Harmonic (%)	3rd	0.39 < 88.3°	2.84 < -75.6°	0.25 < 2.7°	6.61 < -73.1°	0.21 < -59°	1.95 < 54.3°
	5th	0.22 < 79.1°	2.96 < -27.1°	0.07 < 3.7°	6.27 < -16.9°	0.29 < 58.2°	1.04 < -33.1°
	7th	0.17 < 58.8°	1.81 < -83.6°	0.1 < -36.8°	4.75 < 84.9°	0.28 < -59.5°	0.34 < -80°
	9th	0.12 < 48.7°	2.28 < -31.7°	0.13 < 12.1°	4.65 < -29.5°	0.06 < -42.4°	0.26 < -88.6°
THD (%)		2.2	7.1	6.8	15.9	18.9	27.7

Table 3.2 – THD of Level III charger: The 3rd through 9th harmonics, including both percent magnitude and phase angle, and the THD for a three-phase charger (Level II) at six different points across a charging cycle.

3.3 TOTAL DEMAND DISTORTION FOR THE ELECTRIC AVENUE FEEDER

TDD is a metric of the impact harmonic distortion has on a feeder or branch circuit. TDD weighs the magnitude of the current harmonics against the loading capability of the circuit, as discussed in Section 1.1.2. Data for calculation of TDD was collected at the point of common coupling; the service entrance where all of the branches of Electric Avenue aggregate into the feeder. This data represents the total system demand of Electric Avenue as opposed to any one particular charger. From this data we were able to calculate TDD for Electric Avenue. Shown in Figure 3.6 are TDD calculations at five-minute intervals during a time period when five of the chargers were in use concurrently.
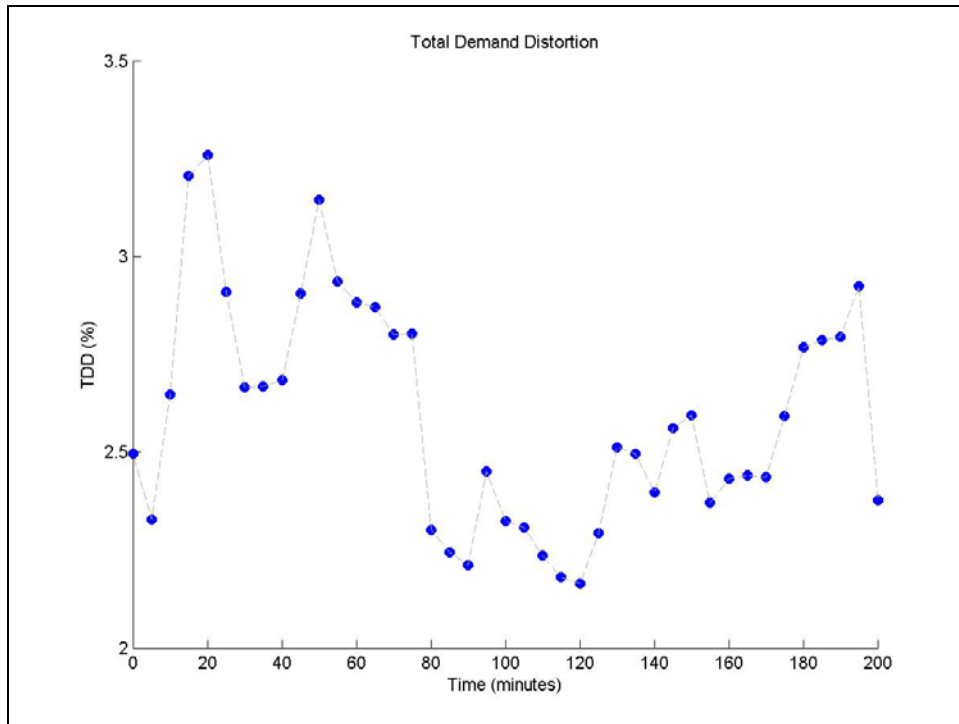
Figure 3.6: The Total Demand Distortion (TDD) on the Electric Avenue feeder with five chargers in use concurrently.

The average current for the maximum demand over the previous 12 months was calculated based on power readings collected at the site by sets of the CTs and PTs that are permanently installed there. The available fault current at the PCC was calculated based on drawings for the site made available by our partners at PGE. From these two calculations, we determined the TDD limit as recommended by IEEE Standard 519.1992 to be 8%.

In Figure 3.6, TDD varies as a function of time, though the magnitude of that variation is slight, ranging from around 2.2% to just above 3.2% during the course of the data recording. These low TDD values indicate that, despite the THD of the controllers, the size of the Electric Avenue feeder was sufficient to keep TDD below the 8% limit. However, it must be noted that during the time of data collection the EATON Level III charger was out of service. This particular charger is a three-phase DC fast charger with an operating of current of up to 200A per phase. Had this charger been operating at the time of data collection, it could have had a substantial impact on the TDD calculation, possibly even causing the defined limits to be exceeded.

When designing distribution systems to accommodate EV charging, the TDD limit must be understood, as this metric will help determine system component sizing. In the absence of appropriate modeling tools, the PQ issues associated with a proposed system cannot accurately be described. The next phase of our research involves developing models of charge controllers that reflect the behavior of their THD. These THD models could then be used by a distribution engineer to design feeder circuits that maintain acceptable TDD limits.

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3.4 OTHER POWER QUALITY ISSUES OBSERVED

In addition to harmonic distortion, we observed several other PQ issues during our study at Electric Avenue. This includes phantom loading, load imbalance (resulting in current in neutral lines), and DC offsets.

3.4.1 Phantom Loading

An anomaly that was originally noticed after the first data collection phase was the consumption of power by some of the charging stations even when there were no EVs connected to those stations. There turned out to be two types of this "phantom" loading. We attribute a minor amount of phantom loading to the digital circuitry, LCD screens and indicator lights featured in most of the charging stations. These ancillary circuits consume a low level of power at all times, irrespective of whether an EV is charging at the station or not. This parasitic consumption was quantified to be approximately 50 Wh per 15-minute period, a power consumption rate of 0.2 kW.

We attributed the second type of phantom loading to the Level III DC quick charger that has a battery bank. Power consumption by this charging station was recorded consuming around 300 Wh per 15-minute period, a power consumption rate of 1.2 kW, which is substantially greater than the first type of phantom loading. The battery bank, which is located apart from the charger at the site, enables the charger to direct power from both the battery bank and the utility, thereby limiting current surges on the utility feeder. The 1.2 kW "trickle" of power serves to keep the battery bank at a full charge.

3.4.2 Load Imbalance

Generally, systems are designed so that the loads are balanced across the three phases. By balancing the loads, the current in each of the three branches is roughly the same and the resulting terminal voltages are also roughly the same. However, because of the large number of Level I/II charging stations at Electric Avenue, which are single-phase units, the loading on the system was found to be much heavier for one phase or another, depending on which units were in use at any given time (Yan and Saha 2013). Unbalanced loading can result in currents within the neutral line. Because neutral lines tend to be undersized compared to the hot lines, these neutral currents can lead to excessive heating in extreme cases. Load imbalance also leads to voltage imbalance, which can be problematic for three-phase loads expecting equal phase voltages. Imbalance in a three-phase system is defined as the ratio of the magnitude of the negative sequence component to the magnitude of the positive sequence component, expressed as a percentage (IEEE Std 1159-1995). The voltage imbalance in the system was found to never exceed 1% at any given time. This is well below the IEEE's recommended maximum of 3%.

3.4.3 DC Offset

An item that should be noted about the harmonic spectrum in Figure 3.7 is the peak at 0 Hz (i.e., DC). This denotes a DC offset in the AC power flow. A pictorial depiction of the offset can also be seen in the waveform in Figure 3.7 as the peaks of the positive half of each wave reach above

5 A, while the negative half of each wave does not reach the same magnitude. DC in AC networks can be detrimental due to an increase in transformer saturation and associated heating, additional stressing of insulation, and other adverse effects (IEEE Std 1159-1995). A similar DC offset was found in many of the charging events at various points throughout the cycle and in all three phases. The impact that this anomaly has on the distribution system should be included in any simulations of the EV chargers.
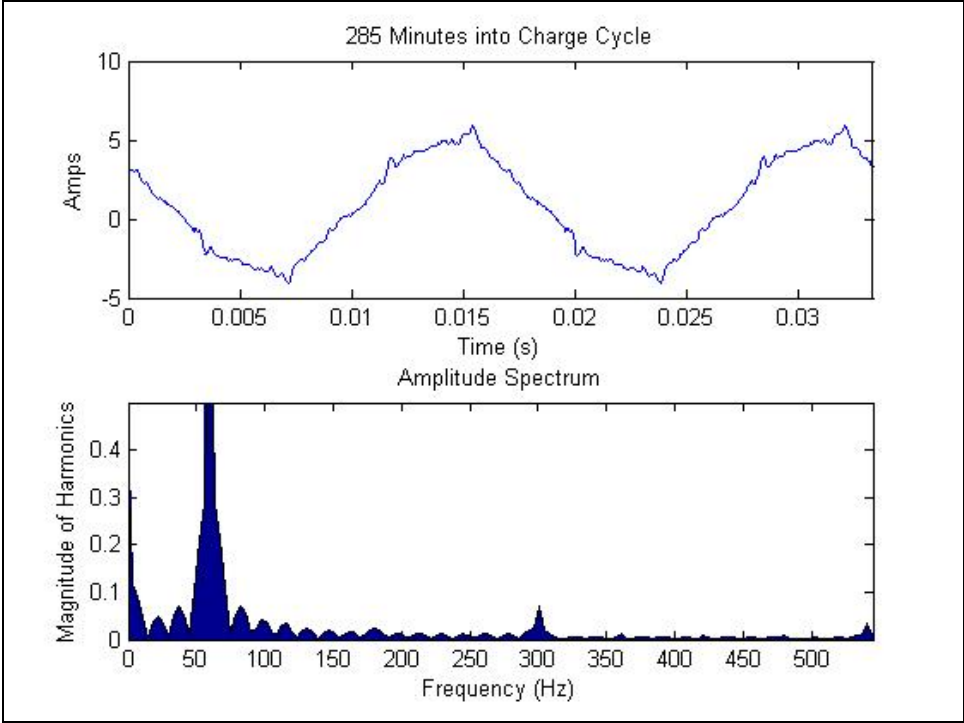
Figure 3.7: DC offset in a single-phase charger.

4.0   CONCLUSION

We investigated the PQ associated with Level I/II and Level III EV charge controllers, applied the IEEE 519.1992 standard towards analysis of harmonic distortion, and drew conclusions pertaining to our initial hypotheses. We measured the performance of a wide variety of Level I/II charge controllers, since various makes/models of EVs connected to the charging stations during our data collection period.

4.1   RESEARCH FINDINGS

At the beginning of our research, we stipulated three hypotheses. One, that PQ issues associated with charge controllers could have an impact on distribution assets. Two, that EV charge controllers would exhibit time-dependent changes in THD as the chargers progressed through the charging cycle. And three, that the cumulative effects of multiple charge controllers on a single feeder would result in distortion greater than that of any single charger.

As a result of our data collection and subsequent analysis, we noted evidence that charge controllers can, at times, demonstrate relatively high levels of THD, which is associated with adverse impacts on distribution assets, particularly magnetic devices. Our analysis also showed that THD of EV chargers changes during the charging cycle, typically starting out low during the high-current period of the cycle, but then tapering upwards as current decreases. And, we calculated the cumulative effects that concurrent operation of multiple charge controllers have on TDD.

In addition to quantifying the harmonic-related PQ issues associated with EV charge controllers, we also investigated other PQ issues, including phantom loading, DC offset and load imbalance. All of these other PQ issues were observed within the data gathered from Electric Avenue, and all of these can have detrimental effects on distribution assets if the distribution system is not properly designed to mitigate these problems.

Electric Avenue is a robustly designed EV charging system, as demonstrated by very low values of TDD, low levels of voltage imbalance and low neutral currents. Our research did not aim to discover problems with the design at Electric Avenue. Rather, we used Electric Avenue as a test bed for gathering data about electric vehicle charging, and inferring the PQ issues that *could* arise if design constraints relating to PQ were not properly considered.

4.2   FUTURE WORK

Future research at Electric Avenue will continue with support from PGE through the fall of 2013. The power research group at PSU will conduct research that will further broaden the understanding of the impacts EVs and charging stations may have on the electric utility industry, particularly distribution systems. Also, the grant from PGE will support PSU to develop

additional EV-related research opportunities, thereby further leveraging Electric Avenue as a R&D opportunity.

4.3   NONLINEAR LOAD MODELING

Using the data collected from Electric Avenue, we will develop nonlinear models of various EV charge controllers using a simulation environment such as MATLAB/Simulink. Such models can be used to predict possible effects that charge controllers may have on distribution hardware, thereby aiding planning distribution system upgrades and asset management. The modeling will permit us to relate electric car charging to recommendations for asset parameters, such as the k-type rating for distribution transformers. We will also be able to investigate potential problems such as core saturation, load imbalance, transformer insulation aging, transformer hot spots and zero-sequence currents.

4.3.1 Investing in upgrades to the Electric Avenue metering system

We will also investigate how the existing Electric Avenue metering infrastructure may be reconfigured to improve sample rate and resolution, and how much such an upgrade might cost. Currently, the third party that aggregates the meter data, NorthWrite, is providing their service *pro bono*. If an upgrade in data quantity or quality is requested, a subscription fee may be required. Also, the CTs that are in place now, from the Veris H8053 series, have a field-selectable pulse output field. The solution could be as simple as changing the pulse output field on the CTs. The meters for the data collection rate likely can be tailored such that both the time and kW metrics are finer grained. If so, the data are likely to be suitable for the modeling work done by the National Renewable Energy Laboratory (NREL) concerning usage patterns, grid integration and grid impacts.

The meters currently installed at Electric Avenue do not have sampling rates fast enough to measure harmonics content. We will investigate the potential for adding constant PQ metering to the Electric Avenue service. This may be as simple as swapping out the existing revenue meter for one capable of measuring power quality, such as an ION8600. Costs for hardware, communications infrastructure and labor will need to be factored. This upgrade would allow us to develop statistically significant PQ models for various Level I/II vehicle charge controllers, and models for the two DC fast chargers, since a greater number of charging events could be recorded.

APPENDIX A

THD TABLES

A-1 SINGLE-PHASE CHARGERS

		Time in Charging Cycle (minutes)					
		3	**10**	**32**	**56**	**64**	**69**
Harmonic (%)	**3rd**	1.33 < -70.2°	0.43 < -52.9°	1.21 < -81.3°	0.57 < 13.8°	6.54 < -76°	2.66 < 17.4°
	5th	0.82 < 50.5°	0.73 < -72.4°	0.22 < 77.4°	0.5 < 68.2°	2.83 < 82.2°	0.63 < 46.7°
	7th	0.89 < -25°	0.98 < 83.6°	0.31 < -60.4°	0.23 < -46.3°	2.44 < -85.3°	0.81 < -87.6°
	9th	1 < -15.5°	0.65 < -51.8°	0.13 < 40.1°	0.21 < 53.8°	3.55 < -45.9°	0.68 < 3.3°
THD (%)		2.7	2.7	2.4	2.4	10.6	6.5

Table A-1.1: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)					
		3	**12**	**34**	**59**	**82**	**97**
Harmonic (%)	**3rd**	1.56 < 12.6°	2.67 < 48.5°	2.26 < -61.2°	0.42 < -75.4°	4.03 < 57.6°	0.53 < -63.9°
	5th	0.67 < -2.2°	1.26 < 67°	1.73 < -40.9°	0.11 < -43.4°	2.07 < -60.7°	0.27 < 74.2°
	7th	0.7 < -61.2°	0.7 < -62.6°	1.14 < 17°	0.12 < 82.2°	1.24 < 5.3°	0.12 < -62.8°
	9th	0.55 < 10.9°	0.14 < -40.9°	0.42 < 0.4°	0.12 < -63.1°	0.34 < 45.7°	0.14 < -87.1°
THD (%)		2.5	3.3	3.7	1.9	5.1	5.0

Table A-1.2: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)				
		1	**46**	**79**	**111**	**69**
Harmonic (%)	**3rd**	8.65 < -60°	0.21 < -75.3°	0.19 < 89.8°	0.62 < 77.1°	0.35 < 13.3°
	5th	2.2 < -32.2°	0.09 < -23.1°	0.08 < 82.2°	0.01 < -75.7°	0.21 < -55.9°
	7th	1.35 < 1°	0.09 < 59.7°	0.09 < 84.8°	0.27 < -55.1°	0.16 < 55.7°
	9th	0.53 < -28.5°	0.08 < -39.1°	0.07 < -52.8°	0.13 < 64°	0.13 < 4.1°
THD (%)		9.3	2.1	2.1	2.6	2.3

Table A-1.3: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)							
		2	77	49	77	125	173	199	208
Harmonic (%)	3rd	14.2 < 85.8°	0.5 < 67.2°	5.17 < -54.6°	0.5 < 67.2°	4.78 < 19.6°	4.58 < -30.5°	11.05 < 3.4°	12.95 < 9.8°
	5th	5.01 < 81°	0.22 < 53.9°	2.18 < 77.8°	0.22 < 53.9°	2.48 < 49°	2.65 < -1.6°	1.53 < -82.6°	1.97 < -46°
	7th	1.38 < 70.7°	0.11 < 33.4°	1.41 < 43.3°	0.11 < 33.4°	1.37 < 36°	1.67 < -0.7°	0.57 < 69.7°	0.54 < 87.7°
	9th	1.02 < -40.5°	0.04 < 5.8°	1.56 < 84.7°	0.04 < 5.8°	1.3 < -24.9°	1.24 < -50.7°	0.38 < -18.2°	0.59 < -84.3°
THD (%)		15.3	3.0	6.2	3.0	5.9	5.9	11.5	13.8

Table A-1.4: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)					
		18	63	1	71	91	111
Harmonic (%)	3rd	3.03 < -54.6°	0.56 < -64.1°	0.6 < -74°	3.73 < -86.7°	0.3 < 24.9°	4.22 < 67.8°
	5th	0.81 < -38.4°	0.39 < 83.4°	0.34 < 79.6°	0.63 < 52.5°	0.23 < 42.7°	0.83 < 77.2°
	7th	1.74 < 11.4°	0.19 < 55.9°	0.11 < 47°	0.7 < 0.7°	0.2 < 73.2°	0.24 < -38.2°
	9th	0.55 < 61.4°	0.04 < 61.1°	0.04 < 41.3°	0.43 < -50.9°	0.18 < -88.1°	0.17 < 40.8°
THD (%)		3.8	2.5	2.4	4.2	1.4	4.9

Table A-1.5: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)						
		3	11	26	61	94	120	142
Harmonic (%)	3rd	9.06 < -66.6°	9.08 < 9.2°	0.26 < 17.5°	9.15 < -44°	9.7 < 10.4°	0.52 < -58.4°	0.37 < -75.6°
	5th	2.04 < 81.1°	1.94 < 16.1°	0.05 < 89.9°	1.68 < -33.1°	1.38 < 64.9°	0.31 < 85.8°	0.16 < -70°
	7th	1.39 < 35.9°	1.35 < 22.5°	0.11 < -21.8°	1.17 < 36.8°	1.29 < -23°	0.11 < 71.7°	0.08 < -81.8°
	9th	0.44 < -40.1°	0.41 < 6.2°	0.08 < -62°	0.42 < 26.5°	0.47 < 38.2°	0.08 < -86°	0.06 < -52.6°
THD (%)		9.7	9.6	2.5	9.6	10.1	2.3	2.3

Table A-1.6: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)					
		3	23	52	77	94	101
Harmonic (%)	3rd	0.22 < 57.8°	4.26 < -37°	0.73 < -78.2°	4.16 < 87.8°	5.89 < -41.7°	0.62 < -84.5°
	5th	0.14 < -66.1°	2.1 < -0.8°	0.14 < 56°	2.76 < -64.4°	3.28 < 72.5°	0.26 < -37.7°
	7th	0.21 < -59.1°	1.49 < 63.3°	0.28 < 52°	1.27 < -28.7°	2.47 < 6.8°	0.32 < 57.7°
	9th	0.16 < -85.8°	1.05 < -48.1°	0.22 < -19.1°	0.94 < -29.1°	1.49 < -83.6°	0.33 < -83.7°
THD (%)		3.2	5.4	2.6	5.6	7.6	9.0

Table A-1.7: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)							
		3	24	46	61	79	94	99	102
Harmonic (%)	3rd	0.27 < 41.4°	0.39 < 42.6°	1.76 < 71.6°	2.04 < 50.5°	2.45 < 30.6°	2.33 < 65.5°	0.08 < 84°	11.16 < 13.5°
	5th	1.62 < 14.3°	0.35 < -57.2°	1.56 < -42.4°	2.01 < -45.6°	1.83 < 14.7°	2.12 < 80.4°	0.53 < -61.4°	11.87 < -63.4°
	7th	2.18 < -86.1°	0.12 < 66.2°	1.35 < 66.7°	0.95 < -58.2°	1.19 < 40.4°	0.9 < -55.1°	0.31 < -87.3°	5.03 < -24.7°
	9th	0.53 < 53.5°	0.22 < -59.3°	0.77 < -77.9°	0.65 < 2.6°	0.95 < 12.5°	1.56 < -50.2°	0.09 < 28°	5.98 < -65.6°
THD (%)		3.3	2.3	3.1	3.4	3.8	4.0	8.3	19.2

Table A-1.8: THD of Level I/II single-phase charger.

		Time in Charging Cycle (minutes)							
		1	33	77	135	191	3	33	34
Harmonic (%)	3rd	9.03 < 12.1°	8.88 < 33.9°	8.55 < -89.1°	8.75 < -24.2°	8.73 < 23.2°	9.16 < -43.3°	0.47 < -54.5°	8.41 < -68.7°
	5th	4.31 < 21.7°	0.67 < 7°	0.84 < 35.8°	0.91 < 51.6°	1.02 < -29.4°	1.43 < 24.3°	0.33 < -86.2°	1.27 < -25°
	7th	2.41 < -27.7°	0.95 < 15.6°	0.75 < 32.7°	1.28 < 5.6°	0.72 < -18.1°	0.82 < 51°	0.13 < 63.7°	0.79 < 20.2°
	9th	0.98 < -52.5°	0.35 < -52.5°	0.28 < -58.1°	0.67 < -61.2°	0.48 < -88.1°	0.51 < -79.8°	0.05 < -62°	0.66 < 38.4°
THD (%)		11.1	9.1	8.8	9.1	9.0	9.5	1.7	8.7

Table A-1.9: THD of Level I/II single-phase charger.

Harmonic (%)		Time in Charging Cycle (minutes)					
		3	29	62	91	126	137
	3rd	0.25 < 70.9°	7.65 < -23.7°	7.51 < 16.8°	0.48 < -89.1°	7.11 < -10.6°	0.25 < 30.4°
	5th	0.23 < 85.7°	1.93 < -83°	2.12 < 79.6°	0.27 < -79.1°	2.34 < 31.9°	0.49 < -65.3°
	7th	0.11 < -71.8°	1.54 < -89°	1.22 < 28°	0.2 < -77.7°	1.47 < -57.6°	0.03 < -88.3°
	9th	0.12 < -85.2°	0.97 < 86.8°	0.73 < 18.9°	0.17 < -69.2°	0.83 < 76.7°	0.28 < 85.1°
THD (%)		3.3	8.4	8.3	3.3	8.1	6.4

Table A-1.10: THD of Level I/II single-phase charger.

Harmonic (%)		Time in Charging Cycle (minutes)					
		1	24	50	85	114	126
	3rd	0.48 < 71.6°	0.57 < 73.1°	2.13 < -14.4°	1.14 < 80.9°	0.34 < -71.7°	0.26 < 66°
	5th	0.31 < 67.5°	0.22 < 50.8°	2.58 < -74.2°	3.19 < -63°	0.15 < -74.2°	0.17 < 61.3°
	7th	0.22 < 67.8°	0.07 < 43.9°	1.43 < -61.1°	1.06 < 28.6°	0.13 < -75.6°	0.13 < 71.7°
	9th	0.15 < 69.3°	0.02 < -40.3°	1.03 < -75.1°	0.92 < 89.6°	0.08 < -78.2°	0.11 < -74.3°
THD (%)		2.5	3.6	4.2	4.3	3.2	10.0

Table A-1.11: THD of Level I/II single-phase charger.

A-2 THREE-PHASE CHARGERS

Phase A		Time in Charging Cycle (minutes)					
		1	6	13	22	30	32
Harmonic (%)	3rd	0.56 < -59.4°	0.99 < 50.7°	0.25 < 42°	0.24 < -27.8°	0.41 < -16.1°	0.93 < 71°
	5th	0.05 < -56.9°	0.93 < 42.2°	0.28 < 44.4°	0.17 < -72.5°	0.04 < -39.1°	0.19 < 50.4°
	7th	0.25 < -73.3°	1.11 < -48.4°	0.28 < 67°	0.11 < -37°	0.39 < -69.6°	0.06 < -34.5°
	9th	0.07 < -47.7°	0.76 < 76.6°	0.29 < 73°	0.11 < 76.7°	0.21 < -60.1°	0.37 < -73.4°
THD (%)		1.9	3.5	3.7	5.8	10.4	11.4
Phase B							
Harmonic (%)	3rd	0.31 < -78°	0.95 < 58.4°	0.6 < -59.7°	0.91 < 65.6°	0.47 < 47.8°	0.47 < -7.3°
	5th	0.24 < -75.4°	1.15 < 74°	0.35 < -10°	0.5 < 57.4°	0.6 < 75.7°	0.35 < 59.1°
	7th	0.2 < -39.3°	0.06 < 26.3°	0.18 < 8.1°	0.3 < 50.6°	0.33 < -14.5°	0.1 < 57.1°
	9th	0.21 < -77.5°	0.21 < 73.2°	0.16 < 67.6°	0.23 < 51.5°	0.3 < 15.7°	0.29 < 12.4°
THD (%)		1.5	2.8	2.4	4.1	6.5	7.6
Phase C							
Harmonic (%)	3rd	0.31 < -41.1°	1.93 < 52°	0.68 < -80.4°	0.91 < 80°	0.43 < -75.7°	1.07 < 46.8°
	5th	0.28 < -72.6°	0.6 < -51.7°	0.29 < -60.2°	0.6 < 69.1°	0.55 < 79.7°	0.48 < 54.4°
	7th	0.14 < 57.9°	1.1 < -51.2°	0.23 < -74.3°	0.29 < 71.1°	0.32 < 59.8°	0.11 < 33.4°
	9th	0.15 < 88°	0.99 < 76°	0.12 < 80.6°	0.31 < 59.1°	0.29 < 57.6°	0.4 < 67.6°
THD (%)		1.9	3.6	3.1	6.4	10.3	12.3

Table A-2.1: THD of Level III three-phase charger.

Phase A		Time in Charging Cycle (minutes)					
		1	5	14	19	25	31
Harmonic (%)	3rd	0.97 < -73°	1.66 < -6°	1.1 < -80.5°	0.49 < 53.3°	0.6 < -68.6°	0.43 < 80.8°
	5th	0.62 < -72.5°	0.23 < -48.2°	0.84 < 40°	0.4 < 85.8°	0.31 < 45.8°	0.31 < 17.3°
	7th	0.61 < -63.5°	0.66 < 49.2°	0.94 < 48.8°	0.29 < -60.5°	0.06 < 68.7°	0.14 < -36.8°
	9th	0.88 < -74.1°	0.47 < 88.5°	0.83 < -82°	0.15 < -27.2°	0.2 < -71.4°	0.32 < 47.2°
THD (%)		3.4	3.4	3.3	3.4	5.0	8.1
Phase B							
Harmonic (%)	3rd	1.13 < 58.1°	0.69 < 14.9°	1.1 < -80.5°	0.49 < 53.3°	0.6 < -68.6°	0.68 < 77°
	5th	0.58 < -56°	0.76 < -22.9°	0.84 < 40°	0.4 < 85.8°	0.31 < 45.8°	0.32 < -84°
	7th	0.59 < -51.7°	0.36 < 5.6°	0.94 < 48.8°	0.29 < -60.5°	0.06 < 68.7°	0.2 < -70.6°
	9th	0.18 < -27.2°	0.22 < 35.8°	0.83 < -82°	0.15 < -27.2°	0.2 < -71.4°	0.38 < -71.3°
THD (%)		3.1	2.9	3.3	3.4	5.0	5.2
Phase C							
Harmonic (%)	3rd	1.94 < 79°	1.11 < -21.1°	1.1 < -80.5°	0.49 < 53.3°	0.6 < -68.6°	0.23 < 71.2°
	5th	0.17 < 39.4°	0.55 < -13.5°	0.84 < 40°	0.4 < 85.8°	0.31 < 45.8°	0.46 < 56.3°
	7th	1.18 < -57.8°	0.46 < 81.5°	0.94 < 48.8°	0.29 < -60.5°	0.06 < 68.7°	0.3 < -56.4°
	9th	0.77 < -83.7°	0.61 < 72.2°	0.83 < -82°	0.15 < -27.2°	0.2 < -71.4°	0.34 < -20.7°
THD (%)		3.8	3.2	3.3	3.4	5.0	9.2

Table A-2.2: THD of Level III three-phase charger.

Phase A		Time in Charging Cycle (minutes)					
		1	5	14	19	25	31
Harmonic (%)	3rd	0.97 < -73°	1.66 < -6°	1.1 < -80.5°	0.49 < 53.3°	0.6 < -68.6°	0.43 < 80.8°
	5th	0.62 < -72.5°	0.23 < -48.2°	0.84 < 40°	0.4 < 85.8°	0.31 < 45.8°	0.31 < 17.3°
	7th	0.61 < -63.5°	0.66 < 49.2°	0.94 < 48.8°	0.29 < -60.5°	0.06 < 68.7°	0.14 < -36.8°
	9th	0.88 < -74.1°	0.47 < 88.5°	0.83 < -82°	0.15 < -27.2°	0.2 < -71.4°	0.32 < 47.2°
THD (%)		3.4	3.4	3.3	3.4	5.0	8.1
Phase B							
Harmonic (%)	3rd	1.13 < 58.1°	0.69 < 14.9°	1.1 < -80.5°	0.49 < 53.3°	0.6 < -68.6°	0.68 < 77°
	5th	0.58 < -56°	0.76 < -22.9°	0.84 < 40°	0.4 < 85.8°	0.31 < 45.8°	0.32 < -84°
	7th	0.59 < -51.7°	0.36 < 5.6°	0.94 < 48.8°	0.29 < -60.5°	0.06 < 68.7°	0.2 < -70.6°
	9th	0.18 < -27.2°	0.22 < 35.8°	0.83 < -82°	0.15 < -27.2°	0.2 < -71.4°	0.38 < -71.3°
THD (%)		3.1	2.9	3.3	3.4	5.0	5.2
Phase C							
Harmonic (%)	3rd	1.94 < 79°	1.11 < -21.1°	1.1 < -80.5°	0.49 < 53.3°	0.6 < -68.6°	0.23 < 71.2°
	5th	0.17 < 39.4°	0.55 < -13.5°	0.84 < 40°	0.4 < 85.8°	0.31 < 45.8°	0.46 < 56.3°
	7th	1.18 < -57.8°	0.46 < 81.5°	0.94 < 48.8°	0.29 < -60.5°	0.06 < 68.7°	0.3 < -56.4°
	9th	0.77 < -83.7°	0.61 < 72.2°	0.83 < -82°	0.15 < -27.2°	0.2 < -71.4°	0.34 < -20.7°
THD (%)		2.6	2.5	4.9	10.3	9.0	17.3

Table A-2.3: THD of Level III three-phase charger.

Phase A		Time in Charging Cycle (minutes)			
		3	9	13	20
Harmonic (%)	3rd	1.48 < -80.8°	0.59 < 75.5°	3.09 < -80.1°	0.98 < -80.8°
	5th	0.89 < 1.1°	0.35 < -77.5°	0.34 < -79.5°	1.55 < 77.5°
	7th	1.63 < -64.5°	0.1 < -21.1°	0.54 < -81.2°	2.78 < 56.6°
	9th	1.06 < 11.5°	0.02 < -9.9°	0.41 < -81.8°	0.98 < -30.5°
THD (%)		2.8	1.3	3.2	3.7
Phase B					
Harmonic (%)	3rd	5.14 < -72.9°	0.47 < -58.7°	5.1 < -28°	8.31 < 24.3°
	5th	1.21 < -16.7°	0.22 < -89.1°	0.57 < 54.3°	1.77 < -24.3°
	7th	1.6 < -31.6°	0.1 < 71.2°	0.88 < 65°	2.7 < -73.1°
	9th	1.2 < 20.3°	0.1 < -41.3°	0.92 < 66°	1.85 < -38.2°
THD (%)		5.8	1.3	5.3	9.2
Phase C					
Harmonic (%)	3rd	4.06 < 42.4°	0.46 < 37.7°	6.95 < 75°	4.16 < -25.8°
	5th	1.2 < -18.5°	0.26 < -65.5°	0.18 < 45.7°	2.52 < 71.5°
	7th	1.71 < -87.7°	0.13 < 15.8°	0.97 < -79.3°	1.8 < 40.7°
	9th	1.1 < 23.9°	0.09 < -38.7°	1.15 < 75.4°	1.38 < -17.5°
THD (%)		4.8	1.1	7.2	5.5

Table A-2.4: THD of Level III three-phase charger.

Phase A		Time in Charging Cycle (minutes)			
		3	17	23	31
Harmonic (%)	3rd	1.76 < -10.9°	0.2 < -83.2°	0.76 < 83.8°	0.59 < 66.5°
	5th	0.6 < 11.1°	0.36 < 44.7°	0.46 < 63.5°	0.15 < 53.1°
	7th	0.8 < 63.6°	0.22 < -45.6°	0.15 < -89°	0.35 < -67.4°
	9th	0.47 < 50.9°	0.06 < -76.4°	0.27 < -74.6°	0.08 < -28.5°
THD (%)		2.2	1.2	1.9	2.7
Phase B					
Harmonic (%)	3rd	4.82 < -40°	0.31 < -88.5°	0.12 < 4.7°	0.79 < 65.8°
	5th	1.08 < -14.1°	0.32 < 72.4°	0.22 < -74°	0.12 < 65.2°
	7th	1 < -67.7°	0.21 < -61.2°	0.11 < 77.1°	0.28 < 82.6°
	9th	1.38 < 82.2°	0.08 < -81.1°	0.08 < -70.8°	0.1 < -21.5°
THD (%)		5.3	1.6	1.5	2.7
Phase C					
Harmonic (%)	3rd	5.22 < 79.9°	0.45 < -83°	0.82 < -89.2°	0.22 < -77.2°
	5th	0.54 < -2.6°	0.24 < 3.6°	0.44 < 55.4°	0.04 < 19.7°
	7th	1.18 < 48.7°	0.09 < -4.4°	0.11 < -79.1°	0.14 < -12.2°
	9th	1.32 < 80.6°	0.15 < -74.5°	0.27 < -71.6°	0.05 < -89.8°
THD (%)		5.6	1.4	2.3	3.0

Table A-2.5: THD of Level III three-phase charger.

Phase A		Time in Charging Cycle (minutes)				
		1	5	14	19	25
Harmonic (%)	3rd	0.45 < -6.6°	1.18 < 56.5°	0.55 < -67.7°	0.39 < 78.4°	2.45 < 18.4°
	5th	1.87 < 76.1°	1.51 < -41.8°	0.16 < -45.1°	1.41 < -35°	2.72 < -42.9°
	7th	1.53 < 5.6°	1.35 < -45.8°	0.02 < -60.1°	3.06 < 27.2°	4.16 < -53.8°
	9th	1.34 < 17.7°	0.91 < 18.7°	0.15 < 82.7°	1.47 < -26.5°	2.15 < -41.1°
THD (%)		3.0	2.6	2.3	3.9	6.4
Phase B						
Harmonic (%)	3rd	4.05 < -14.7°	1.18 < 56.5°	0.55 < -67.7°	0.39 < 78.4°	10.25 < 74.8°
	5th	0.94 < -6.9°	1.51 < -41.8°	0.16 < -45.1°	1.41 < -35°	1.07 < -73.6°
	7th	1.11 < 35.2°	1.35 < -45.8°	0.02 < -60.1°	3.06 < 27.2°	3.48 < -12.9°
	9th	1.03 < 11.2°	0.91 < 18.7°	0.15 < 82.7°	1.47 < -26.5°	2.66 < -68.9°
THD (%)		4.6	2.6	2.3	3.9	11.3
Phase C						
Harmonic (%)	3rd	4.88 < -62.9°	1.18 < 56.5°	0.55 < -67.7°	0.39 < 78.4°	4.51 < 22.8°
	5th	1.75 < -72.1°	1.51 < -41.8°	0.16 < -45.1°	1.41 < -35°	2.26 < -1.4°
	7th	1.94 < -2.2°	1.35 < -45.8°	0.02 < -60.1°	3.06 < 27.2°	3.06 < -74.7°
	9th	1.42 < 48°	0.91 < 18.7°	0.15 < 82.7°	1.47 < -26.5°	2.51 < -42.6°
THD (%)		5.8	2.6	2.3	3.9	6.6

Table A-2.6: THD of Level III three-phase charger.

Phase A		Time in Charging Cycle (minutes)			
		1	12	26	35
Harmonic (%)	3rd	2.7 < -46°	2.91 < 50.8°	3.08 < -27.9°	6.02 < -0.4°
	5th	1.29 < 16.3°	1.83 < 75.3°	1.45 < 28.2°	7.51 < 10.4°
	7th	0.47 < 53.3°	0.6 < 41°	0.5 < -5.7°	3.16 < 64.9°
	9th	0.6 < -21.6°	0.34 < 17.3°	0.27 < 16.7°	3.12 < 29.1°
THD (%)		3.2	3.6	3.6	11.2
Phase B					
Harmonic (%)	3rd	4.59 < 1.1°	2.91 < 50.8°	3.08 < -27.9°	11.45 < 35.3°
	5th	0.68 < -26.4°	1.83 < 75.3°	1.45 < 28.2°	1.38 < -60.9°
	7th	0.53 < -77.5°	0.6 < 41°	0.5 < -5.7°	2.49 < -77.5°
	9th	1.54 < -56.4°	0.34 < 17.3°	0.27 < 16.7°	2.68 < -3.7°
THD (%)		5.1	3.6	3.6	12.9
Phase C					
Harmonic (%)	3rd	6.18 < -83.1°	2.91 < 50.8°	3.08 < -27.9°	6.65 < -26.8°
	5th	0.97 < 4.8°	1.83 < 75.3°	1.45 < 28.2°	9.21 < 43°
	7th	0.38 < 51.9°	0.6 < 41°	0.5 < -5.7°	1.4 < 32.3°
	9th	0.79 < -43.1°	0.34 < 17.3°	0.27 < 16.7°	3.16 < 15.7°
THD (%)		6.3	3.6	3.6	12.0

Table A-2.7: THD of Level III three-phase charger.

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