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CALIFORNIA ENERGY COMMISSION

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SECONDARY DISTRIBUTION IMPACTS OF RESIDENTIAL ELECTRIC VEHICLE CHARGING

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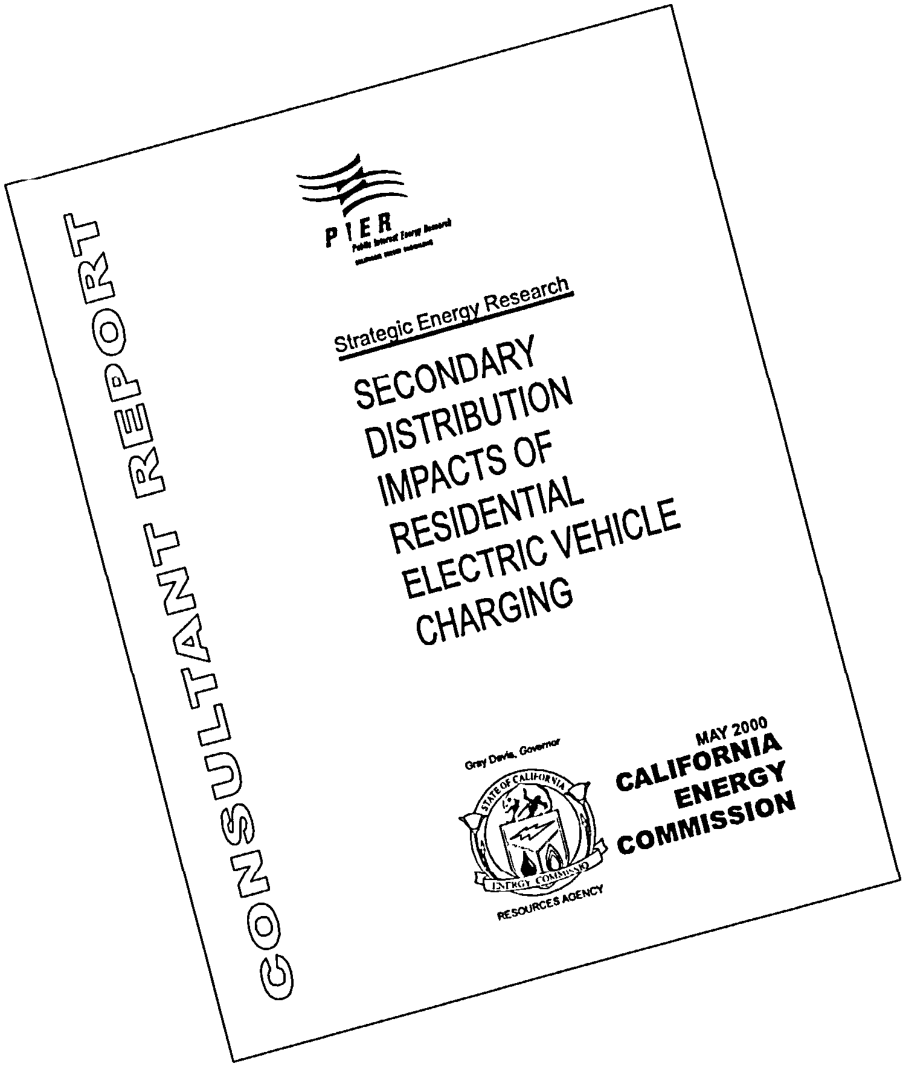

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Final Report

Secondary Distribution Impacts of Residential Electric Vehicle Charging

May 11, 2000

Home of the 1996 Olympic Village
Georgia Institute of Technology

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the NEETRAC Project No. 99-373 conducted by the Georgia Institute of Technology. The report is entitled secondary Distribution Impacts of Residential Electric Vehicle Charging. This project contributes to the Strategic Energy Research program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Secondary Distribution Impacts of Residential Electric Vehicle Charging

Executive Summary

The market penetration of large single-phase residential loads, such as the Electric Vehicle (EV) charger, is a potential power quality, power delivery and energy consumption concern for electric power providers and consumers in terms of distribution reliability, house or site electrical system reliability and vehicle life cycle costs. Charging systems with high harmonic current distortion can result in secondary distribution line de-rating or losses resulting in economic and quality of service consequences. These losses also have an economic penalty to consumers because they ultimately increase the cost of electricity to the end user. The objective of this project was to examine the secondary distribution impacts of EV charging.

This research was sponsored by the California Energy Commission, California Electric Transportation Coalition, Florida Power and Light, Georgia Power Company, Pacific Gas and Electric Company, Sacramento Municipal Utility District, Southern California Edison, and Virginia Power Company.

The project team was composed of the following technical advisors: California Energy Commission – Mark Rawson, California Electric Transportation Coalition – Cecile Martin, Florida Power and Light – Bob Suggs, Georgia Power Company – John Kennedy, Pacific Gas and Electric Company – Christina Jennings and Gil Hensley, Sacramento Municipal Utility District – Steve Revenaugh, Southern California Edison – Brian Sisco and Ernie Morales, and Virginia Power Company – Dan Ward. These advisors were experienced in both power quality and electric vehicle charging systems and were responsible for providing technical oversight and direction for the project.

The National Electric Vehicle Infrastructure Working Council (IWC); composed of utilities, automobile companies, and equipment manufacturers; was initiated to develop consistent standards for the EV infrastructure to meet the needs of the marketplace. John Kennedy served as Chairman of the Distribution, Load Management, and Power Quality Committee of the IWC. This committee developed a Record of Consensus on the power factor and current distortion requirements for light duty on-road EV chargers and identified the need for this project to validate their recommendations.

The project was divided into four phases:

Phase 1: Data Collection
Phase 2: Model Development and Validation
Phase 3: Simulation Case Studies
Phase 4: Field Site Testing and Validation

Phase 1 of the project was designed to collect data from residential electrical appliances and EV chargers. A "case study" approach based on two homes was selected to collect data for the simulation studies. Profiles were captured for nominal and undervoltage conditions from over seventy appliances and seven EV chargers. Distribution system configurations likely to see EV loads were obtained from the utilities along with distribution transformer and service data.

In the second phase, all appliances and EV chargers were modeled as non-linear loads, based on the measurements taken in the first phase of the project. The models developed for this study were implemented and simulated in Electrotek's HarmFlo+ workstation package. The model development process was automated by a Translator program written in PASCAL, which takes in the appliance data and generates the HarmFlo+ code. The models were validated by comparing the simulations to actual measurements for particular case scenarios performed at one of the homes used in the initial characterization of the appliances. The measurements taken and simulations performed during this stage validated the models implemented in Electrotek's HarmFlo+ software for the appliances and electric vehicle chargers.

During the third phase, simulation case studies representative of the electrical service configurations of the participating utilities were performed. Utility system data were provided to a Compiler program written in PASCAL to translate the input data into HarmFlo+ input files. The studies considered various mixes of appliances and chargers and provided a significant evaluation of worst-case conditions. Further, evaluations of the utility distribution transformer and secondary distribution conductors for both de-rating and line losses due to the increase in harmonic currents were also performed. The worst-case simulation scenario resulted in a voltage total harmonic distortion (THD) of 5.1% on the secondary side of the distribution transformer, which is just over the Institute of Electrical and Electronic Engineers (IEEE) 519 Recommended Practice which recommends a 5% limit for voltage distortion. This value was obtained with a computer simulation of a charger designed to the absolute limits of current distortion at each harmonic frequency (IEC 1000-3-4) and is not representative of current commercial light-duty on-road EV chargers. The 5% level of IEEE 519 is a recommended limit that has turned out to be generally a conservative number. In normal practice, levels up to 8% may not cause a problem. Specific harmonic frequencies may cause problems below that level as opposed to the aggregated value of THD.

Field Tests were performed by three participating utilities during the fourth phase of this project. The field test sites were comprised of two residential sites and a commercial site. Measurements were taken at the three field test sites for a month. The absolute worst-case recorded voltage THD was 4.1%, which is below the IEEE 519 recommended 5% limit for voltage distortion. Simulation of one of the test sites was performed to compare the actual field data with the simulation model results. The field data and the simulation results for the voltage THD matched within 2.9%, thus validating the simulation process. Temperature variation on the transformer due to EV charging was also studied in one field site.

The main conclusions of the project based upon the utility systems and chargers investigated are:

- Commercial light-duty on-road EV chargers engineered to National Electric Vehicle Infrastructure Working Council (IWC) guidelines based upon IEC 1000-3-4 do not give rise to excessive voltage THD on the secondary side of the transformer. Two critical elements that make these guidelines effective are a minimum total power factor of 95% and a maximum current THD of $\leq 20\%$.

- The rise in voltage THD due to EV charging was found to be within 0.8% in all three field test sites and should not be a cause for concern. Load management strategies like off peak charging should be encouraged to minimize the load impacts on the distribution system.

- The influence of EV charging on transformer temperature at one field site was studied. Temperature rise was not attributable to voltage THD but was affected rather by the extra loading on the transformer from the EVs.

- The main cause of concern is the overloading of the distribution transformer with widespread use of EV chargers, assuming the chargers meet voluntary IWC guidelines such that voltage THD is not an issue. Still, utility service planning groups should ask for kVA and true power factor values in addition to kW values for any rectifier or other non-linear load.

Interim results of this project have been presented and published at the North American Electric Vehicle Infrastructure Conference in November of 1999. A final report will be presented at the Electric Vehicle Symposium in October of 2000. Project results have also been provided to the IEEE Task Force on Single Phase Harmonics and a summary will be provided to EPRI for release to the IWC.

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First Interim Report

Secondary Distribution Impacts of Residential EV Charging

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FIRST INTERIM REPORT

April 1999

Project Title: Secondary Distribution Impacts of Residential EV Charging

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Abstract: This first of three interim reports documents electrical appliance and charger profiles captured during the data collection phase of this project. The report also documents typical distribution transformer and circuit data from participating utilities.

Secondary Distribution Impacts of Residential EV Charging

First Interim Report

Abstract

This first of three interim reports documents electrical appliance and charger profiles captured during the data collection phase of this project. The report also documents typical distribution transformer and circuit data from participating utilities.

Background

The market penetration of large single-phase residential loads, such as the 6.6 kW electric vehicle (EV) battery charger, is a potential power quality, power delivery, and energy consumption concern for electric power providers and consumers in terms of distribution system reliability, house or site electrical system reliability, and vehicle life cycle costs. Charging systems with high harmonic current distortion can result in secondary distribution line de-rating or losses resulting in economic and quality of service consequences. These losses also have an economic penalty to consumers because they ultimately increase the cost of electricity to the end user. The objective of this project is to examine the secondary (customer-side) distribution impacts of residential EV charging. The project is divided into four phases:

Phase 1: Data Collection (Winter 1999)
Phase 2: Model Development and Validation (Spring 1999)
Phase 3: Simulation Case Studies (Summer and Fall 1999)
Phase 4: Site Testing and Validation (Summer and Fall 1999, Winter 2000)

Methodology

A two-step selection process was used in choosing the appliances for this study. First, two homes were randomly chosen. The first home was built in the early 1970's and the second home was built in the early 1990's. Every appliance (whose power consumption exceeded five watts) in these two homes was tested for inclusion in the appliance library for possible use in Phase 3 of this project. This list of appliances was then reviewed by the utility sponsors, and additional appliances were added based on that input.

The sampling of appliances was intentionally not biased towards a "worst case" or a "most likely" scenario. Instead, this project is taking a "case study" approach based on two randomly sampled homes for simulation study and a number of field test sites for experimental study. In the simulation studies, various scenarios will be considered – including a "worst case" mix of appliances and a "typical" mix of appliances.

A statistically significant sample of appliances, corresponding to the national distribution of use patterns is well beyond the scope of this study. The approach taken in this study is more appropriately thought of as contributing convincing "circumstantial evidence" to the existing body of experience and practice. The simulation case studies, together with the field tests in Phase 4 of this project is expected to provide ample "circumstantial evidence" to the utility participants to allow them to forecast the likely secondary distribution impacts of residential EV charging.

Electrical Appliance Summary

A total of 40 appliances were tested at both rated (100%) and reduced (90%) voltage. The summary tables below provide an overview of electrical characteristics organized by appliance category. It was noted that high current distortion (low power factor) appliances were primarily home entertainment and home office appliances. Complete data for each appliance is included in the Appendices A.2 -A.7.

Kitchen Appliances

Appliance	Power (W)	Power Factor	THD (Current) %	DPF
Mixer (High Power)	109.29	0.99	6.69	0.99
Mixer (Low Power)	58.29	0.60	77.33	0.76
Coffee Maker	960	1.0	1.77	1.0
Microwave	1340	0.97	21.82	1.0
Toaster	790	1.0	1.18	1.0

Home Entertainment

Appliance	Power (W)	Power Factor	THD (Current) %	DPF
Television Set	70	0.57	135.23	0.96
VCR	27.10	0.85	50.56	0.95
Cassette Player	19	0.53	138.80	0.90
CD Player	13.09	0.78	77.54	1.00
Stereo	110	0.76	78.79	0.97
Satellite Dish	19	0.53	138.80	0.90

Home Office

Appliance	Power (W)	Power Factor	THD (Current) %	DPF
Hard Disk Drive	60.0	0.59	131.91	0.99
Monitor	71.07	0.61	108.68	0.90
Scanner	17.06	0.62	117.93	0.99
Printer	16.06	0.74	54.54	0.86
Photo Copier (at start)	920	1.0	6.83	1.0
Photo Copier (at end)	90	0.79	75.70	0.99
FAX Machine	22	0.62	94.27	0.86
Answering Machine	9	0.71	82.99	0.96
UPS	60.06	0.80	68.85	0.98

Other Household Appliances

Appliance	Power (W)	Power Factor	THD (Current) %	DPF
Light Bulb	60.01	0.99	7.38	0.99
Compact Fluorescent Bulb	13	0.63	101.80	0.93
Compact Fluorescent Light	25	0.59	125.35	0.98
Light Dimmer	50.52	0.73	68.30	0.88
Electronic ballast	21.52	0.63	15.18	0.62
Vacuum Cleaner	1250	0.98	13.29	0.99
Portable Heater	1370	1.00	2.51	1.00
House Fan (High Speed)	620	0.80	2.49	0.80
House Fan (Low Speed)	300	0.50	31.63	0.51
Hair Dryer (High Power)	1070	1.00	1.65	1.00
Hair Dryer (Low Power)	520	0.91	44.20	1.0
Garbage Disposal Unit	117.79	0.87	46.26	0.95
Drill	220	0.96	21.63	0.98
Garage Door Opener	510	0.95	18.88	0.98

Heating and related Equipment

Appliance	Power (kW)	Power Factor	THD (Current) %	DPF
Heat Pump (Low Power)	0.51	0.93	4.27	0.93
Heat Pump (Medium Power)	2.32	0.78	8.60	0.78
Heat Pump (High Power)	4.81	0.95	7.13	0.95
Water Pump	1.18	0.78	7.02	0.78
Water Heater	4.33	1.0	2.05	1.0
Air Conditioner	1.68	0.97	9.41	0.98

Other High Power Appliances

Appliance	Power (kW)	Power Factor	THD (Current) %	DPF
Washing Machine	0.42	0.54	5.24	0.53
Washing Machine (Spin Cycle)	0.42	0.56	5.54	0.56
Drier	4.81	1.0	2.04	1.0
Refrigerator	0.61	1.0	1.96	1.0
Oven	5.81	1.0	1.78	1.0
Range	10.02	1.0	1.46	1.0
Dish Washer	1.27	0.97	2.95	1.0

Charger Data Summary

Four chargers were characterized at rated (100%) and reduced (90%) voltage at the beginning and end of charging. The tables below provide a summary of the charger characteristics. Complete data for each charger is included in Appendix A.8. The harmonic data of the chargers is also presented in the Appendix A.9.

Charger Characteristics at beginning of charging

Vehicle	Charger and Connecting Station	Power (KW)	Power Factor	THD (Current) %	DPF
GM EV1	WM200 on SCI	7.05	1.0	3.00	1.0
GM S10	WM200 on SCI	7.11	1.0	2.98	1.0
Toyota RAV4	SCI	4.83	1.0	2.53	1.0
	EVI#00617	4.74	1.0	2.36	1.0
Ford Ranger	SCI	5.61	1.0	5.26	1.0

Charger Characteristics at end of charging

Vehicle	Charger and Connecting Station	Power (KW)	Power Factor	THD (Current) %	DPF
GM EV1	WM200 on SCI	1.07	0.96	28.11	0.99
GM S10	WM200 on SCI	1.13	0.96	27.57	0.99
Ford Ranger	SCI	0.78	0.99	8.59	0.99

A comparison was undertaken to examine how different types of conductive connecting stations influenced the charger load characteristics. A Toyota Rav-4 was tested on two different connecting stations. Allowing for differences in test conditions, the effect of connecting station on the charger characteristics was negligible as is evident from the table below. More detailed test results are provided with the charger characteristics in AppendixA.8

Comparison of charger characteristics for different connecting stations

Connecting Station	Power (KW)	Power Factor	THD
SCI	4.83	1.0	2.53
EVI	4.74	1.0	2.36

Load Model Summary

The summary tables in this section provide an overview of electrical characteristics organized by electrical load model type: constant impedance (linear) or constant power. This was determined by comparing the electrical characteristics at rated voltage (100%) and reduced voltage (90%). When an appliance exhibited less than 5% change in impedance or power, the loads were classified into one of these two categories. Some appliances had several operating modes, and it was noted that constant power or constant impedance behavior depended on the operating mode. Four such appliances are given in the "dual mode" table.

The analysis presented in this section will be utilized during the next phase of this project to more accurately model the electrical appliances for computer simulation. Complete data for each appliance is included in Appendices A.2-A.7.

Constant Impedance Loads (High Power)

Appliance	Power (kW)	Power Factor	Impedance at rated voltage (ohms)	Impedance at reduced voltage (ohms)	% change in Impedance
Drier	4.81	1.0	11.67	11.65	0.17
Water Heater	4.33	1.0	13.35	13.22	0.97
Refrigerator	0.61	1.0	24.08	24.55	1.7
Oven	5.81	1.0	9.50	9.19	3.26
Range	10.02	1.0	5.41	5.15	4.8
Toaster	0.79	1.0	17.33	17.27	0.35
Garage Door	0.51	0.95	26.22	26.64	1.6
Vacuum Cleaner	1.25	0.98	11.41	11.43	0.18

Constant Power Loads

Appliance	Power Factor	Power at rated voltage(W)	Power at reduced voltage(W)	% change in Power
VCR 1	0.49	16.09	16.09	0.0
Satellite Dish	0.53	19.00	20.0	5.3
Computer 2	0.66	120.00	120.0	0.0
FAX Machine	0.62	22.00	22.00	0.0
Battery Recharger	0.49	35.09	35.09	0.0
Scanner	0.61	17.06	17.06	0.0
Computer Monitor	0.61	71.07	71.07	0.0

Dual Mode Devices

Appliance	Power (W)	Power Factor	THD (Current) %	% change in impedance for 10 % reduction in voltage	% change in current for 10% reduction in voltage
Coffee Maker (heating)	960.00	1.00	1.77	1.47	12.98
Coffee Maker (resting)	13.76	.76	35.24	10.14	0.0
Mixer (high)	109.29	.99	6.68	4.65	5.40
Mixer (low)	58.29	.60	61.17	7.44	2.40
Fan (High Speed)	620	.80	2.50	9.98	0.59
Fan (Low Speed)	300	.50	31.63	4.92	17.0
Hair Dryer (High Power)	1070	1.0	1.65	0.39	9.95
Hair Dryer (Low Power)	520	0.91	44.20	0.50	9.38

Harmonic Diversity Summary for Appliances

The phasor diagrams shown in Fig. 1 present the harmonic data in a phasor diagram format (harmonic current amplitude and phase angle for each individual appliance appears as a single line). The circle border represents an amplitude of 0.6 Amps. This format is intended to provide a means of identifying trends and not specific appliances. It can be seen that for the higher harmonic frequencies, the current amplitudes are very small for the appliances tested.

Differences in phase angle will result in harmonic phase cancellation by the currents injected by the various appliances. This effect is illustrated in Fig. 2, where the phasor sum of all appliances show the net current that would be expected at the service panel entrance if all appliances were on simultaneously. For these plots, the circle border represents an amplitude of 5 Amps.

The harmonic phasor sum diagrams in Fig. 2 clearly illustrate that the 3rd and 5th harmonic currents are expected to be the most significant. The 3rd and 5th harmonics are examined in more detail in Fig. 3 on 0.6 Amp circles. In this figure, the appliances are categorized as low power if they consume less than 150 W, and high power if greater than 150 W. The diagrams of Fig. 3 illustrate that harmonic currents resulting from low power appliances are expected to be relatively significant when compared to high power appliances. When considering the impact of harmonic currents, it is the magnitude of harmonic current in amps that is of importance. The current THD can be very misleading when considering lower power levels, since the current THD figure is a percentage of the fundamental. For example, there is not a significant difference in the EV charger harmonic current magnitude at the beginning (high power) and end (low power) of the charge cycle. The current THD is higher, not because the harmonic levels are higher but because the fundamental component is lower. Consequently, for the specific EV chargers tested the changes in harmonic characteristics over a charge cycle will not be a critical variable. This is illustrated Fig. 4 and Appendix A.9.

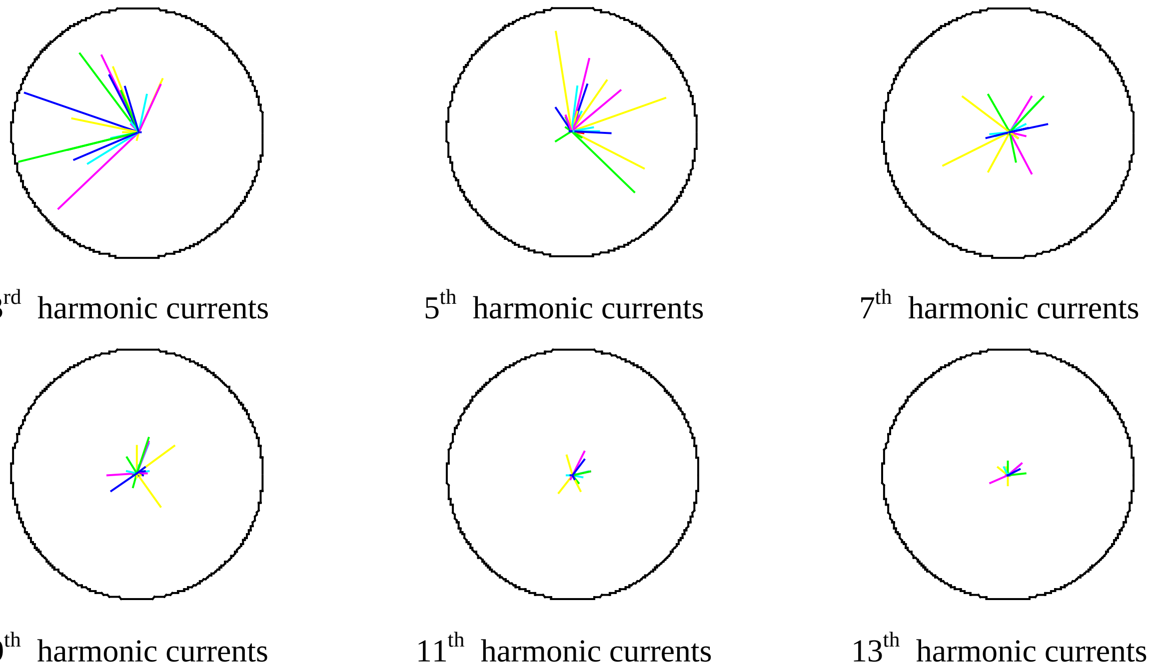

Figure 1: Phasor diagram of harmonic currents for all appliances on 0.6 A circles

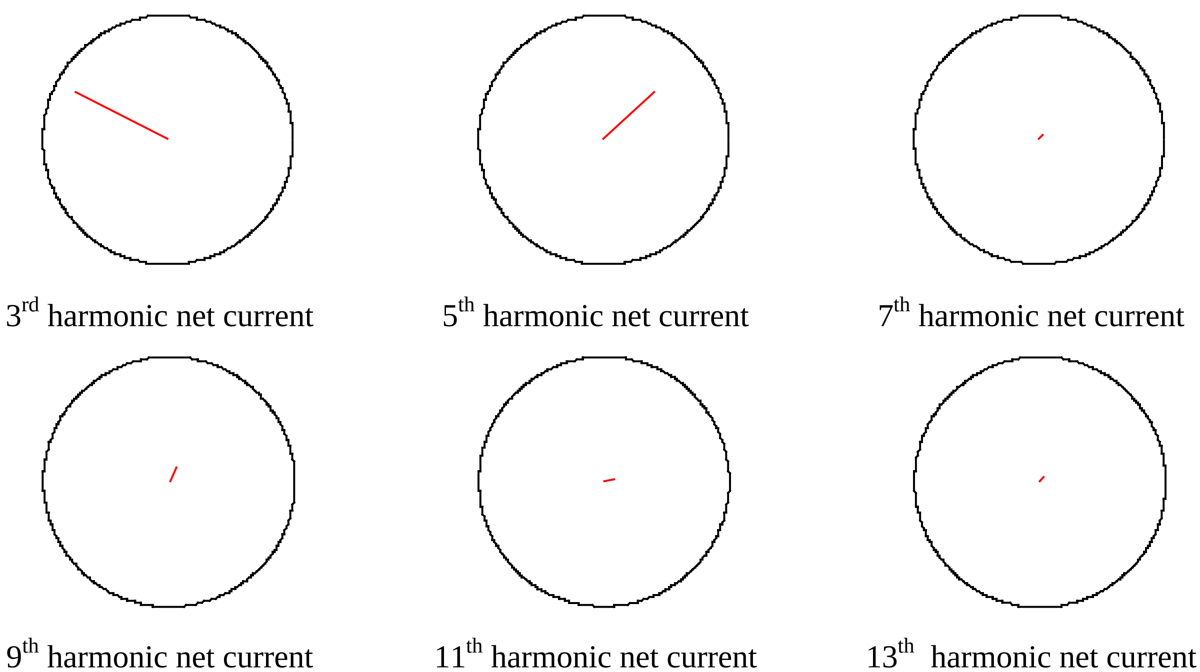

Figure 2: Phasor sum of harmonic currents for all appliances on 5.0 A circles

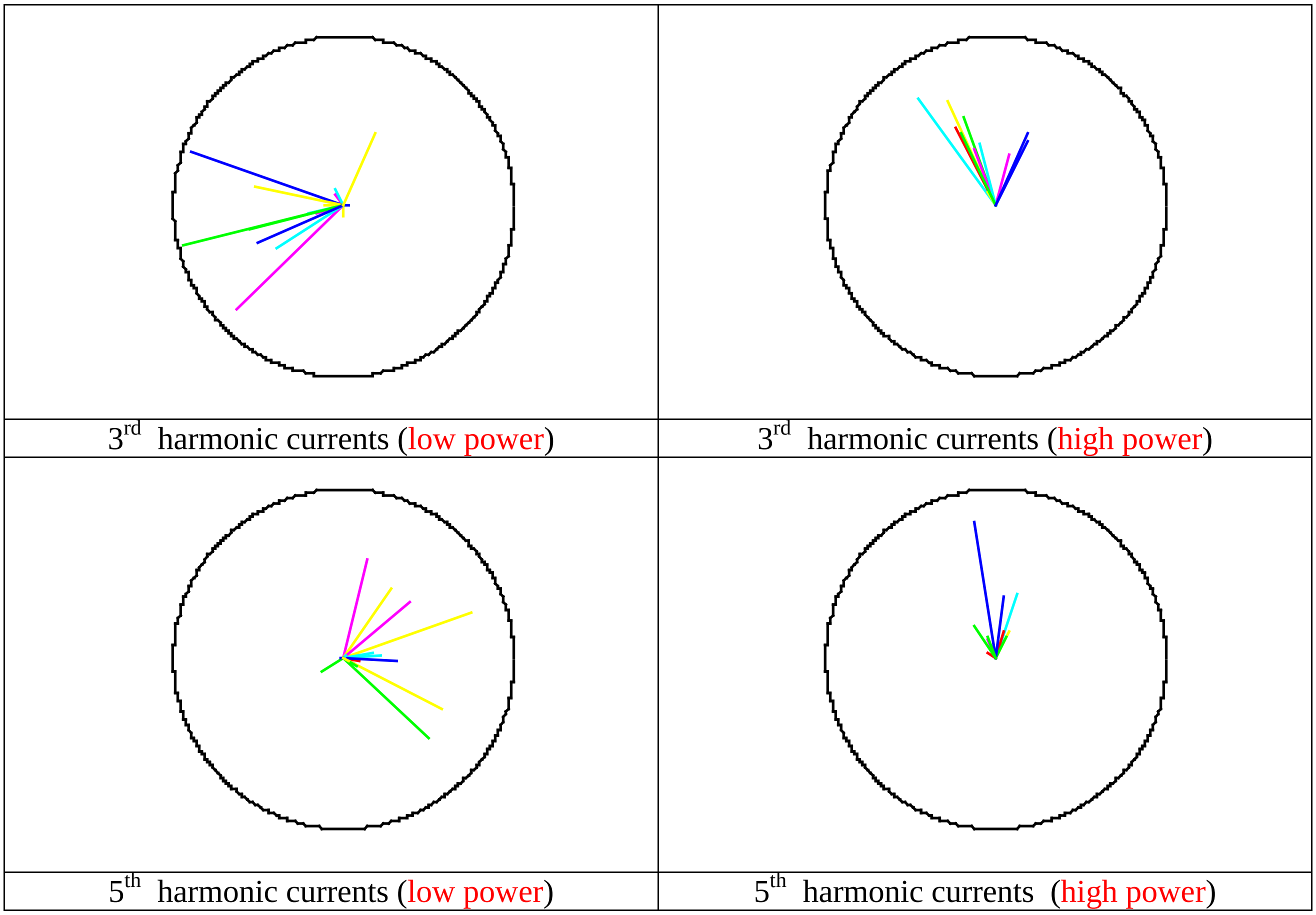

Figure 3: Phasor diagram of 3rd and 5th harmonic currents for low power (< 150 W) and high power (> 150 W) appliances on 0.6 A circles

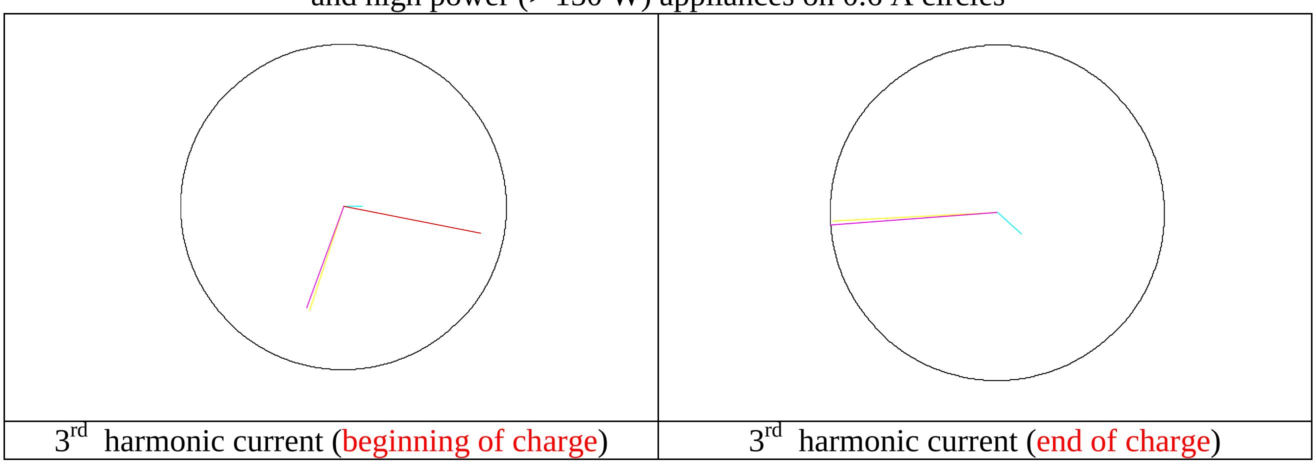

Figure 4: Phasor diagram of 3rd harmonic currents for 4 EV Chargers at beginning and end of charge cycle on 1.25 A circles

Instrument Comparison

A Fluke 41B harmonics meter was used to capture the voltage and current waveforms at 100% and 90% rated voltage. For comparison purposes, a BMI 3030A was also used to characterize several appliances. A summary of these comparisons appears in Appendix A.1. The BMI measurements deviate less than 10% from the Fluke measurements. THD (current) is the exception, where discrepancies of as much as 27% were noted.

The data presented in this section is not intended to be complete or conclusive. It is simply intended to present an example that illustrates the variance in instrument accuracy. If measurement repeatability were an issue, this would certainly be a concern. However, for this simulation study high precision measurements are not required because of the variability introduced by the random selection of appliances and the mix of appliance operation considered in Phase 3.

Utility System Data

The utilities represented in this report are identified in an identity-protected format. Each utility was asked to provide typical distribution transformer and secondary line data in their service territory. The tables below summarize the key data provided by the utilities. Complete transformer and line data provided by the utilities is included as Appendix A.10.

Overhead Line Data

	Util. "A"	Util. "B"	Util. "C"	Util. "D"	Util. "E"	Util. "F"
Rated KVA	37.5	25	25/50	37.5	50	*
Impedance (%)	1.75	2.06	1.2-1.4	1.4	2.17	*
Customers Served	15	13	*	4	4	*
Service Length (ft.)	100	80	*	75	200	*

Underground Line

	Util. "A"	Util. "B"	Util. "C"	Util. "D"	Util. "E"	Util. "F"
Rated KVA	50	25	25/50	50/75	50	*
Impedance (%)	1.75	1.87	1.2-1.4	1.8	2.17	*
Customers Served	20	6-8	*	5-7	8	*
Service Length (ft.)	125-130	110	*	200	200	*

* information not provided.

Second Interim Report

Secondary Distribution Impacts of Residential EV Charging

Home of the 1996 Olympic Village
Georgia Institute of Technology

SECOND INTERIM REPORT

June 1999

Project Title: Secondary Distribution Impacts of Residential EV Charging

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Abstract: This second of three interim reports documents the modeling protocol of electrical appliance and EV charger profiles captured during the data collection phase of this project. The report also describes how the measurements taken and simulations performed during this stage conclusively validate the models implemented in Electrotek's HarmFlo+ software for the appliances and electric vehicle chargers. This report documents the successful completion of Phase 2 of the planned project outline.

Secondary Distribution Impacts of Residential EV Charging

Second Interim Report

Abstract

This second of three interim reports documents the modeling protocol of electrical appliance and EV charger profiles captured during the data collection phase of this project. The report also describes how the measurements taken and simulations performed during this stage conclusively validate the models implemented in Electrotek's HarmFlo+ software for the appliances and electric vehicle chargers. This report documents the successful completion of Phase 2 of the planned project outline.

Translators

The process of translating appliance and EV charger data in the form of harmonic summaries into HarmFlo code can be a time-consuming and a tedious process. Since the information is already in electronic form, it is possible to automate the process of generating the HarmFlo libraries of the models. Appliance data in the form of Fluke41 files were provided to a Conversion Program written in PASCAL to translate these files to HarmFlo model code.

Modeling Protocol

All appliances and electric vehicle chargers were modeled as non-linear loads based on the measurements taken in the first phase of this project. The models developed for this study were implemented in Electrotek's HarmFlo+ workstation simulation package. In addition, the option of linear load modeling was incorporated into the Conversion Program to reduce the complexity of the simulation process. As an example, the models of the oven and the Ford Ranger EV charger with EVSE (EV Supply Equipment) are shown in Appendix B.1. The models were incorporated into library files, which were classified in a similar fashion to that done in the first phase of the project.

Model Validation

The models were validated by comparing the simulations to actual measurements for particular case scenarios performed at a test home. One of the homes used in the initial characterization of the appliances was used as the model validation home. This home is the only load connected to a 25 kVA pad-mounted UD transformer with a 14.4 kV primary side line voltage. The configuration of the tested feeder is provided in Fig. 1. The typical parameters of the conductors and the transformer are shown in Tables A and B. Data were collected on the secondary of the distribution transformer with the Fluke41B Power Harmonics Analyzer for various case scenarios. Since HarmFlo does not provide a transformer model with a split secondary winding for +120V, 0V, -120V, the measurements were done with the 120V loads connected to the same 120V feeder. A sample measurement of the voltage at the low side of the transformer was taken and then reflected back to the high side to be used in the simulations to take into account the background voltage distortion on the primary feeder. A source impedance corresponding to a fault current of 2kA was assumed based upon the location of the test transformer on the distribution feeder. The actual measurements were then compared to simulations run on HarmFlo+ workstation simulation package to validate the models.

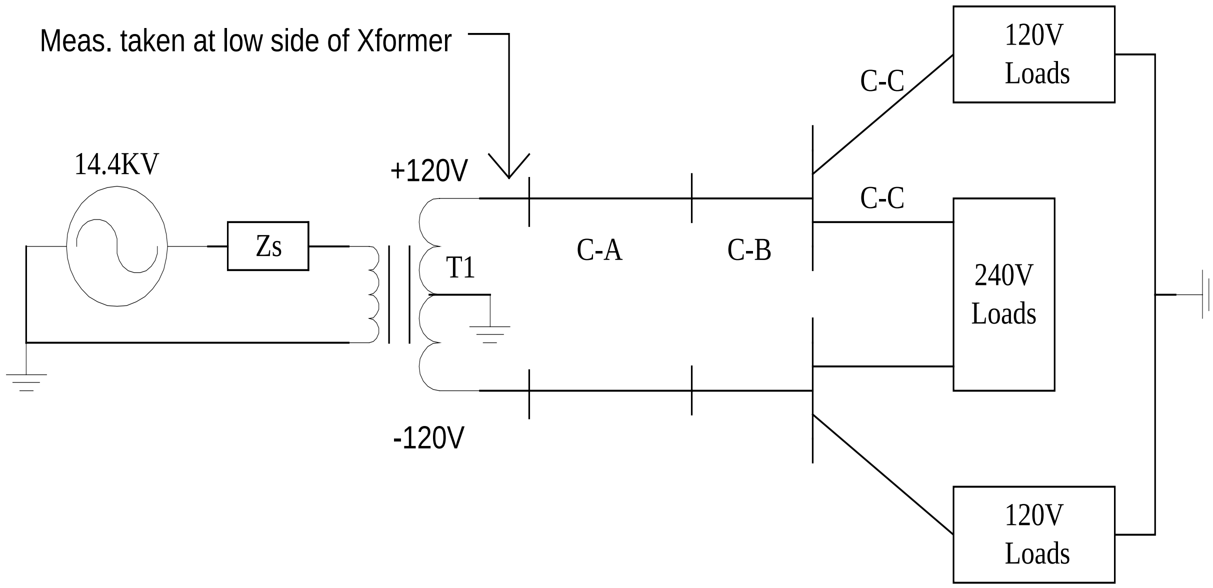

Figure 1. Feeder selected for measurements

Table A. Typical parameters for each type of conductor used in Fig.1

Type	Conductor	Length of conductor (ft.)	Impedance (Ω/1000 ft.)
C-A	350 MCM Al	110	0.0628+j0.0286
C-B	4/0 Al	50	0.100+j0.041
C-C	#12 Cu	50	2.000+j0.054

Table B. Typical parameters for distribution transformer used in Fig. 1

Type	KVA	%Z	X/R
Pad-mounted	25	2.1	1.4

The case scenarios were based on the worst and best case loads in the test home. The loads with the maximum current THD in each category, such as home office, high power loads, etc., were chosen for the worst case scenario. The best case scenario included mostly the loads with low distortion in current. A marginal case scenario with a mix of the best and worst case scenarios was also performed. The specific configurations and a comparison of the actual measurements and the simulation results are provided in the sections below.

Worst Case Scenario

For the “worst case” scenario, the appliances and EV charger selected have the highest THD in their categories. A listing of the appliances chosen for this scenario is shown in Table C. The measurements and simulations were performed with the non-linear loads and the Ford Ranger EV charger and EVSE taken separately as well as together. In all the scenarios, the X1 and X3 line currents correspond to the currents in the +120V and -120V line feeders. A comparison of the measurements and simulations is shown in Tables D and E for the above mentioned sub-cases. For case 1(c), the voltage and current waveforms for X1 are shown in Fig. 2. Detailed data for each current harmonic component are included in Appendix B.2

Table C. Worst case scenario appliances

Appliance	RMS Current (A)	THD(%)
Television	1.3	96.0
Stereo	1.2	78.8
Computer	1.6	111.7
Drill	2.0	21.6
Ford Ranger	23.4	5.2

Table D. Comparison of current measurements and simulation results

	Appliances included	X1 Line Current				X3 Line Current			
		Meas. (A)	Sim. (A)	Meas. THD %	Sim. THD %	Meas. (A)	Sim. (A)	Meas. THD %	Sim. THD %
Case 1(a)	Ford Ranger EV Charger w/EVSE	23.3	23.2	5.3	5.5	23.5	23.5	5.4	5.5
Case 1(b)	Television, Stereo, Computer, Drill	4.7	5.9	55.9	67.2	0.0	0.0	0.0	0.0
Case 1(c)	Television, Stereo, Computer, Drill, Ford Ranger EV Charger w/EVSE	27.4	27.3	7.5	9.6	23.5	23.2	5.5	5.6

Table E. Comparison of voltage measurements and simulation results

	Appliances included	Secondary Line Voltage (V)		Secondary Line Voltage THD %	
		Meas.	Sim.	Meas.	Sim.
Case 1(a)	Ford Ranger EV Charger w/EVSE	248.0	246.7	1.6	1.5
Case 1(b)	Television, Stereo, Computer, Drill	124.2	124.0	1.7	1.6
Case 1(c)	Television, Stereo, Computer, Drill, Ford Ranger EV Charger w/EVSE	248.4	246.8	1.7	1.6

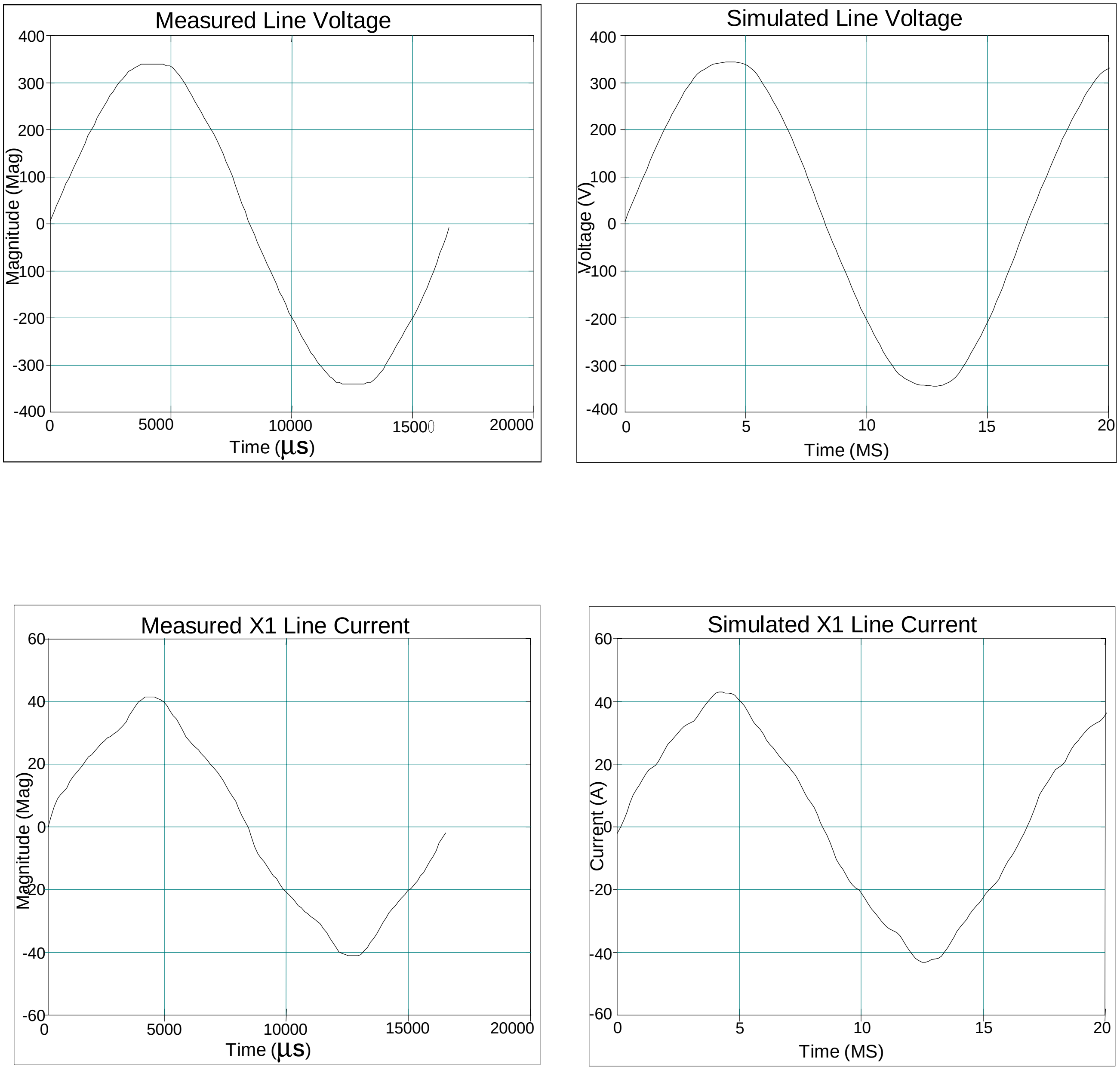

Figure 2. Current and voltage waveforms for X1 for case 1(c)

Best Case Scenario

For the "best case" scenario, the appliances selected were the ones with the lowest current THD. Two sub-case scenarios, with and without the lights included with the appliances, were studied. A listing of the appliances chosen for this scenario is shown in Table F. A comparison of the measurements and simulations is shown in Tables G and H for the above mentioned sub-cases. For case 2(a), the voltage and current waveforms for X1 are shown in Fig. 3. Detailed data for each current harmonic component are included in Appendix B.2

Table F. Best case scenario appliances

Appliance	RMS Current (A)	THD(%)
Oven	24.7	1.8
Refrigerator	5.0	2.0
Light Bulbs - 24 of 100W each	20.4	7.4

Table G. Comparison of current measurements and simulation results

	Appliances included	X1 Line Current				X3 Line Current			
		Meas. (A)	Sim. (A)	Meas. THD %	Sim. THD %	Meas. (A)	Sim. (A)	Meas. THD %	Sim. THD %
Case 2(a)	Oven, Refrigerator, Lights	40.6	40.6	2.2	1.5	34.0	35.7	2.0	1.7
Case 2(b)	Oven, Refrigerator	26.4	25.6	2.6	1.8	30.5	30.7	2.2	1.8

Table H. Comparison of Voltage measurements and simulation results

	Appliances included	Secondary Line Voltage (V)		Secondary Line Voltage THD %	
		Meas.	Sim.	Meas.	Sim.
Case 2(a)	Oven, Refrigerator, Lights	247.5	247.0	1.7	1.5
Case 2(b)	Oven, Refrigerator	247.7	247.2	1.7	1.5

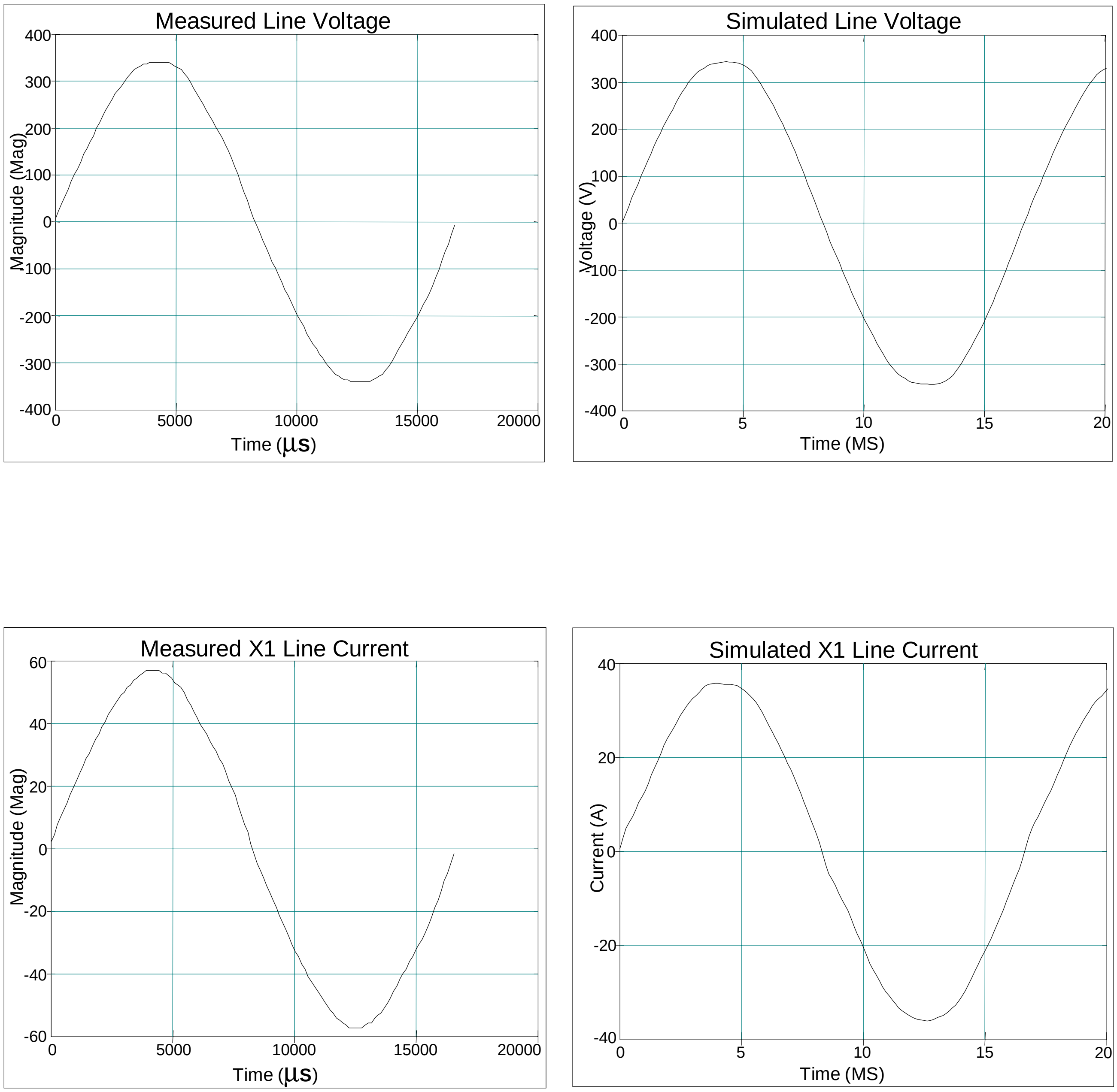

Figure 3. Current and voltage waveforms for X1 for case 2(a)

Marginal Case Scenario

For the "marginal case" scenario, the appliances and EV charger selected were a mix of the best and worst loads indicated in the previous case scenarios. This case corresponds to a "real world" case with the effect of non-linear loads and EV chargers being studied when a non-distorting load is present. A comparison of the measurements and simulations is shown in Tables I and J for the above mentioned sub-cases. For case 3(c), the voltage and current waveforms are shown in Fig. 4. Detailed data for each current harmonic component are included in Appendix B.2

Table I. Comparison of current measurements and simulation results

	Appliances included	X1 Line Current				X3 Line Current			
		Meas. (A)	Sim. (A)	Meas. THD %	Sim. THD %	Meas. (A)	Sim. (A)	Meas. THD %	Sim. THD %
Case 3(a)	Oven, Refrigerator, Ford Ranger EV Charger w/EVSE	49.8	46.5	2.7	2.9	52.3	51.5	2.9	2.7
Case 3(b)	Oven, Refrigerator, Stereo, Computer, Drill, Television, Ford Ranger EV Charger w/EVSE	53.6	50.9	4.7	5.3	52.0	51.5	2.8	2.7
Case 3(c)	Oven, Refrigerator, Lights, Ford Ranger EV Charger w/EVSE, Stereo, Drill, Television, Computer	67.1	68.4	3.3	4.0	57.1	56.3	2.5	2.5

Table J. Comparison of voltage measurements and simulation results

	Appliances included	Secondary Line Voltage (V)		Secondary Line Voltage THD %	
		Meas.	Sim.	Meas.	Sim.
Case 3(a)	Oven, Refrigerator, Ford Ranger EV Charger w/EVSE	246.4	246.0	1.6	1.5
Case 3(b)	Oven, Refrigerator, Stereo, Computer, Drill, Television	246.6	246.0	1.6	1.5
Case 3(c)	Oven, Refrigerator, Lights, Ford Ranger EV Charger w/EVSE, Stereo, Drill, Television, Computer	246.6	245.8	1.6	1.5

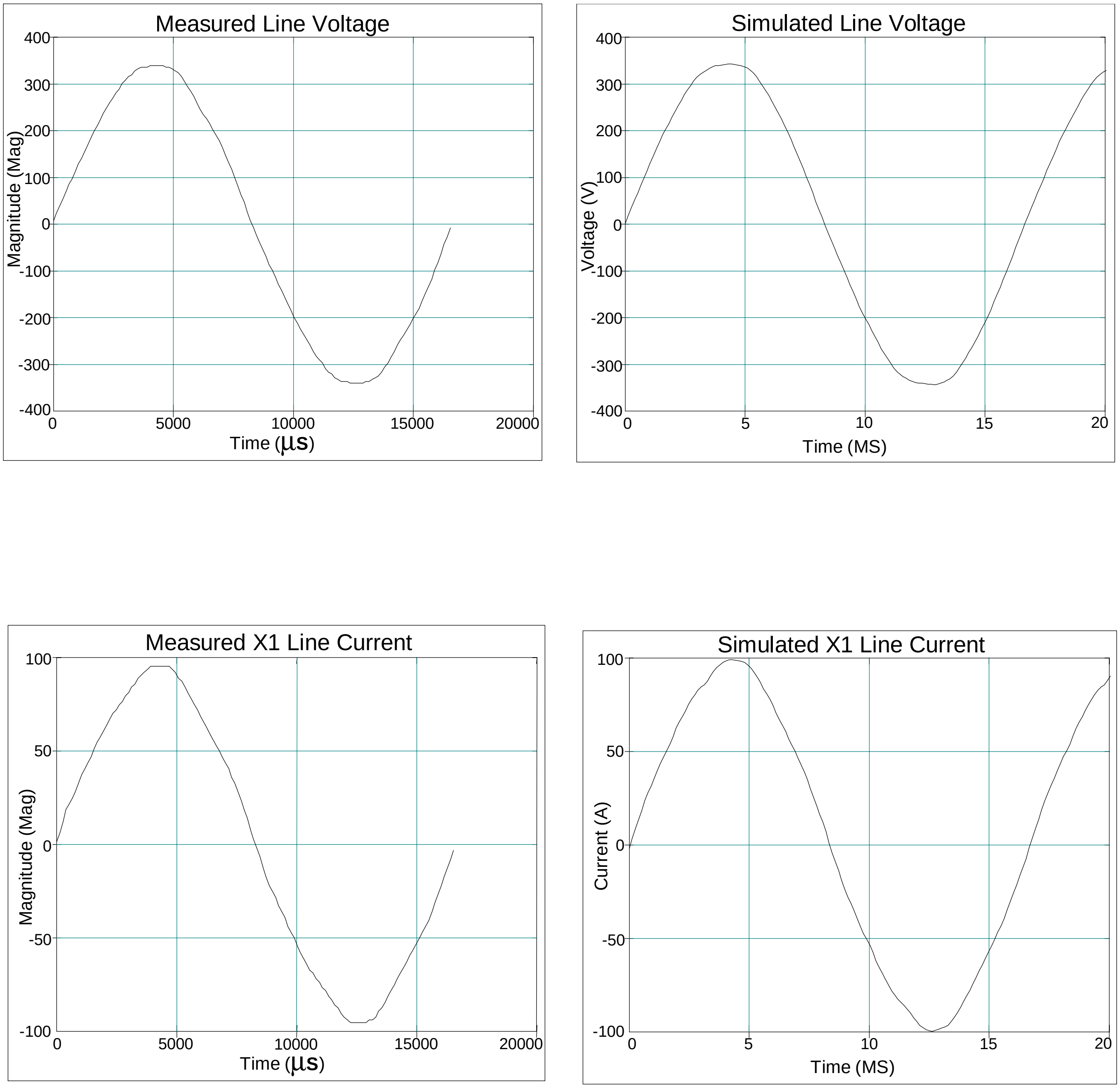

Figure 4. Current and Voltage waveforms for X1 for case 3(c)

Accuracy of model validation

The simulation results and the measurements presented in the above sections are not expected to match exactly but serve to validate the models to the extent possible taking into account the various factors involved. Some of the factors introducing variability in the measurements are:

- The inherent measurement accuracy in the Fluke41B Power Harmonics Analyzer. Error in the current and voltage measurements is less than 0.5% of the reading. Error in the individual harmonic measurements is less than 3% of the reading up to the 13^{th} harmonic, thereafter steadily increasing up to 8% of the reading for the 31^{st} harmonic.
- Background distortion of the high side supply voltage at the feeder introduces differences between the measurements and the simulated values. The models were created with respect to the background voltage distortion present at the time the measurements for individual appliances were taken. The background voltage distortion was different at the time when the measurements for the case scenarios were performed.
- The repeatability of the measurements introduces measurement inaccuracy. Five measurements were performed on a computer in the laboratory over a forty-five minute period using the Fluke41B Power Harmonics Analyzer. The rms current varied from 0.72 to 0.75 amps and the current THD varied from 8.1% to 9.3%.
- Loads classified as constant power loads, such as the computer, cannot be modeled as such in HarmFlo due to the unavailability of a proper model. These loads were modeled as non-linear loads leading to a certain degree of inaccuracy.
- Appliance operating cycles also influence the accuracy of the measurements to a great extent. The dishwasher, heat pump, washing machine etc., which have more than one cycle of operation, also lead to variability in the measurements. For this reason, these cycling loads were not included in the case scenarios. The data recorded in the library for these appliances was taken during the cycle with the worst current distortion.

Conclusion

The modeling of the loads characterized during Phase 1 of the project was accomplished during this phase of the project. The models created in Electrotek's HarmFlo+ software were validated by measurements taken at a test home. The case scenarios presented show close correlation between the simulated results and measured values. Further, the reasons for differences between measured and simulated results were established. This report completes Phase 2 of the project.

Third Interim Report

Secondary Distribution Impacts of Residential EV Charging

Home of the 1996 Olympic Village
Georgia Institute of Technology

THIRD INTERIM REPORT

February 7, 2000

Project Title: Secondary Distribution Impacts of Residential EV Charging

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Vinod Rajasekaran, NEETRAC, ECE Graduate Research Assistant
Jason Pierce, NEETRAC, ECE Graduate Research Assistant
John Kennedy, Georgia Power Company (Project Advisor)

Abstract: This third of four interim reports documents the simulation case studies representative of the electrical service configurations of the participating utilities. An evaluation of worst and best case conditions with respect to the transformer parameters and circuit configurations was performed. The report also documents the effects of harmonic currents on line and transformer losses and transformer de-rating aspects. The absolute worst case simulation scenario resulted in a voltage THD of 5.1%, which is on the edge of the recommended limits for voltage distortion (i.e. 5%). Simulation results from all of the participating utilities are included. This report documents the successful completion of Phase III of the planned project outline.

Secondary Distribution Impacts of Residential EV Charging

Third Interim Report

Abstract

This third of four interim reports documents the simulation case studies representative of the electrical service configurations of the participating utilities. An evaluation of worst and best case conditions with respect to the transformer parameters and circuit configurations was performed. The report also documents the effects of harmonic currents on line and transformer losses and transformer de-rating aspects. The absolute worst case simulation scenario resulted in a voltage THD of 5.1%, which is on the edge of the recommended limits for voltage distortion (i.e. 5%). Simulation results from all of the participating utilities are included. This report documents the successful completion of Phase III of the planned project outline.

Compilers

The process of translating utility system data into HarmFlo code can be a time-consuming and tedious process. It is possible to automate the process of generating the HarmFlo files for any case scenario given the utility data. Utility system data were provided to a Compiler Program written in PASCAL to translate the input data into HarmFlo input files. A short summary of the program and an example have been provided in Appendix C.1.

Simulation Protocol

The simulation variables were:

- EV charger type and mix
- Distribution transformer capacity (kVA) and impedance
- Conductor impedance (size and length)
- Number of customers
- Maximum demand

Worst and typical case conditions were identified for each of these variables by the participating utilities. The worst case conditions for the simulation procedure identified from the utility data were:

- EV charger with highest current THD
- Lowest transformer capacity (kVA)
- Highest transformer impedance
- Highest conductor impedance
- Maximum number of customers
- Maximum demand

All case scenarios were simulated with and without the EV charger to study the system performance on introduction of chargers. Due to diversity effects leading to phase cancellation of the harmonic currents, the changes in voltage THD with the addition of chargers cannot be attributed only to the chargers. Rather, the changes in voltage THD signify the effects of chargers interacting with other home appliances in a real world situation.

A study of the line and transformer losses was also undertaken for the various case scenarios. In general, a transformer in which the current distortion exceeds 5% is usually considered for de-rating for harmonics. The "IEEE recommended practice for establishing transformer capability when supplying non-sinusoidal load currents" as defined in IEEE Std. C57.110-1998 was used for de-rating the transformers. The Harmonic Loss Factor (F_{HL}) can be defined solely in terms of the harmonic currents as follows:

$$F_{HL} = \frac{\left(I_h^2 \times h^2\right)}{I_h^2} \qquad (3.1)$$

Then, in terms of the Harmonic Loss Factor, the de-rating of the transformer can be derived to be

$$D = \sqrt{\frac{1 + P_{EC-R}}{1 + F_{HL} \times P_{EC-R}}}(per\,unit) \qquad (3.2)$$

where P_{EC-R} = eddy current loss factor (in terms of the conduction loss)
h = harmonic number
I_h = harmonic current

A typical per unit eddy current loss factor of 8% was assumed for performing the calculations. The 8% value is based upon industry experience.

Simulation Results

This section presents the results of the three different simulation case scenarios. The three scenarios are:

- Worst Case Scenario
- Marginal Case Scenario
- Typical Case Scenario

A comparative study of the simulation parameters for the three cases is shown below in Table A.

Table A. Comparison of Simulation Parameters

	Worst	Marginal	Typical
EV Charger Penetration %	100%	100%	50%
EV Charger Current THD	17.0 %	14.3 %	14.3 %
Distribution Service Transformer	15 kVA	15 kVA	50 kVA
	%R=4.5,%X=4.0	%R=4.5,%X=4.0	%R=0.9,%X=1.1
Conductor Used	#2Al Triplex	#2 Al Triplex	350 Al Triplex
Length of conductor	120 ft.	120 ft.	75 ft.
No. of customers	2	2	4
Total Load	25.7 kW	24.7 kW	40 kW
% Loading	172 %	165 %	76 %

Worst Case Scenario

For the “worst case” scenario an EV charger model was constructed from the IEC 1000-3-2 recommended limits for harmonic currents for equipment. This simulated charger has a current THD of 17.3%. These limits have been adopted in the form of an IWC Record of Consensus (ROC) recommendation for EV charger current distortion. The recommended limits place absolute limits on the harmonic currents as a percentage of the fundamental. The current waveform and its harmonic spectrum are shown in Fig 1. The worst case scenario assumed that all EV owners used the same EV charger thus removing the effects of harmonic phase cancellation.

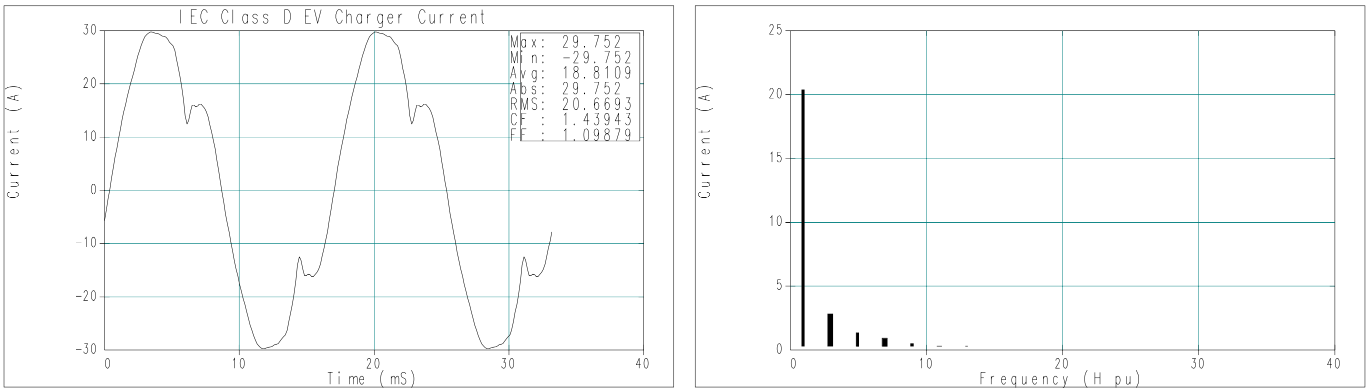


Fig. 1. IEC Class-D EV Charger Current Waveform and Spectrum

The worst case conditions for the other simulation parameters provided by the utility participants is shown in Table B. The results obtained for the various utilities for their worst case scenarios is shown in Table C.

Table B. Utility Data for Worst case conditions

	Utility A	Utility B	Utility C	Utility D†	Utility E	Utility F
Distribution Transformer	15kVA %Z=6% X/R=0.9	333 kVA %Z=3.7% X/R=3.6	45 kVA %Z=2% X/R=1.0	100 kVA %Z=2.2% X/R=1.9	15 kVA %Z=2% X/R=1.1	25 kVA %Z=4% X/R=1.0
Line conductor	#2 Al Triplex	R=143.3mΩ X=25.2 mΩ	2/0 Cu	#1/0 Al Triplex	#4 Al	1/0 Al
Length of conductor	75 ft.	-	120 ft.	300 ft.	80 ft.	100 ft.
Number of customers	2	40	2	8	5	4
Type of loading	Residential	Residential	Commercial	Residential	Residential	Residential
Maximum Demand	172%	183%	95%	50%	145%	161%
Background Voltage Distortion	1.5%	3.4%	1.5%	1.5%	1.5%	1.5%
EV Charger Current THD %	17.3%	17.3%	17.3%	55.0%	17.3%	17.3%
Single/Three Phase	Single	Single	Three	Single	Single	Single

† Utility D requested all simulations be performed with an EV charger current THD of 55%.

Table C. Worst Case Utility Simulation Results

	Utility A	Utility B	Utility C*	Utility D	Utility E	Utility F
X1 Line Current	98.4 A 8.0 %THD	2.53 kA 6.3 %THD	95.4 A 35.0 %THD	185.7 A 21.8 %THD	98.6 A 8.2 %THD	156.5 A 5.0 %THD
X3 Line Current	94.1 A 8.3 %THD	2.57 kA 6.5 %THD	95.7 A 39.3 %THD	213.2 A 20.6 %THD	75.3 A 11.7 %THD	161.6 A 8.0 %THD
Secondary Line Voltage	217.0 V 5.1 %THD	242.8 V 4.1 %THD	207.4 V 1.9 %THD	238.3 V 2.0 %THD	233.3 V 2.5 %THD	237.6 V 3.0 %THD
Line Losses	45.0 W	48.7 kW	436.2 W	340.8 W	135.4 W	264.0 W
Transformer Losses	800.8 W	10.6 kW	197.9 W	167.4 W	546.3 W	1.8 kW
Harmonic Loss Factor	1.2	1.1	2.7	2.2	1.1	1.1
Transformer De-rating	0.99	1.0	0.94	0.96	1.0	1.0
Incremental Voltage THD due to introduction of chargers	2.5%	0.8%	0.0%	0.4%	0.7%	0.7%

*** Utility C was a three-phase system. X1 and X3 in this case refer to Phase A and Phase C.**

An "absolute worst" case scenario was created from the worst case conditions provided by the various utilities by selecting worst values from data provided by all utilities. The simulation parameters for the worst case scenario are reported in Table D. The field configuration used for the worst case is shown in Fig.2. The source voltage was assumed to have a background voltage distortion of 1.5%. The background source voltage used was derived from the measurements taken for model validation at one of the test homes during Phase II of the project. The mix of appliances used for the worst case scenario are shown in Table E. The results obtained are shown in Fig 3 and Table F. The system performance with regard to line and transformer losses is shown in Table G.

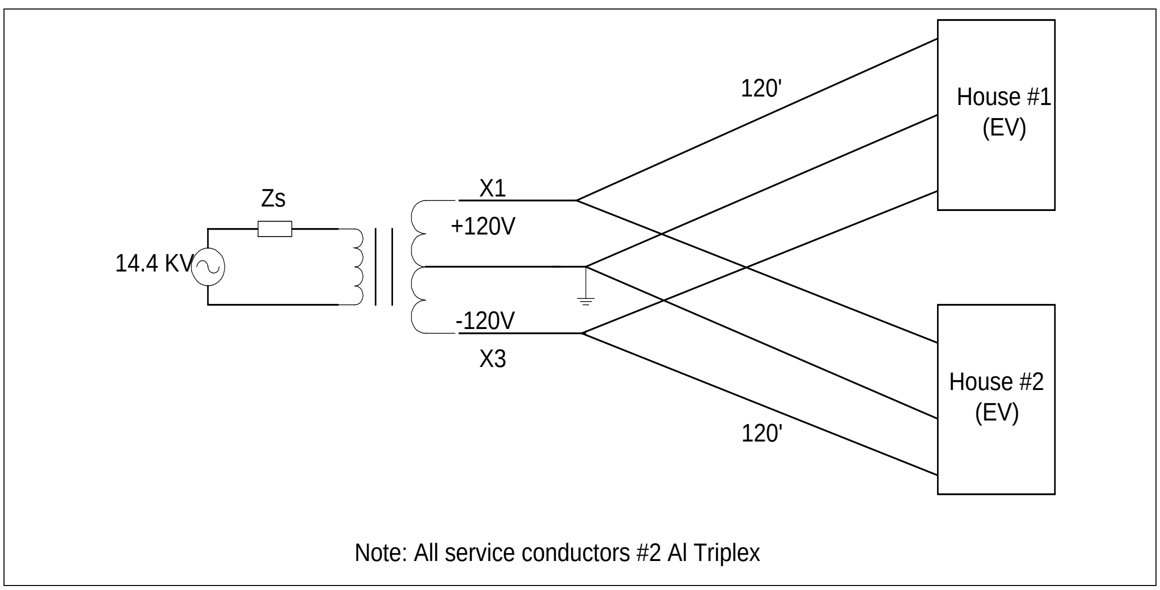


Fig. 2. Field Site Configuration for Absolute Worst Case Simulation

Table D. Absolute Worst Case Simulation Parameters

	Value
EV Charger	17% current THD
Distribution Service Transformer	15 kVA %R=4.5,%X=4.0
Conductor Used	#2 Al Triplex
Length of conductor	120 ft.
No. of customers	2

Table E. Appliances Used In Simulation

House #1		**House #2**	
Appliance	Load (kW)	Appliance	Load (kW)
Refrigerator	0.6	Refrigerator	0.6
Air Conditioner	2.3	Air conditioner	2.3
Microwave	1.3	Toaster	0.8
Hair Dryer	1.1	VCR	0.1
Computer	0.1	Television	0.1
Dryer	4.8	Washing Machine	0.4
EV charger (IEC)	5.6	EV Charger (IEC)	5.6
Total Load	**15.8 kW**	**Total Load**	**9.9 kW**

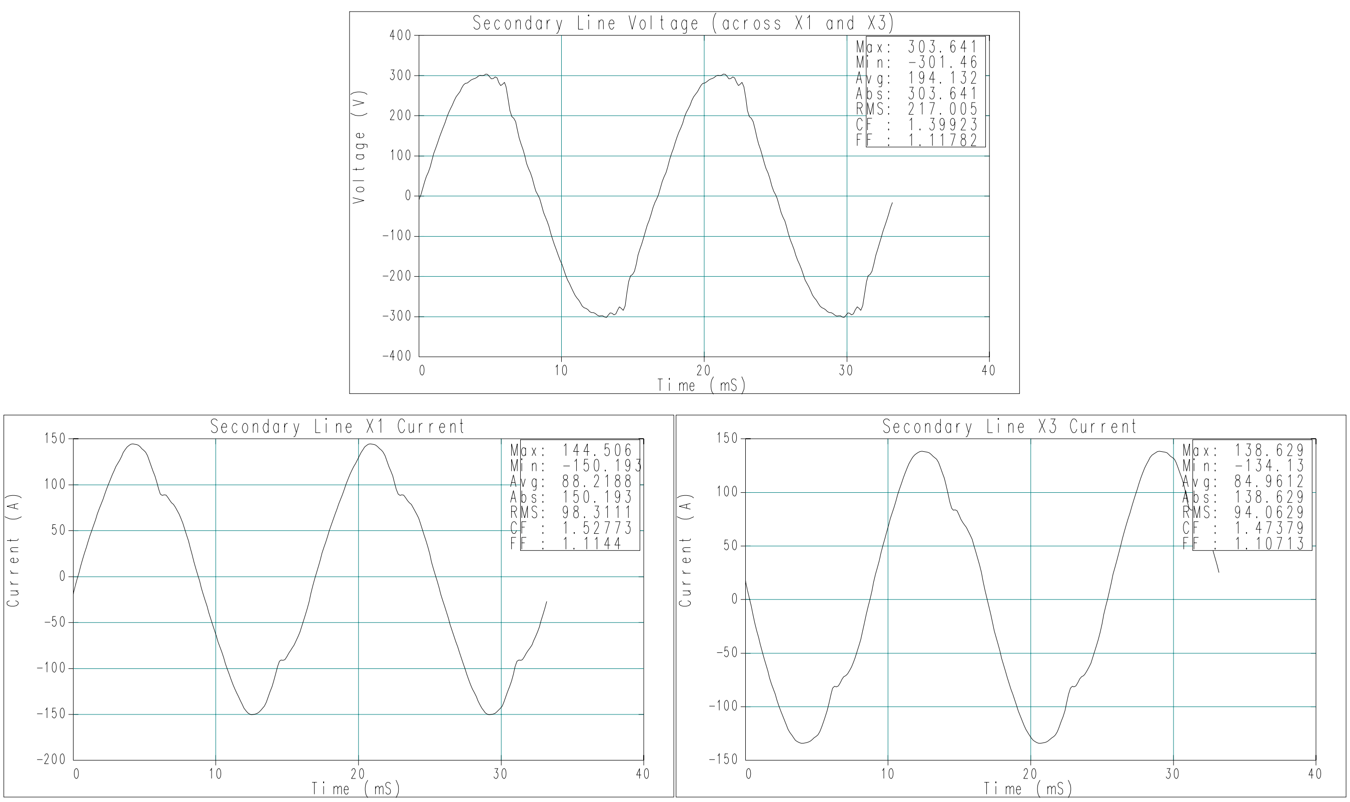


Fig 3. Absolute Worst Case Simulation Results

Table F. Absolute Worst Case Simulation Results

	X1 Line Current		X3 Line Current		Sec. Line Voltage (V)	Sec. Line Voltage THD (%)
	Sim. (A)	THD (%)	Sim. (A)	THD(%)		
Without Charger	61.2	8.6	56.7	5.4	225.7	2.6
With Charger	98.3	8.0	94.1	8.3	216.7	5.1

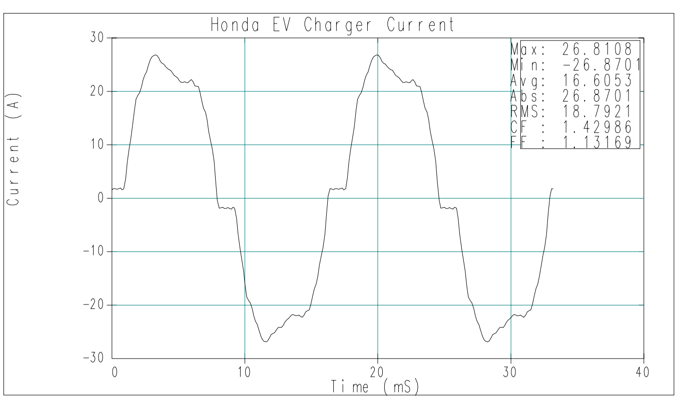
Table G. Line and Transformer Losses (Absolute Worst Case)

	Line Losses (W)	Transformer Winding Losses (W)	Harmonic Loss Factor	Transformer De-rating
Without Charger	18.5	299.1	1.1	1.0
With Charger	45.0	800.8	1.2	0.99

Utility "A" had the maximum voltage distortion of 5.1% with the introduction of chargers while the rest of the utilities did not have significant changes in voltage THD. Utility "A" had the worst transformer impedance resulting in higher THD. Utilities "C" and "D" were lightly loaded and had average transformer impedances resulting in negligible changes to voltage THD. Utility "B" had a marginal increase in voltage THD by 0.8%.

Marginal Case Scenario

For the marginal case scenario a commercial charger with the highest current THD namely the Honda EV charger with 14.3% THD was used as compared to the worst case scenario charger with 17.3% current THD. The other parameters namely the system data and the appliances remained the same, as in the worst case scenario. The current waveform and its spectrum are shown in Fig 4. The simulation results for the various utilities have been summarized in Table I. An "absolute marginal" case scenario was constructed similar to the "absolute worst" case with the Honda EV charger incorporated into the simulations. The results have been summarized in Tables J and K and Fig. 4.



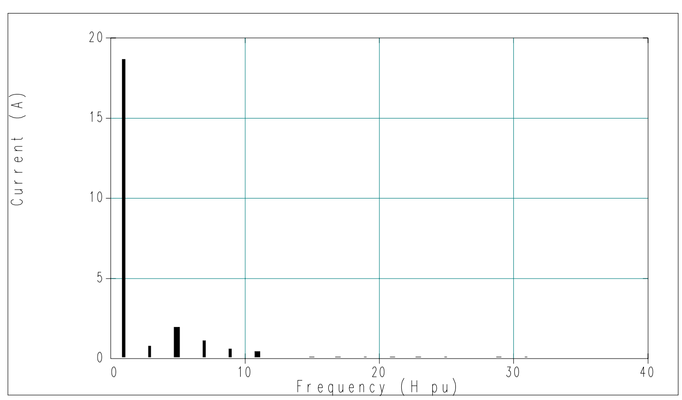


Fig 4. Honda EV Charger Current Waveform and Spectrum

Table H. Utility Data for Marginal Case Conditions

	Utility A	Utility B	Utility C	Utility D	Utility E	Utility F
Distribution Transformer	15 kVA %Z=6% X/R=0.9	333 kVA %Z=3.7% X/R=3.6	45 kVA %Z=2% X/R=1.0	100 kVA %Z=2.2% X/R=1.9	15 kVA %Z=2% X/R=1.1	25 kVA %Z=4% X/R=1.0
Line Conductor	#2 Al Triplex	R=143.3mΩ X=25.2 mΩ	2/0 Cu	#1/0 Al Triplex	#4 Al	1/0 Al
Length of Conductor	75 ft.	-	120 ft.	200 ft.	80 ft.	100 ft.
Number of Customers	2	40	2	8	5	4
Type of Loading	Residential	Residential	Commercia l	Residential	Residential	Residential
Maximum Demand	172%	189%	95%	116.5%	138%	157%
Background Voltage Distortion	1.5%	3.4%	1.5%	1.5%	1.5%	1.5%
EV Charger Current THD	14.3%	14.3%	14.3%	55.0%	14.3%	14.3%
Single/Three Phase	Single	Single	Three	Single	Single	Single

Table I. Marginal Case Utility Simulation Results

	Utility A	Utility B	Utility C*	Utility D	Utility E	Utility F
X1 Line Current	95.0 A 6.2 %THD	2.46 kA 5.2 %THD	94.3 A 37.4 %THD	405.7 A 9.8 %THD	94.6 A 6.8 %THD	152.5 A 4.5 %THD
X3 Line Current	90.7 A 5.6 %THD	2.49 kA 5.3 %THD	94.1 A 39.6 %THD	430.7 A 7.5 %THD	71.1 A 9.1 %THD	157.5 A 7.2 %THD
Secondary Line Voltage	217.7 V 4.5 %THD	242.9 V 3.1 %THD	207.4 V 1.9 %THD	236.6 V 1.9 %THD	233.6 V 2.1 %THD	238.0 3.0 %THD
Line Losses	42.1 W	46.1 kW	412.5 W	1.8 kW	123.2 W	254.1 W
Transformer Losses	745.2 W	10.0 kW	187.2 W	541.3 W	516.1 W	1.8 kW
Harmonic Loss Factor	1.1	1.1	2.9	1.1	1.2	1.1
Transformer De-rating	1.0	1.0	0.94	1.0	0.99	1.0
Incremental Voltage THD Due to Introduction of Chargers	1.9%	-0.2%	0.0%	0.1%	0.3%	0.7 %

*** Utility C was a three-phase system. X1 and X3 in this case refer to Phase A and Phase C.**

Table J. Absolute Marginal Case Simulation Results

	X1 Line Current		X3 Line Current		Sec. Line Volt.(V)	Sec. Line Voltage THD(%)
	Sim. (A)	THD (%)	Sim. (A)	THD (%)		
Without Charger	61.0	8.6	56.6	5.4	225.6	2.6
With Charger	94.9	6.3	90.6	5.7	217.5	4.5

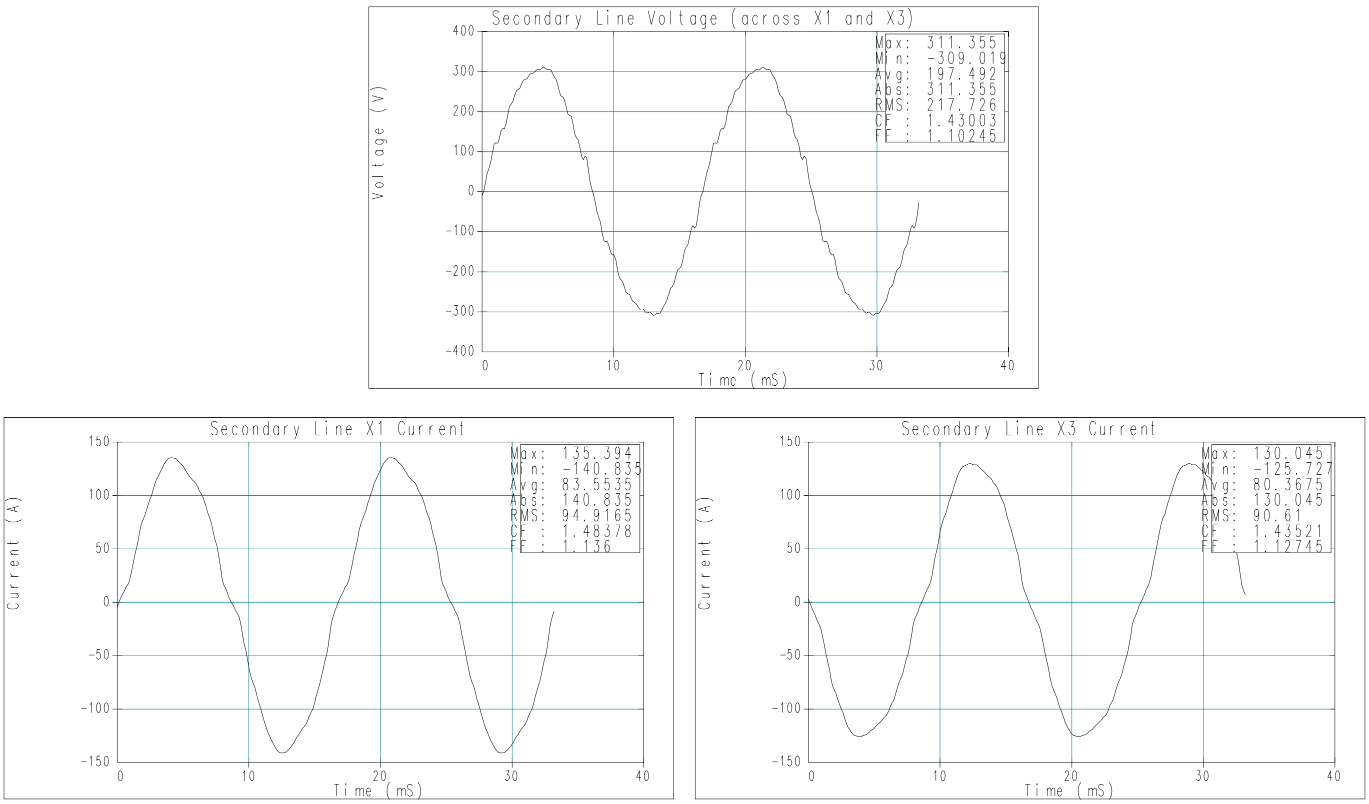


Fig 5. Absolute Marginal Case Simulation Results

Table K. Line and Transformer Losses (Absolute Marginal Case)

	Line Losses (W)	Transformer Winding Losses (W)	Harmonic Loss Factor	Transformer De-rating
Without Charger	18.5	299.1	1.1	1.0
With Charger	42.1	745.2	1.1	1.0

Similar results were obtained for the marginal case simulations as the worst case simulations with a lessening of the voltage THD as an EV charger with lesser current THD was used for the simulations. It was also noticed that the voltage THD in the case of Utility "B" was actually reduced with the introduction of EV chargers. This can be attributed to the harmonic cancellation effect with the introduction of non-linear loads (EV chargers). Utilities “C” and “D” did not have significant increases in voltage THD with the introduction of the chargers.

Typical Case Scenario

The parameters and results obtained for the typical case simulations for each individual utility are shown in Tables L and M. A typical case scenario was also simulated with data selected from the utility transformer and service parameters. The Honda EV charger was used for the simulations. Typical transformer and service parameters were used for the case scenarios and are shown in Table N. The appliances used for the typical case scenario simulation are shown in Table O. The simulation results are shown in Tables P and Q.

Table L. Utility Data for Typical Case Conditions

	Utility A	**Utility B**		**Utility C**	**Utility D**	**Utility E**	**Utility F**
		Under-ground	**Overhead**				
Distribution Transformer	37.5 kVA %Z=1.4% X/R= 0.8	50 kVA %Z=1.8% X/R=1.1	37.5 kVA %Z=1.8% X/R=1.1	100 kVA %Z=2.2% X/R=1.9	300 kVA %Z=4% X/R=1.0	75 kVA %Z=2% X/R=1.1	75 kVA %Z=2% X/R=1.0
Line Conductor	#4/0 Al Triplex	R=19.1mΩ X=19.7mΩ	R=19.1mΩ X=19.7mΩ	#1/0 Al Triplex	2/0 Cu	#2 Al	4/0 Al
Length of Conductor	75 ft.	-	-	100 ft.	30 ft.	80 ft.	100 ft.
No. of Customers	4	20	15	8	1	15	16
***Type of Loading**	R	R	R	R	C	R	R
Maximum Demand	91 %	156%	150%	78%	42%	143%	146%
Background Voltage THD	1.5%	3.4%	3.4%	1.5%	1.5%	1.5 %	1.5%
EV Charger THD %	14.3%	14.3%	14.3%	55.0%	14.3%	14.3%	14.3%
Single/Three Phase	Single	Single	Single	Single	Three	Single	Single

*** Type of Loading – R – Residential, C - Commercial**

Table M. Typical Case Utility Simulation Results

	Utility A	Utility. B		Utility C*	Utility D	Utility E	Utility F
		Under-ground	**Overhead**				
X1 Line Current	137.0 A 6.0 %THD	319.4 A 10.1 %THD	257.7 A 9.2 %THD	281.9 A 17.4 %THD	450.2 A 46.1%THD	421.4 A 5.9 %THD	448.2 A 8.4 %THD
X3 Line Current	134.9 A 5.3 %THD	305.1 A 11.6 %THD	248.7 A 10.5 %THD	307.4 A 13.8 %THD	526.8 A 54.2 %THD	396.8 A 9.4 %THD	466.6 A 8.7 %THD
Secondary Line Voltage	237.3 V 1.6 %THD	243.9 V 3.7 %THD	239.3 V 3.7 %THD	237.6 V 2.1 %THD	206.9 V 2.7 %THD	233.9 V 1.9 %THD	238.5 V 2.1 %THD
Line Losses	115.5 W	277.4 W	228.9 W	902.4 W	1.7 kW	613.2 W	1.9 kW
Transformer Losses	319.3 W	1.4 kW	1.2 kW	262.0 W	1.1 kW	1.1 kW	1.7 kW
Harmonic Loss Factor	1.1	1.4	1.3	1.5	4.2	1.2	1.2
Transformer De-rating	1.0	0.99	0.99	0.98	0.90	0.99	0.99
Incr. Voltage THD Due to Chargers	0.1%	-0.3%	-0.2%	0.3%	0.0%	0.0%	0.3%

* **Utility C was a three-phase system. X1 and X3 in this case refer to Phase A and Phase C.**

Table N. Typical Case Simulation parameters

	Value
Distribution Service Transformer	50 kVA
	%R=0.9,%X=1.1
Conductor Used	350 Al Triplex
Length of conductor	75 ft.
No. of customers	4

Table O. Appliances Used In Simulation

	Appliance	Load (kW)
House #1	Refrigerator	0.6
	Air Conditioner	3.5
	Lights	0.3
	Microwave	1.3
	Computer	0.1
	Hair Dryer	1.1
	EV Charger (Honda)	5.1
	Total Load	**12.0 kW**
House #2	Refrigerator	0.6
	Air conditioner	3.5
	Lights	0.3
	VCR	0.1
	Television	0.1
	EV Charger (Honda)	5.1
	Total Load	**9.7 kW**
House #3	Refrigerator	0.6
	Air Conditioner	3.5
	Lights	0.3
	Washing Machine	0.4
	Dryer	4.8
	Coffee Maker	1.0
	Total Load	**10.4 kW**
House #4	Air Conditioner	3.5
	Lights	0.3
	Stereo	0.1
	CD Player	0.1
	Toaster	0.8
	Microwave	1.3
	Refrigerator	0.6
	Total Load	**6.7 kW**
	Total Load	**38.3 kW**

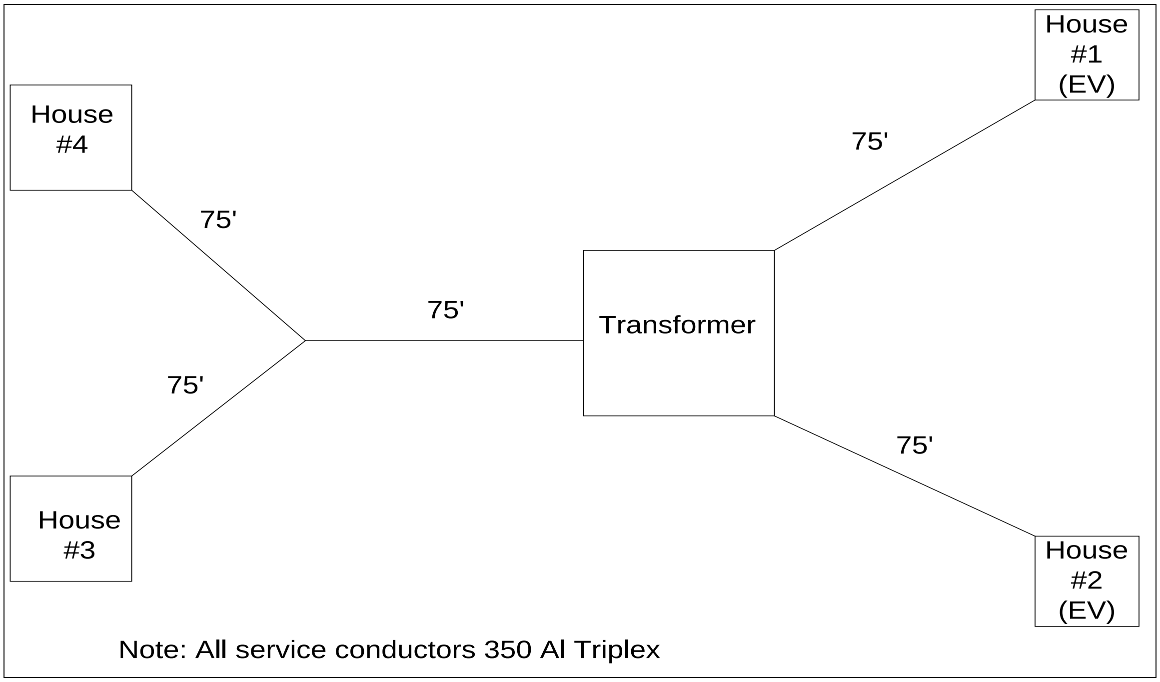


Fig. 6. Field Configuration for Typical Case Simulation

Table P. Typical Case Simulation Results

	X1 Line Current		X3 Line Current		Sec. Line Volt.(V)	Sec. Line Voltage THD(%)
	Sim. (A)	THD (%)	Sim. (A)	THD (%)		
Without Charger	113.8	9.0	111.6	6.8	238.2	1.5
With Charger	153.8	6.4	151.6	5.7	237.7	1.5

Table Q. Line and Transformer Losses (Typical Case)

	Line Losses (W)	Transformer Winding Losses (W)	Harmonic Loss Factor	Transformer De-rating
Without Charger	95.6	167.8	1.1	1.0
With Charger	125.3	337.1	1.1	1.0

In the typical case simulations the introduction of EV chargers did not result in a significant increase in THD for any of the six utilities. This clearly indicates that the introduction of chargers in a typical environment would not lead to a significant increase in THD.

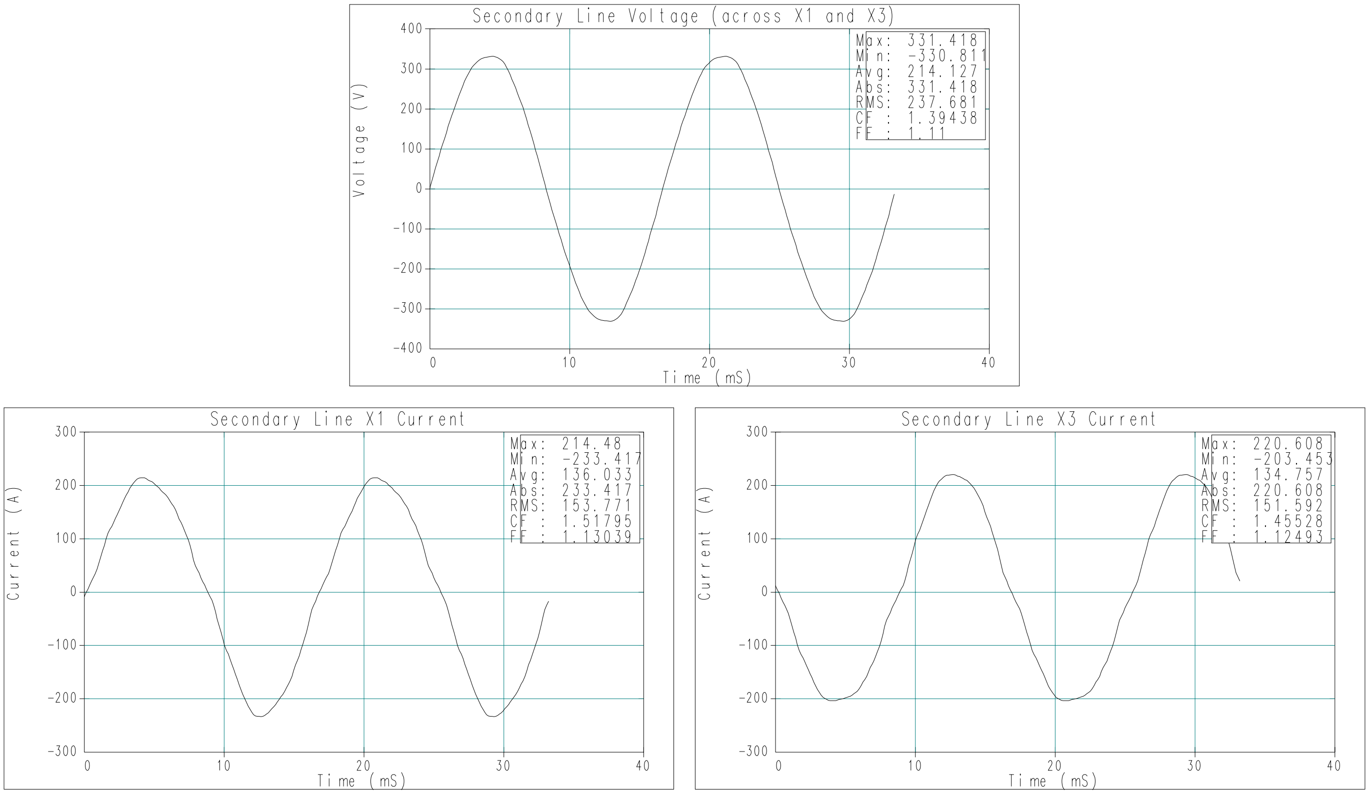


Fig 7. Typical Case Simulation Results

Conclusion

Simulation case studies of the utility service configurations were accomplished. A statistically significant evaluation of worst case service configurations has been performed. It is impossible to evaluate all possible combinations of appliances for predicting the exact worst case performance of the system. The simulation case studies performed are not intended to be complete in all respects but rather serve as valid indicators about the performance of the system under normal and stressed operating conditions. The transformer winding / line losses and transformer de-rating aspects due to the increase in harmonic currents have also been evaluated. It is noted that the de-rating of the transformer remains the same, while the line and transformer winding losses increase with the introduction of the EV chargers.

It can be seen from the simulation results that the EV chargers do not give rise to excessive voltage THD. Rather, as the penetration of EV chargers increases, loading issues will arise before excessive voltage distortion is noticed. This report completes Phase III of the project.

Fourth Interim Report

Secondary Distribution Impacts of Residential Electric Vehicle Charging

Home of the 1996 Olympic Village
Georgia Institute of Technology

FOURTH INTERIM REPORT
April 2000

Project Title: Secondary Distribution Impacts of Residential Electric Vehicle Charging

Investigators: Dr. Richard M. Bass, NEETRAC, ECE Professor (Principal Investigator)
Dr. Ron Harley, NEETRAC, ECE Professor (Co-Principal Investigator)
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Vinod Rajasekaran, NEETRAC, ECE Graduate Research Assistant
Jason Pierce, NEETRAC, ECE Graduate Research Assistant
John Kennedy, Georgia Power Company (Project Advisor)

Field Test Utilities: Pacific Gas and Electric Company
Sacramento Municipal Utility District
Southern California Edison

Abstract: This last of four interim reports documents the field site studies performed jointly by three participating utilities and NEETRAC. The measurements at the three field sites were carried out over a month and are archived in this report. Simulation of one of the test sites was performed to compare the actual field data with the simulation of the models earlier developed. The field data and the simulation results for the voltage THD match within 2.9%, thus validating the simulation process. The absolute worst case recorded voltage THD was 4.1%, which is below IEEE's 519 recommended 5% limit for voltage distortion. The field site data confirm the results reported in the Third Interim Report, that commercial EV chargers engineered to IWC guidelines do not generate excessive voltage THD on the secondary of the transformer. A summary of the worst case conditions in each of the three system configurations is also reported. Temperature variation on the transformer due to EV charging was also studied in one field site. This report documents the completion of the last phase of the planned project outline.

Memorial: This project was initiated and directed by Dick Bass until his tragic death in an auto accident on April 14th, 1999. Bass received his B.E.E. and M.S.E.E. in 1982 and 1983, respectively, from Georgia Tech and earned his Ph.D. from the University of Illinois at Urbana-Champaign in 1990. In 1990, Bass returned to Tech as an assistant professor in electric power and was promoted to associate professor in 1997. During the 1996 Olympics, he and his students and colleagues studied the technologies and electrical distribution impacts of the Olympic Village electric vehicle (EV) transportation system. He was an active participant in the Distribution, Load Management, and Power Quality Committee of the IWC and is sorely missed.

Secondary Distribution Impacts of Residential EV Charging

Fourth Interim Report

Abstract

This last of four interim reports documents the field site studies performed jointly by three participating utilities and NEETRAC. The measurements at the three field sites were carried out over a month and are archived in this report. Simulation of one of the test sites was performed to compare the actual field data with the simulation of the models earlier developed. The field data and the simulation results for the voltage THD match within 2.9%, thus validating the simulation process. The absolute worst case recorded voltage THD was 4.1%, which is below IEEE's 519 recommended 5% limit for voltage distortion. The field site data confirm the results reported in the Third Interim Report, that commercial EV chargers engineered to IWC guidelines do not generate excessive voltage THD on the secondary of the transformer. A summary of the worst case conditions in each of the three system configurations is also reported. Temperature variation on the transformer due to EV charging was also studied in one field site. This report documents the completion of the last phase of the planned project outline.

IWC Guidelines

The National Electric Vehicle Infrastructure Working Council (IWC) Record of Consensus (ROC) (Ref: Electric Power Research Institute's EPRI BR-107842, www.epri.com) serves to document agreements developed through the IWC between automobile manufacturers and the utility industry on electric vehicle infrastructure. Some of the primary guidelines of the IWC pertinent to this analysis are:

- The minimum total power factor for EV charging is recommended to be 95% as measured at full-rated power.
- The maximum value for total current harmonic distortion for EV charging is recommended to be ≤ 20% at full rated power as measured into a resistive load.
- The maximum value for current distortion at each harmonic frequency for Level 2 charging is recommended to be as specified in International Electrotechnical Committee (IEC) 1000-3-4. (Ref: IEC/TS 61000-3-4 Electromagnetic compatibility (EMC) - Part 3-4: Limits-Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A).

Field Site Summary

Field test sites were established by three of the participating utilities on their system. A distribution feeder, which is a likely candidate for EV penetration, was identified by each of the three utilities. Reliable Power Meters' (RPM) Power Recorder system was placed to monitor the distribution transformer secondary. The RPM monitors were chosen for data capture because all of the participating utilities had the model, which precluded the necessity of purchasing new monitors. Additional monitoring equipment was also placed at individual houses, splice boxes connecting the individual feeders to the houses, and at the chargers. Data collected from the three sites over a month have been archived and presented in Appendices D.1-D.3.

The field sites can be broadly classified into two classes:

- Residential (Utilities B and E)
- Commercial (Utility C)

The references to Utilities B, C and E are made in the same basis as was done in the earlier phases of this project. A comparison of the field site configurations is provided below in Table A.

Table A. Comparison of Field Site Configurations

	Utility B	Utility E	Utility C
EV Charger Penetration (%)	67 %	8 %	N/A*
Distribution Service Transformer	50 kVA %Z=2.2 %R=1.5, %X=1.7	50 kVA %Z=1.8	150 kVA %Z =2.3
Secondary Conductor Used	350 Al	350 Al	350 Cu
Service Conductor Used	4/0 Al	#2 Al	2/0 Cu
Average Length of conductor	100 ft.	55 ft.	15 ft.
No. of customers	6	16	N/A*
Type of customer	Residential	Residential	Commercial

***** Utility C test site was a parking garage with commercial office space.

Benchmarking

The monitoring equipment was benchmarked with NEETRAC's RPM Power Recorder. Voltage and current waveforms were sampled with a 14 bit analog to digital converter at a rate providing 128 sampled points per cycle at 60 Hz. The RPM Power Recorder was configured in each case to average the sampled data and record the data every 5 minutes. The RPMs are calibrated to make voltage measurements with a precision of 1% of full scale.

The benchmarking was carried out over a 24-hour period and not over the entire testing period. The benchmarking dates for the utilities are provided in Table B along with the dates of the entire testing process. The absolute values of the current THD and voltage THD, at the time when maximum deviation between the benchmark data and field data was observed, are shown in Table B. The percentage difference between the data as recorded by NEETRAC's RPM and the corresponding utility's RPM is also shown in Table B.

Table B. Benchmarking

	Utility B		**Utility E**		**Utility C**	
Field site test dates	08/24/99-09/20/99		08/12/99-09/13/99		10/19/99-11/01/99	
Benchmarking dates	09/14/99-09/15/99		08/18/99-08/19/99		10/19/99-10/20/99	
	Utility B RPM	NEETRAC RPM	Utility E RPM	NEETRAC RPM	Utility C RPM	NEETRAC RPM
Current THD (%)	18.2	17.6	10.6	10.3	14.0	14.7
Voltage THD (%)	2.14	2.20	1.03	0.98	1.87	1.96
% diff. in voltage THD of benchmarking data	-2.7		+4.9		-4.5	

Residential Field Sites

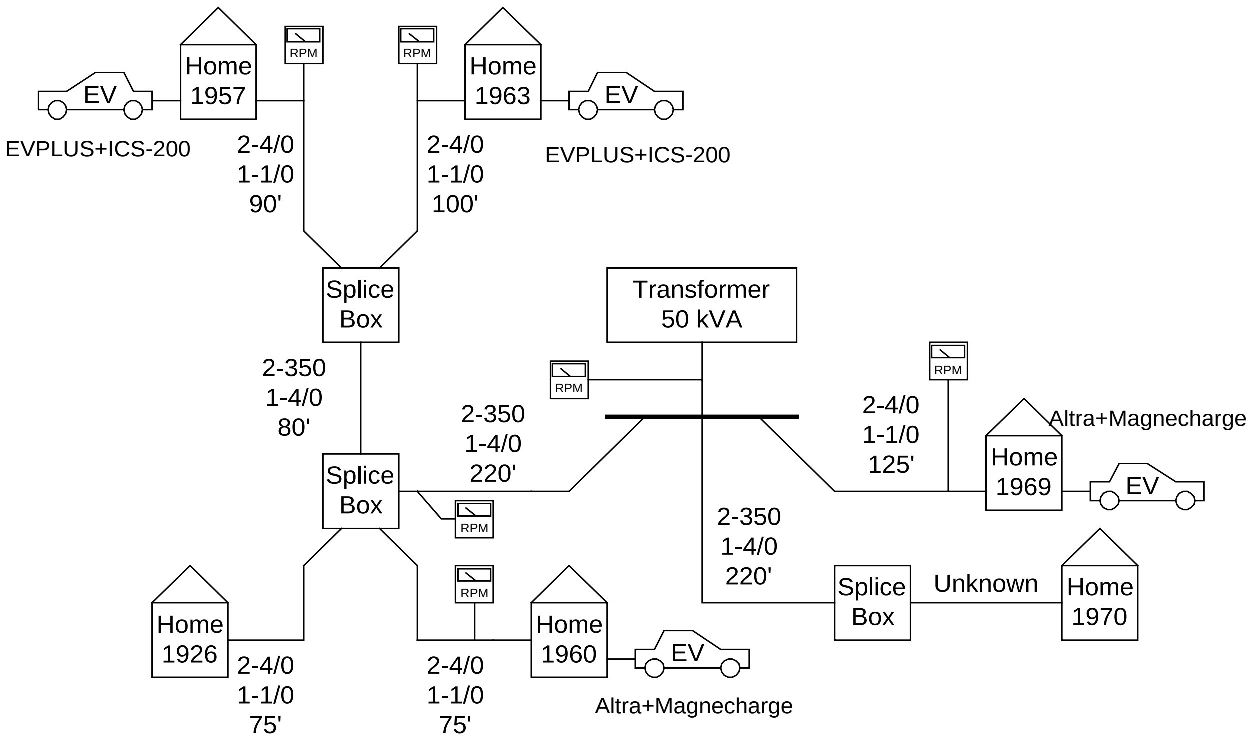
Utility B

The field site configuration of the system is shown in Figure 1. The field site consisted of six customers with four EVs among them. The field test site was chosen based on the proximity of the neighborhood to early EV adopters, the willingness of a utility employee and her neighbors to participate in the project, and the ability of the distribution system and the homes to physically and electrically handle EVs and chargers. The EVs used in the field site were Honda EVPLUSs and Nissan Altras. The chargers used in the testing process were the EVI ICS-200 for the EVPLUSs and Magnecharge models for the Altras.

Data were recorded by RPMs from 8/24/1999 to 9/20/1999. The various parameters of the field site configuration are shown in Table C. Monitoring equipment was placed at the houses with the EVs, a splice box and at the transformer secondary (see Figure 1). The chargers except at Home #1957 were programmed to start charging at midnight to ensure overloading of the transformer did not occur. Utility B used time clocks set to allow charging at midnight because it has a mandatory rate schedule for electric vehicle chargers that is based on time of use charges. Utility B has found that most EV customers use timers to initiate charging at midnight to minimize their EV charging costs. Since the RPMs were located at the service to the house, the EVs cannot be distinguished from the other loads in the home. Hence an analysis of the non-linear characteristics of the EV cannot be performed. The data recorded over a typical 24-hour cycle when three chargers came on at midnight are shown in Figure 2.

Table C. Field Site System Parameters

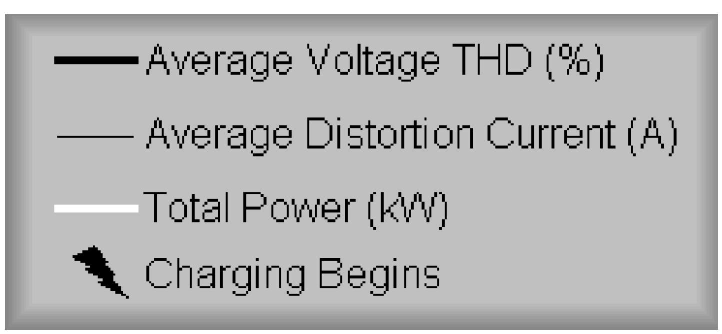
Parameter	Value
EV Charger Penetration %	67 %
Distribution Service Transformer	50 kVA %Z=2.2 %R=1.5, %X=1.7
Secondary Conductor Used	350 Al
Service Conductor Used	4/0 Al
Average Length of conductor	100 ft.
No. of customers	6
Type of customer	Residential



Note:
All conductors are aluminum.

Figure 1. Utility B Test Site

Figure 2. Utility B Test Site Data over a 24-hour cycle



Legend for distortion related graphs
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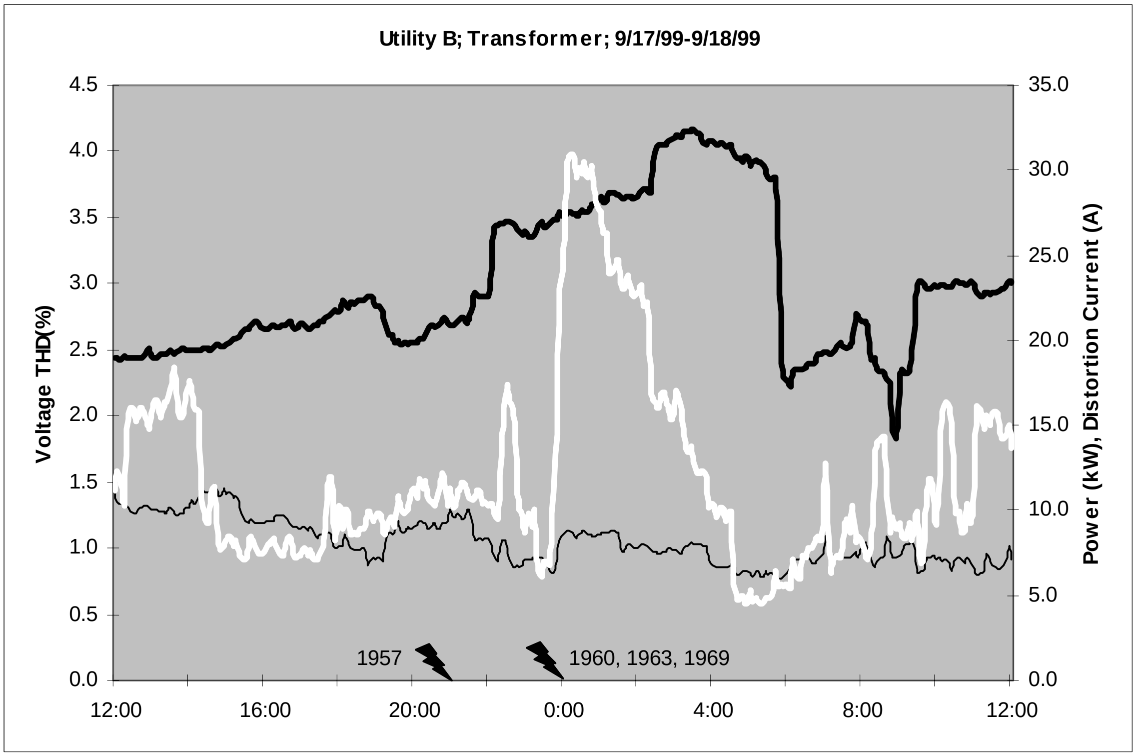
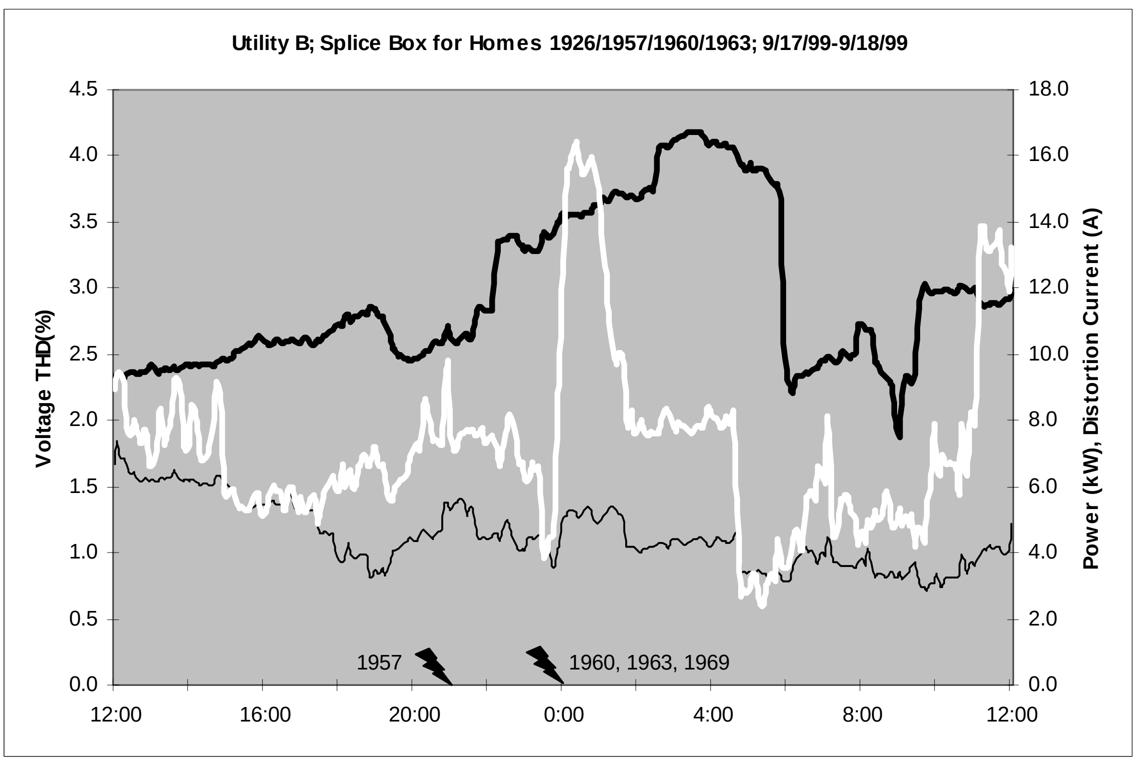
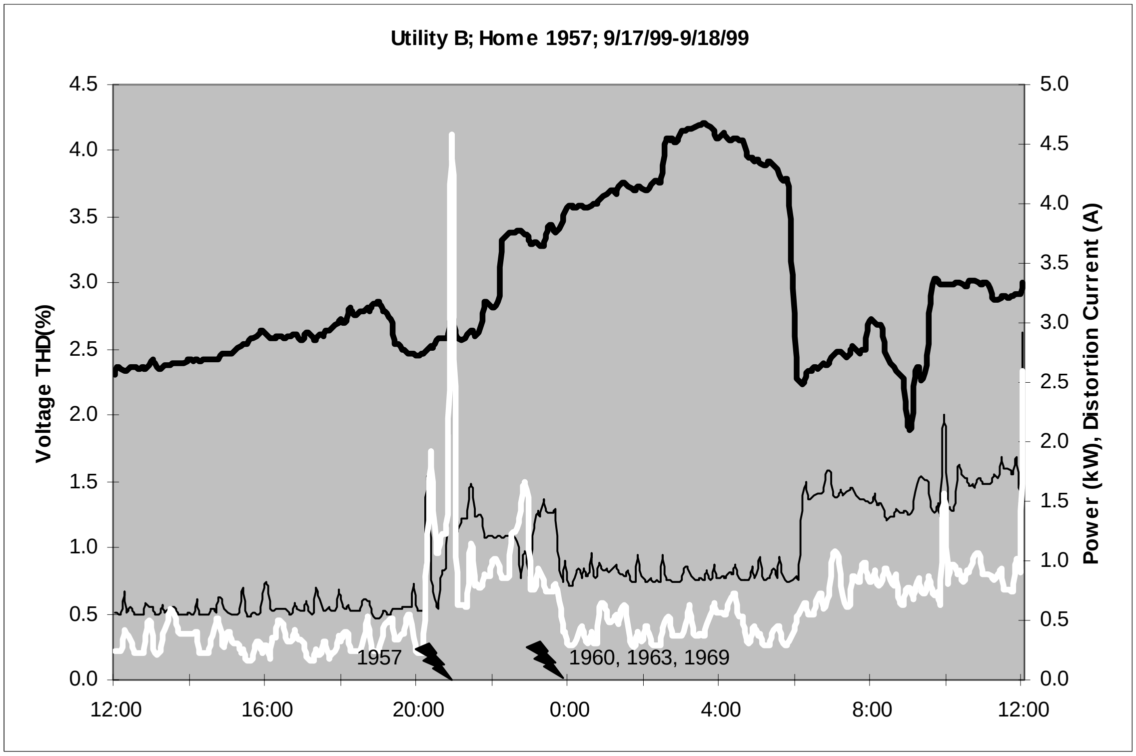
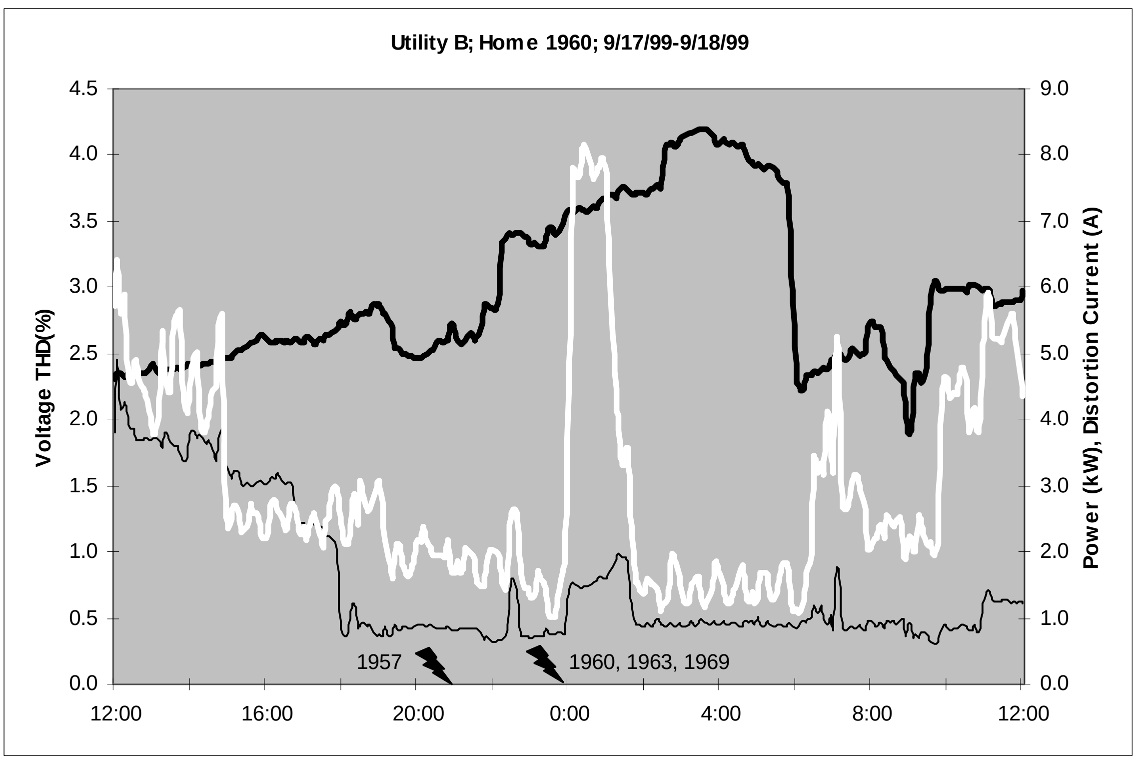

Utility B; Transformer; 9/17/99-9/18/99
Voltage THD(%)
Power (kW), Distortion Current (A)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1957
1960, 1963, 1969
12:00
16:00
20:00
0:00
4:00
8:00
12:00


Utility B; Splice Box for Homes 1926/1957/1960/1963; 9/17/99-9/18/99
Voltage THD(%)
Power (kW), Distortion Current (A)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1957
1960, 1963, 1969
12:00
16:00
20:00
0:00
4:00
8:00
12:00


Utility B; Home 1957; 9/17/99-9/18/99
Voltage THD(%)
Power (kW), Distortion Current (A)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1957
1960, 1963, 1969
12:00
16:00
20:00
0:00
4:00
8:00
12:00


Utility B; Home 1960; 9/17/99-9/18/99
Voltage THD(%)
Power (kW), Distortion Current (A)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1957
1960, 1963, 1969
12:00
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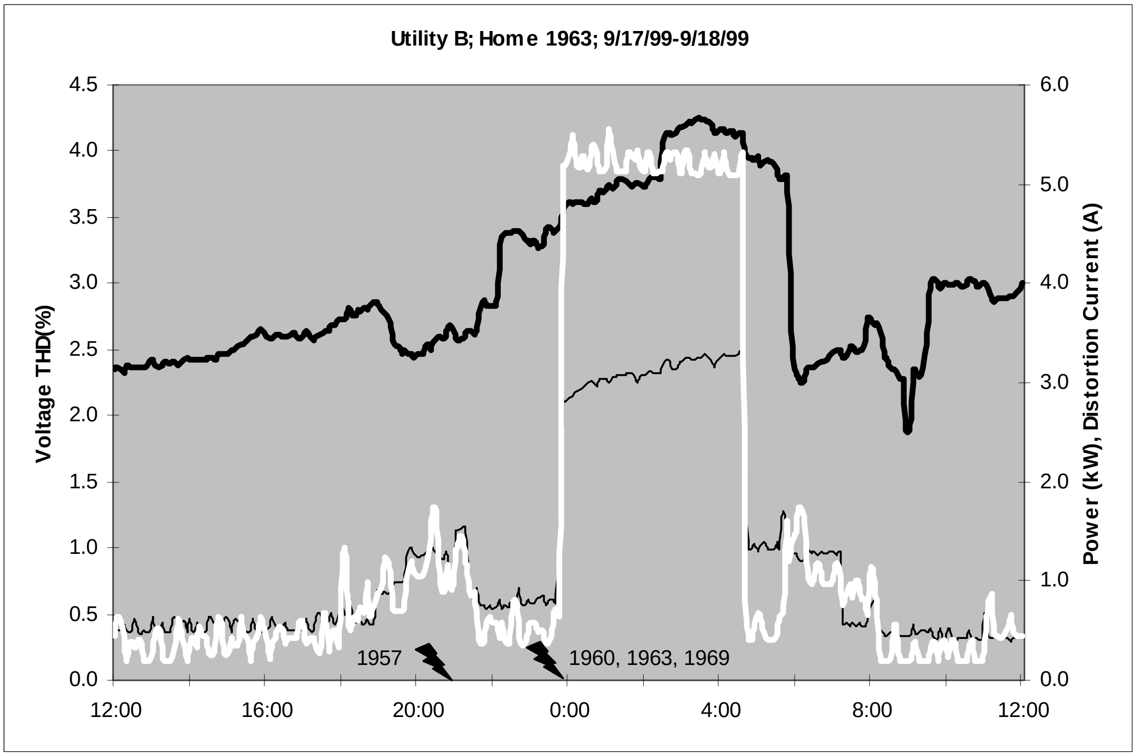
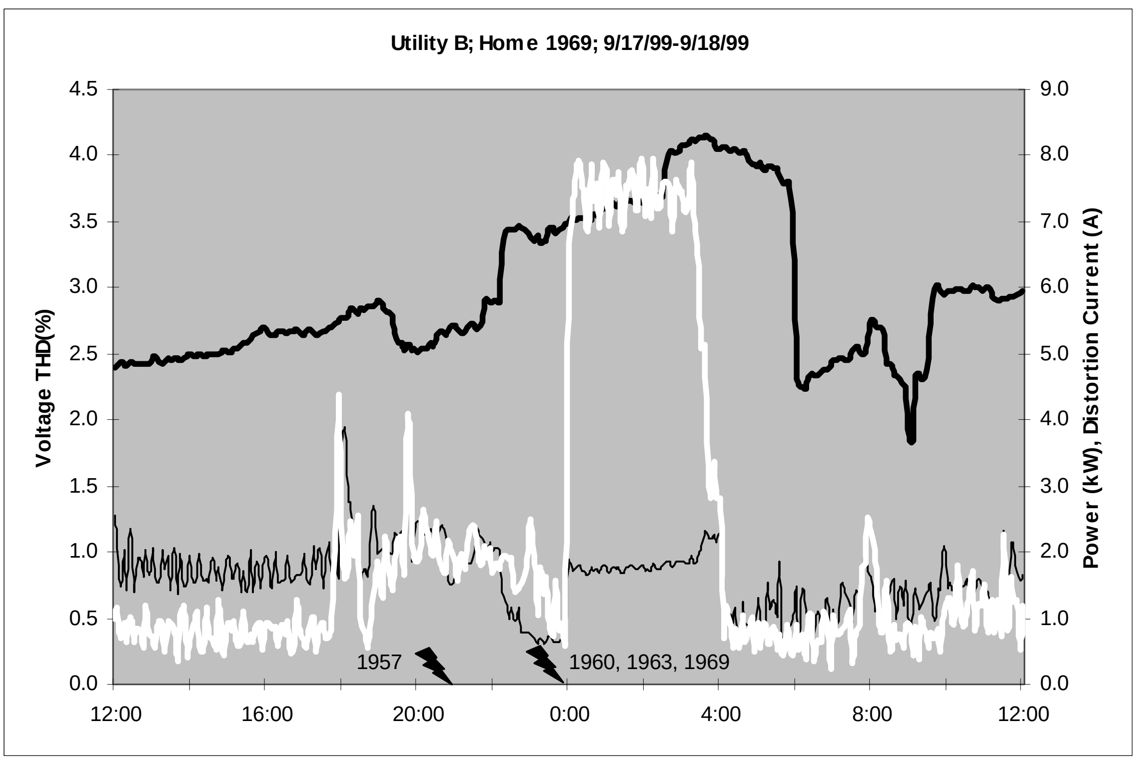
4:00
8:00
12:00





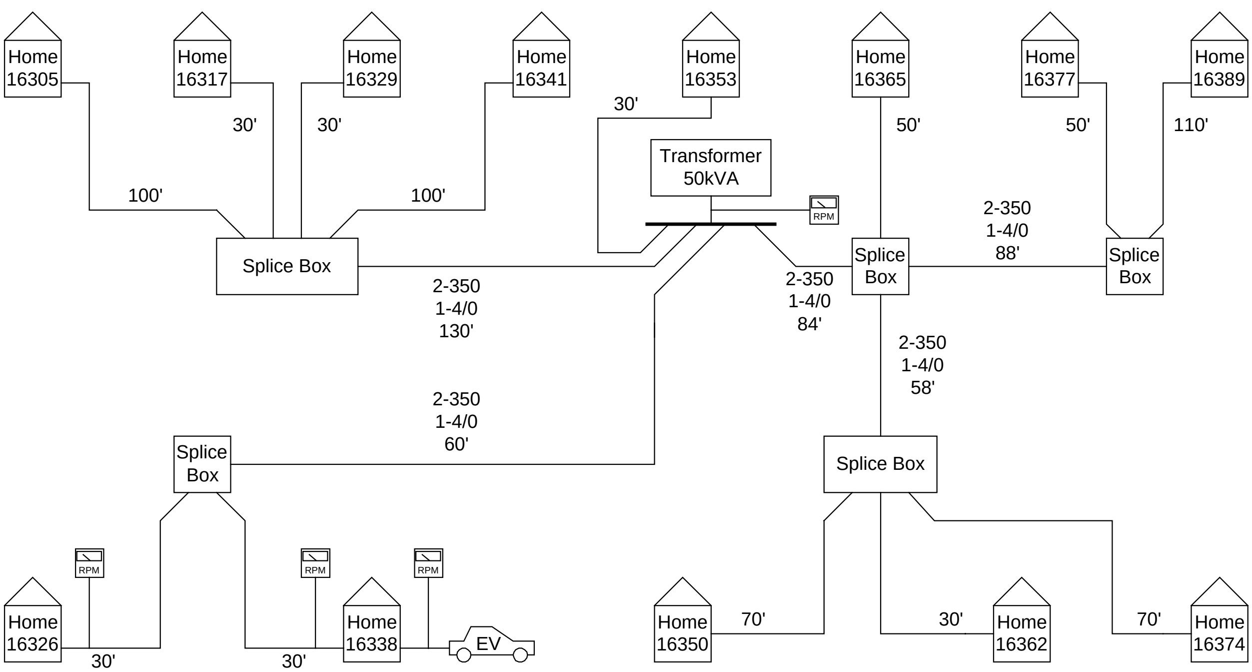
It can be seen from the graphs that the increase in voltage THD due to EV charging is less than 0.8% (see Appendix D.1, pg. 24). Rather, the system shows an increase in voltage THD, regardless of the operation of the charger during nighttime (see Appendix D.1, pg. 4). This is a system phenomenon, which is most likely caused by other non-linear loads on the feeder or an adjacent feeder connected to the same distribution substation transformer.

- **Utility E**

The field site configuration of the system is shown in Figure 3. The field site consisted of thirteen customers with one EV (Ford Ranger) among them. The EVI-ICS-200 charger was used for charging the EV. The various parameters of the field site configuration are shown in Table D. Monitoring equipment was placed at the house with the EV, a neighboring house, at the charger itself and at the transformer secondary (see Figure 3). Data were recorded by RPMs from 8/12/1999 to 9/13/1999. The data recorded over a typical 24-hour cycle are shown in Figure 4.

Table D. Field Site System Parameters

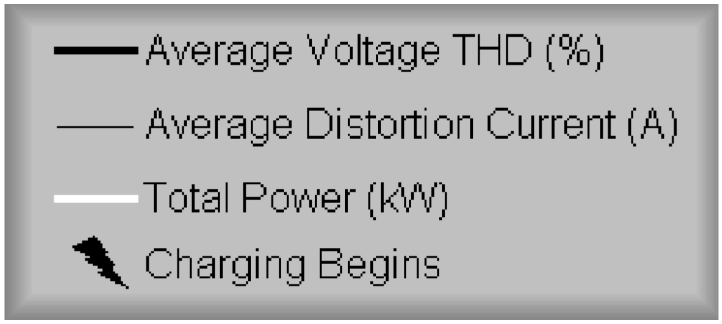
Parameter	Value
EV Charger Penetration %	8 %
Distribution Service Transformer	50 kVA %Z=1.8
Secondary Conductor Used	350 Al
Service Conductor Used	#2 Al
Average Length of conductor	55 ft.
No. of customers	16
Type of customer	Residential



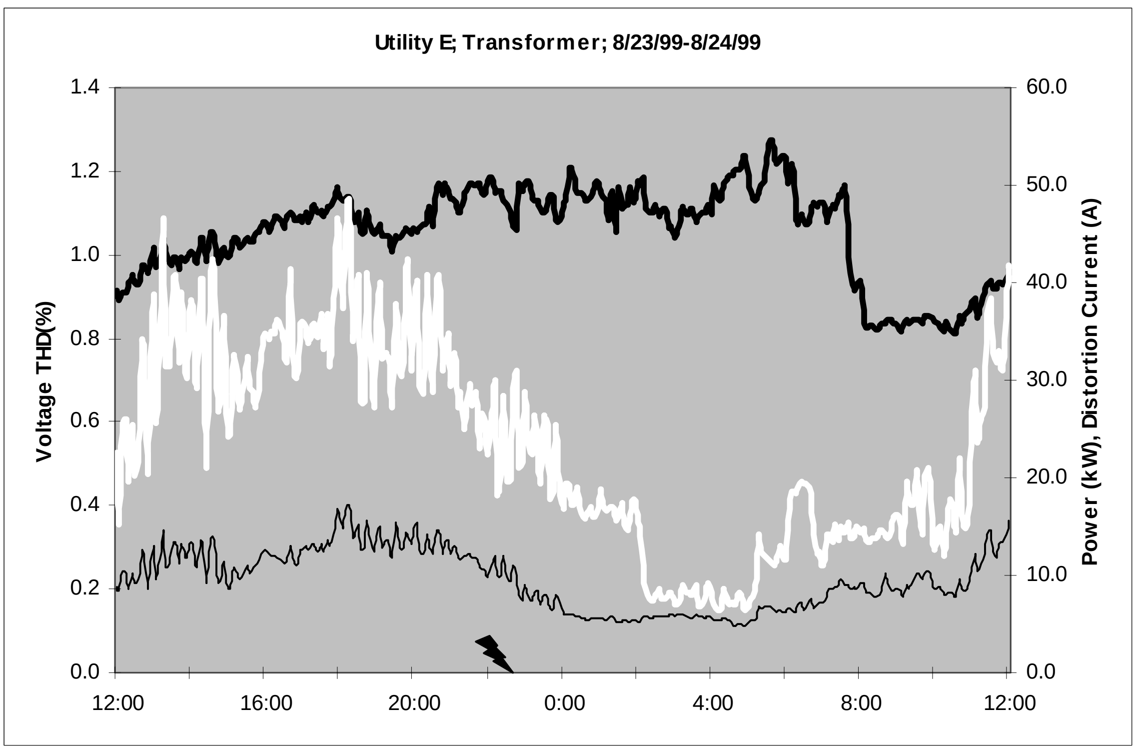
Notes:
All conductors are aluminum.
All service conductors are #2 Al.

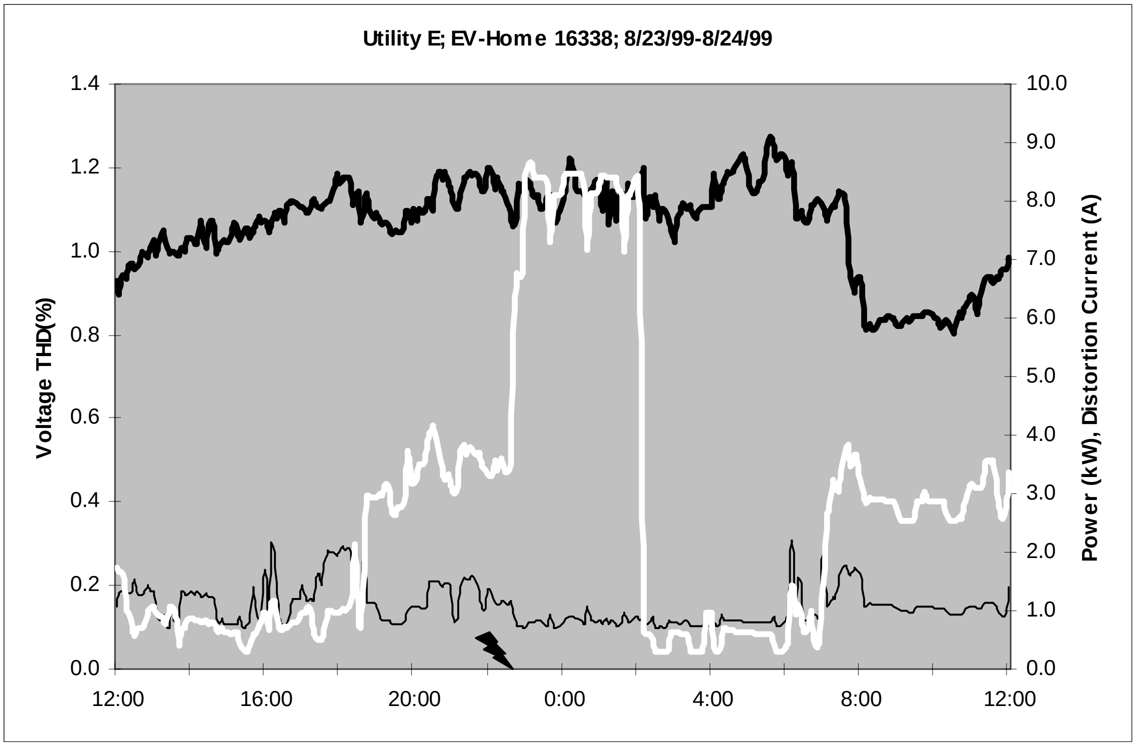
Figure 3. Utility E Test Site

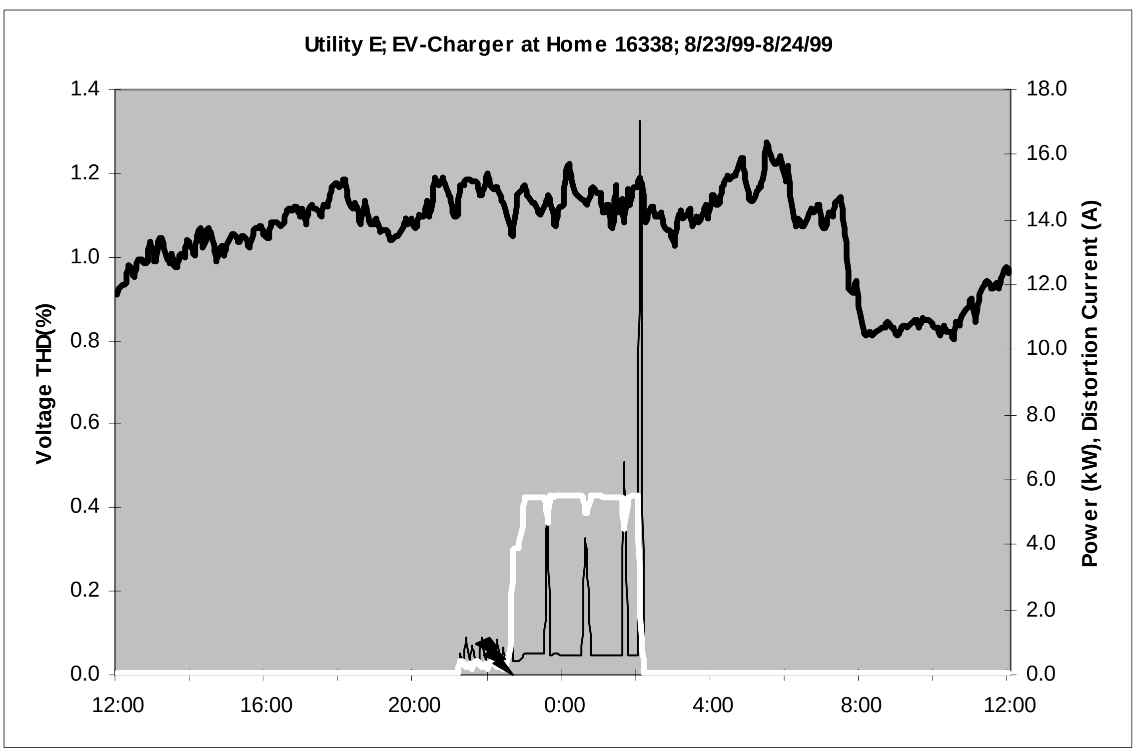
Figure 4. Utility E Test Site Data Over A 24-Hour Cycle

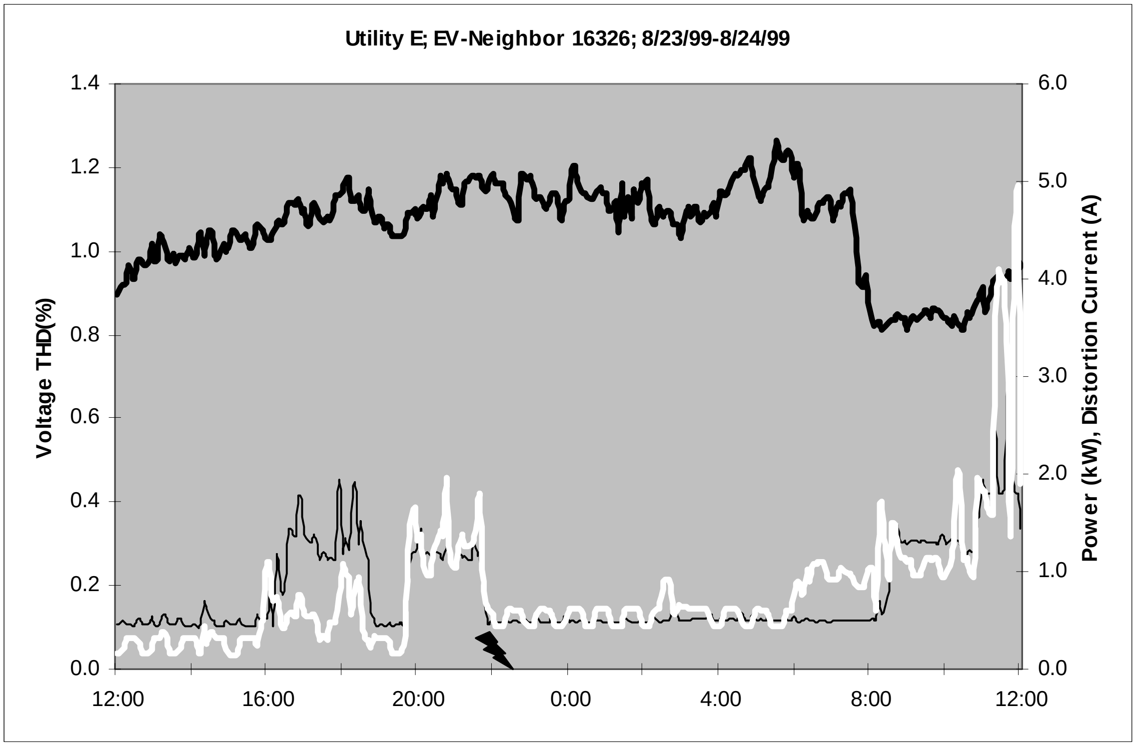


Legend For Distortion Related Graphs
(Graph Scales are different for clarity)




Utility E; EV-Home 16338; 8/23/99-8/24/99
Voltage THD(%)
Power (kW), Distortion Current (A)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
12:00
16:00
20:00
0:00
4:00
8:00
12:00


Utility E; EV-Charger at Home 16338; 8/23/99-8/24/99
Voltage THD(%)
Power (kW), Distortion Current (A)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12:00
16:00
20:00
0:00
4:00
8:00
12:00



As can be seen from the typical graphs, there was no noticeable effect on the voltage distortion due to EV charging. Rather, the voltage THD seems to be a system effect as in Utility B's case.

Commercial Sites

- **Utility C**

Utility C chose a commercial parking deck used for EV fleet charging for its test site. The field site is a parking garage with a street level office complex. The same distribution transformer and service entrance serve the office complex and the EV charging station. The field site configuration is shown in Figure 5. Five EVs (Chrysler Epic, Honda EVPlus, Ford Ranger, General Motors EV1 and Chevrolet S-10) were used for the field tests. The Magnecharge charger was used for charging the EV1 and S-10 while the EVI ICS-200 was used to charge the Ranger and EVPlus. The Lockheed-Martin charger (three phase, 208 volts) was used for the Epic.

Monitoring equipment was placed at the EV charging sub-panel, office sub-panel and the main service entrance. Data were recorded by RPMs from 10/19/1999 to 11/1/1999. Data recorded over a typical 24-hour cycle are shown in Figure 6. Multiple EV charging took place in this site. A maximum of four EV chargers were charged at once at this site based on an EV charging demand of 25kW (see Appendix D.3, pg. 6). Qualitative assessments of whether any combinations of EVs led to worse conditions could not be made because the monitoring equipment was placed at the EV charging sub-panel and not at individual EVs. The symbols on the charts shown in Figure 6 and in Appendix D.3 indicate only the start of charging for the day.

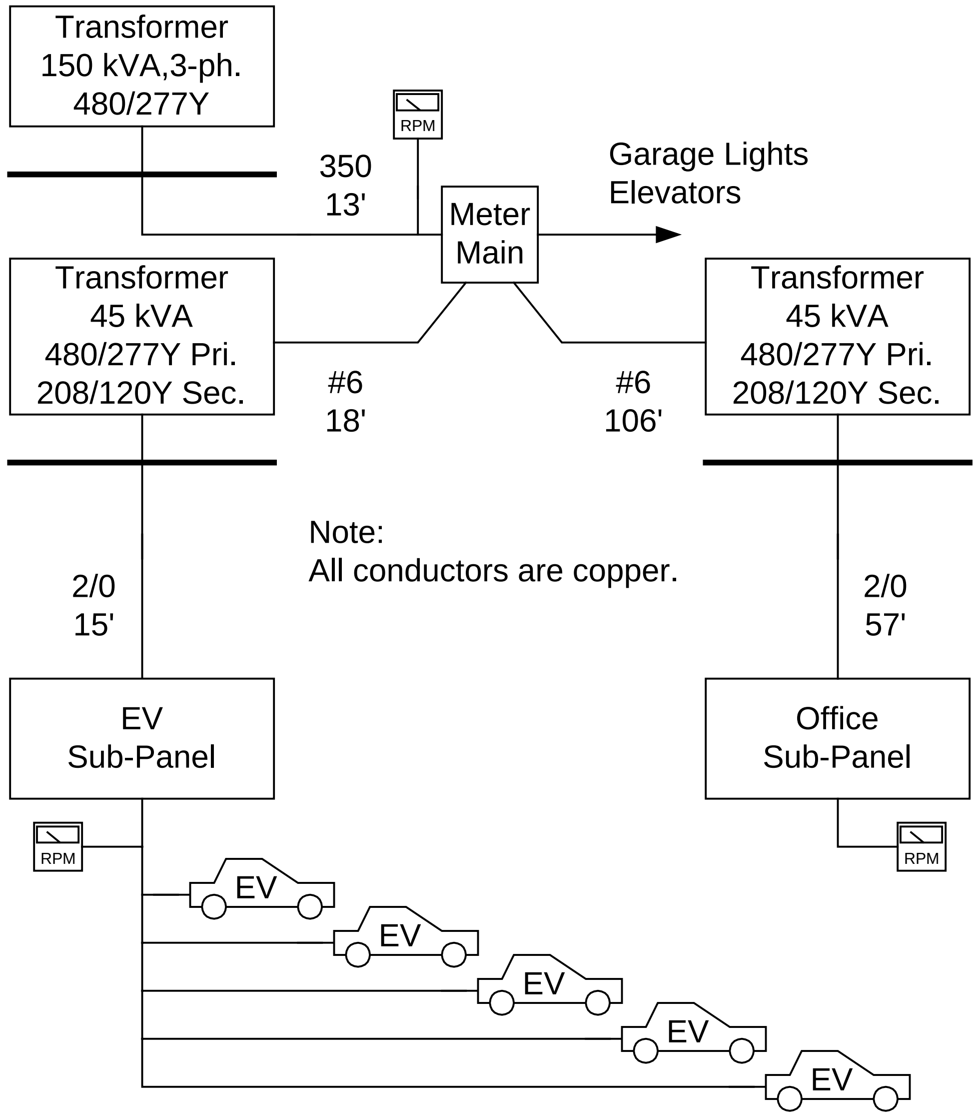


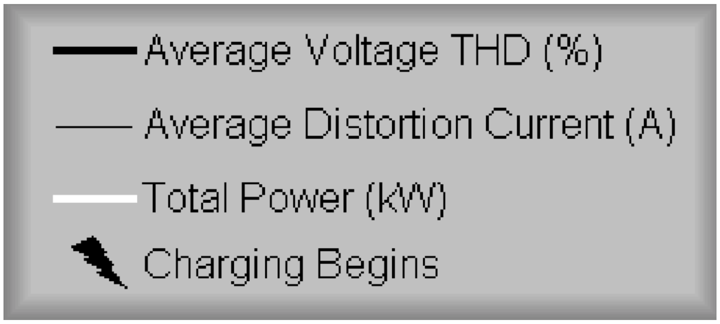
Figure 5. Utility C Test Site

Table E. Field Site System Parameters

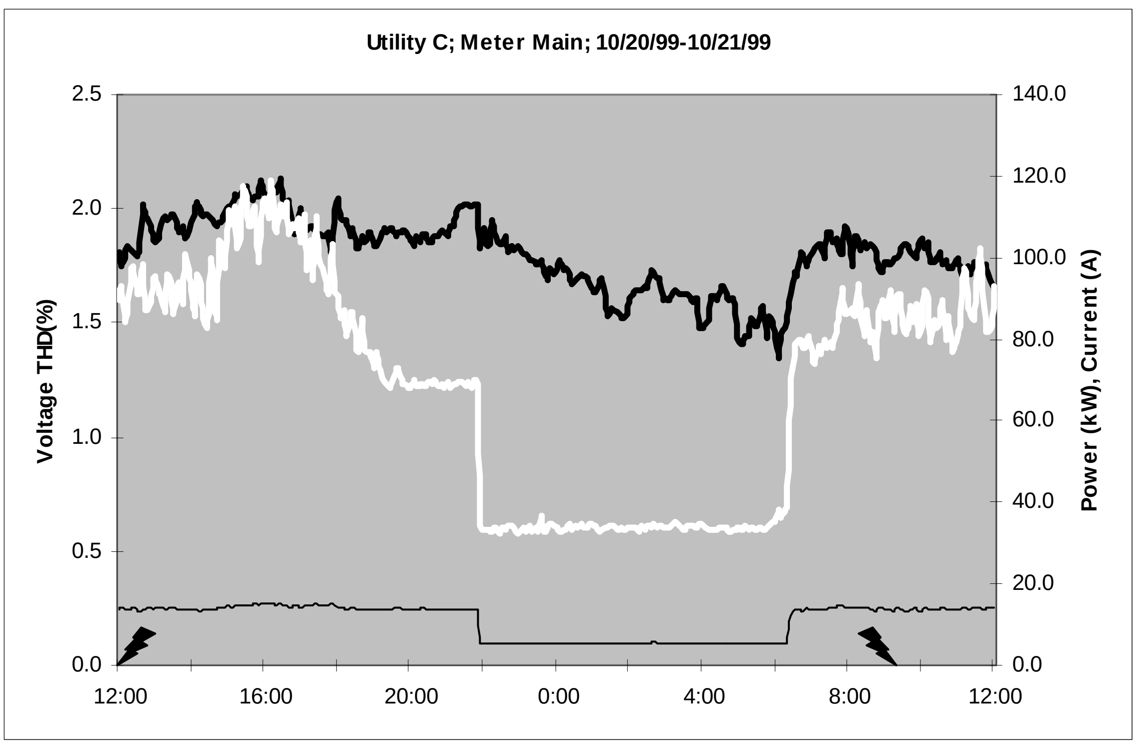
Parameter	Value
EV Charger Penetration %	N/A*
Distribution Service Transformer	150 kVA %Z =2.3
Secondary Conductor Used	350 Cu
Service Conductor Used	2/0 Cu
Average Length of conductor	15 ft.
No. of customers	N/A*
Type of customer	Commercial

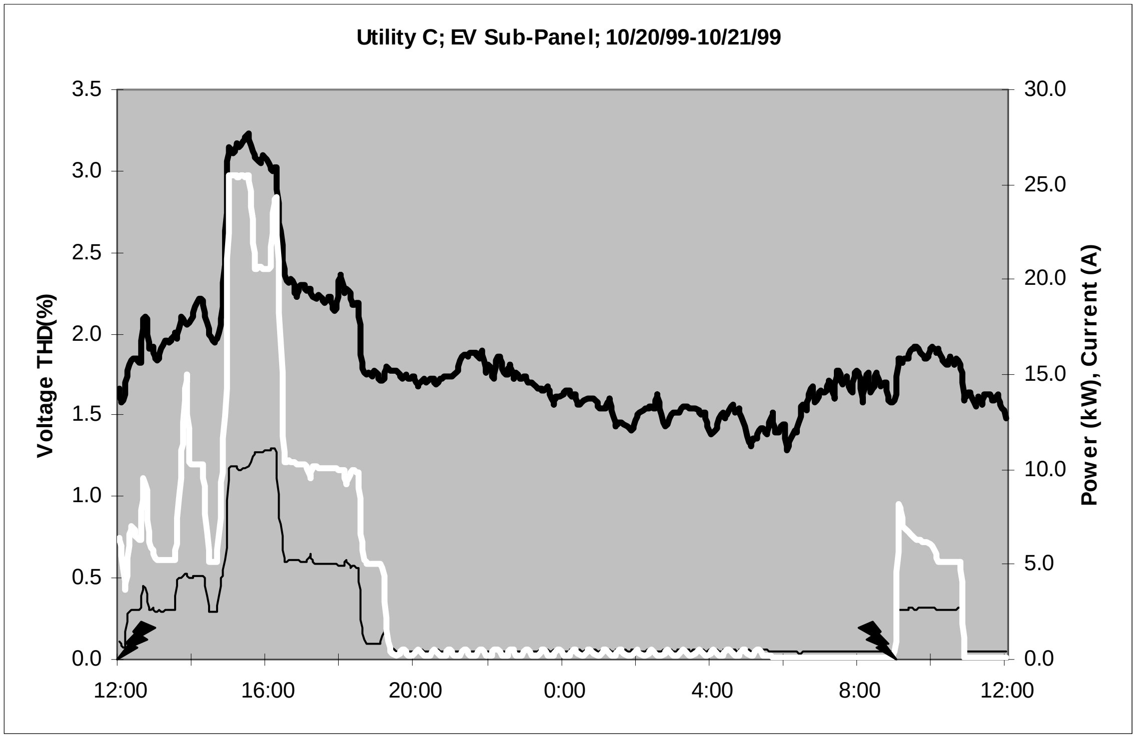
- Utility C test site was a parking garage with commercial office space.

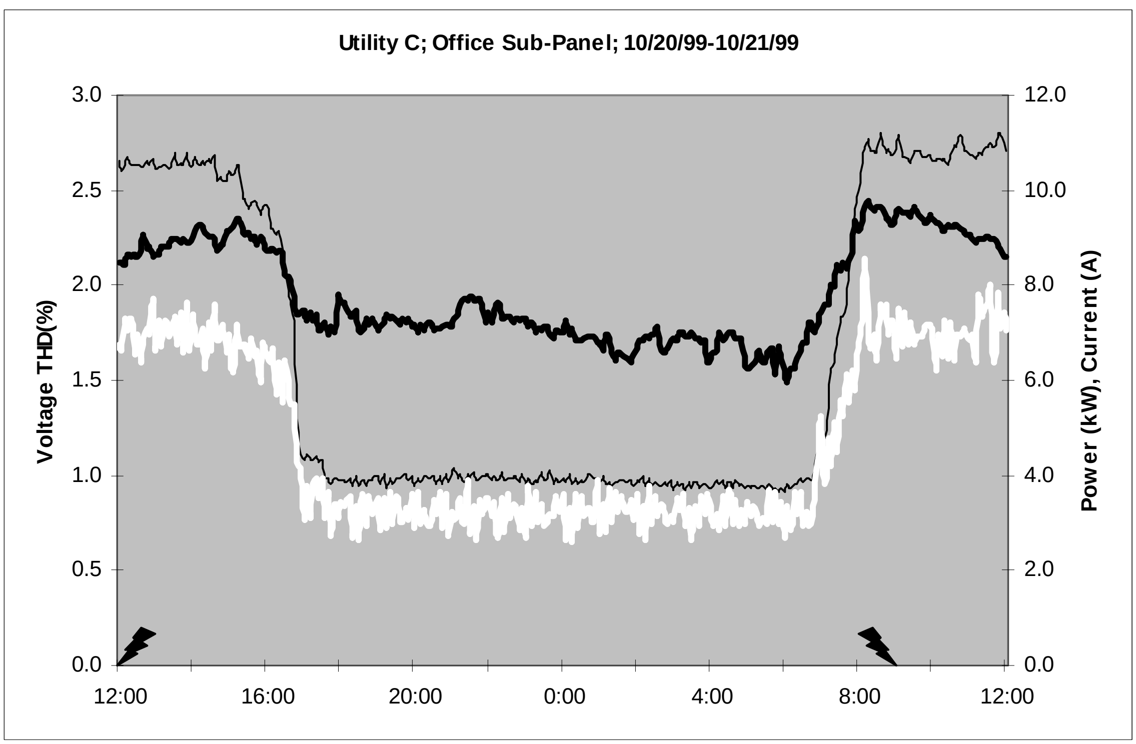
Figure 6. Utility C Test Site Data Over A 24-Hour Cycle



Legend For Distortion Related Graphs
(Graph Scales are different for clarity)




Utility C; EV Sub-Panel; 10/20/99-10/21/99
Voltage THD(%)
Power (kW), Current (A)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
12:00
16:00
20:00
0:00
4:00
8:00
12:00


Utility C; Office Sub-Panel; 10/20/99-10/21/99
Voltage THD(%)
Power (kW), Current (A)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12:00
16:00
20:00
0:00
4:00
8:00
12:00

The effect of EV charging on voltage distortion at the transformer secondary is insignificant as is evident from the graphs. Though there is a rise in voltage distortion of 1.4% at the EV sub-panel, the main entrance does not show significant rise (less than 0.1%) in voltage THD. This could be attributed to the impedance of the wye-wye connected step down transformer and some phase cancellation of the harmonics.

It can also be seen that the voltage distortion at the office sub-panel and the EV sub-panel follows the pattern of the corresponding loads. A plot of the voltage distortion at the transformer secondary, office sub-panel, and EV sub-panel is shown in Figure 7 to illustrate the independence of the voltage distortion at the transformer secondary.

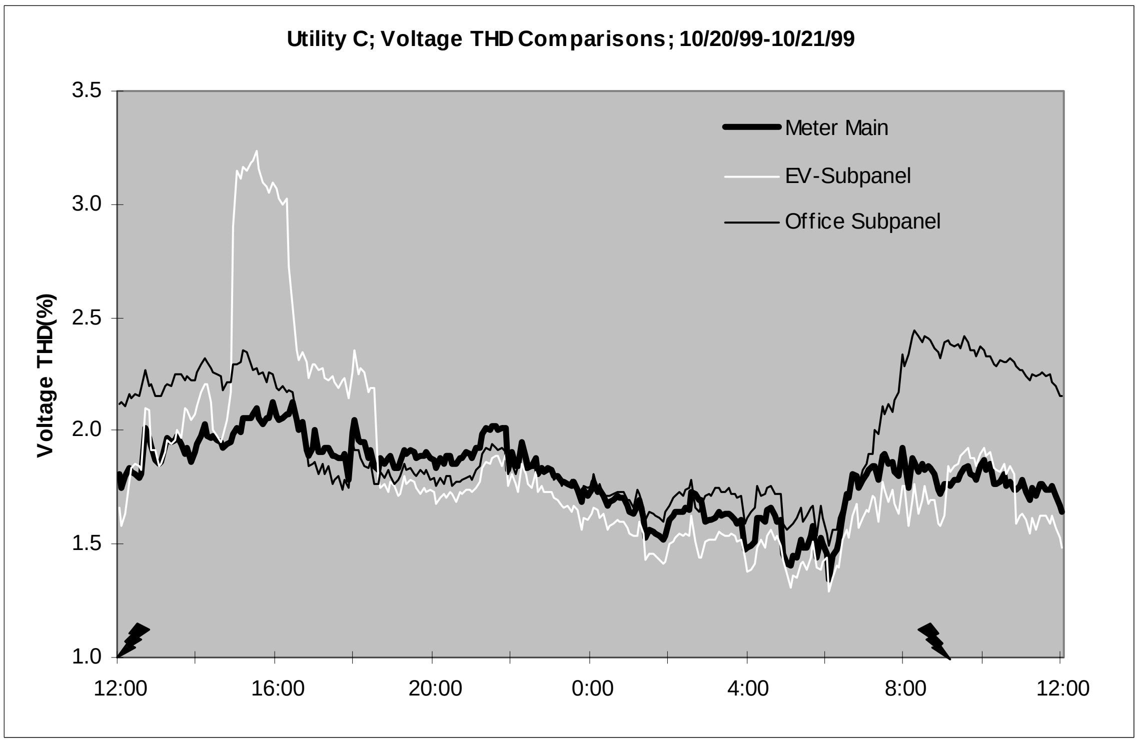


Figure 7. Voltage THD Comparison

Comparative Study

Utility B field test site was modeled and simulated following the methodology described in the earlier phases of the project. The appliances simulated were based on the field test appliances but do not exactly match them. Detailed results and simulation details are given in Appendix D.4. A comparison of the simulation results obtained and the field data is presented in Table F. It can be seen from Table F that the simulation results of the voltage THD closely match the field data to within 2.9%. This serves to validate the modeling and simulation process developed during the course of this project.

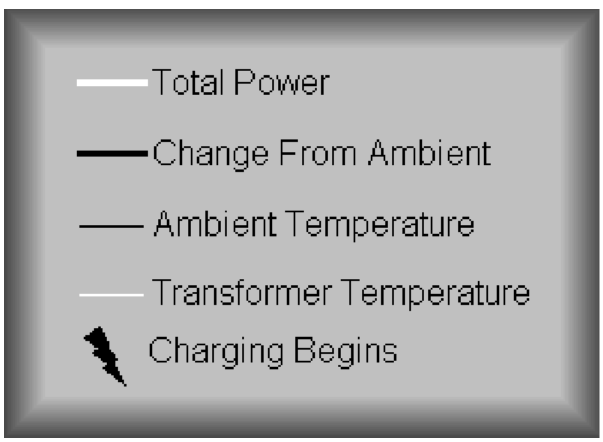
Table F. Comparison of Simulation Results and Field Data

	Before Charging			During Charging		
	Simulation	**Field Data**	**% Diff.**	**Simulation**	**Field Data**	**% Diff.**
X1 Line Current	26.2 A 21.1% THD	24.4 A 23.4% THD	7.4 -9.8	117.9 A 7.6% THD	123.8A 7.2% THD	-4.8 5.6
X3 Line Current	30.8 A 30.8% THD	31.3 A 24.1% THD	-1.6 27.8	122.7 A 7.3% THD	127.3 A 7.1 % THD	-3.6 2.8
Secondary Voltage	119.8 V 3.5% THD	123.8 V 3.4% THD	-3.2 2.9	118.9 V 3.6% THD	123.1 V 3.5% THD	-3.4 2.9
Line Losses	8.3 W	10.1 W	-17.8	16.6 W	18.2 W	-8.8
Transformer Losses	140.4 W	146.2 W	-4.0	252.1 W	288.2 W	-12.5
K Factor	1.5	1.6	-6.3	1.1	1.1	0.0
Transformer De-rating	0.98	0.98	0.0	1.0	1.0	0.0

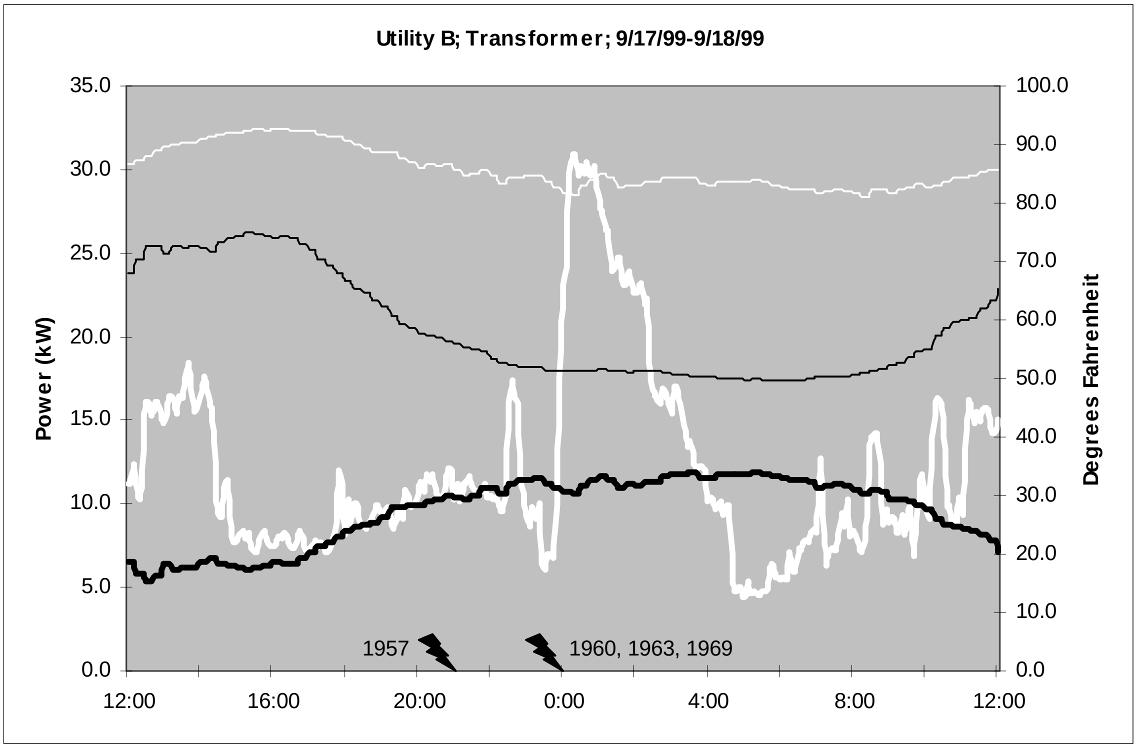
Transformer Temperature Analysis

Transformer temperature data were also recorded in the Utility B test site. The correlation of voltage THD to the rise in temperature, if any, was investigated with the data recorded. The recorded temperature data have been presented in entirety in Appendix D.5. A sample graph of the variation of the transformer temperature over one day is shown in Figure 8. The field test showed that the rise in voltage THD does not influence the heating of the transformer. The change in transformer temperature from ambient tracks the loading of the transformer with a time lag due to the thermal capacitance of the transformer.

Figure 8. 24 Hour Temperature Graph



Legend for Temperature Graph



Field Data Summary

A summary of the recorded data is provided below to identify the worst case conditions for the particular system configuration. The maximum observed values for the system conditions in the recorded data were determined. These could serve as important information for the utilities in identifying overloads and high background distortion levels for the field test site in particular and other similar feeders. The maximum observed values for the system conditions are shown in Table G.

Table G. Maximum Observed Values at Transformer Secondary

	Utility B		Utility E		Utility C	
Maximums	**Without EV Charging**	**With EV Charging**	**Without EV Charging**	**With EV Charging**	**Without EV charging**	**With EV charging**
Voltage THD (%)	4.0 (6:59 AM)	4.1 (2:54 AM)	1.4 (7:30 AM)	1.3 (0:40 AM)	2.3 (3:40 PM)	2.4 (5:10 PM)
Distortion Current (A)	15.1 (11:12 PM)	10.9 (0:20 AM)	17.3 (6:15 PM)	14.7 (11:50 PM)	15.0 (2:40 PM)	15.5 (4:00 PM)
Transformer Loading (%)	84 (8:45 PM)	65 (0:15 AM)	117 (9:30 PM)	77 (9:30 PM)	63 (1:05 PM)	80 (4:25 PM)

Note: The time of observation of each maximum has been provided within brackets.

The low percentage loading and voltage distortion with EV charging are probably due to the chargers coming on at nighttime when the loading is minimal. An assessment of the total loading of the transformer if EVs were charged during peak hours instead of at off-peak hours is made in Table H. It can be noticed that for Utilities B and E the system is overloaded with peak hour EV charging. Since Utility C was a commercial test site, charging was done during peak hours and it can be seen that the assessment matches the field data (See columns for Utility C in Tables G and H). Load management strategies like off peak charging should be encouraged to minimize impacts on the distribution system.

Table H. Impact of Peak Hour EV Charging on Overloading

Maximums	Utility B	Utility E	Utility C
EV loading (%)	36	11	16
No. of EVs charging simultaneously	3	1	4
Transformer Loading with Peak charging (%)	120	128	79

Conclusions

- Field site studies were performed by three utilities.
- Selected data from the field test sites are shown in the appendices.
- The field site data confirm the results reported in the Third Interim Report, that commercial EV chargers engineered to IWC guidelines do not give rise to excessive voltage THD on the secondary of the transformer. Two critical elements that make these guidelines effective are a minimum total power factor of 95% and a maximum current THD of ≤ 20%.
- The rise in voltage THD due to EV charging was found to be within 0.8% in all the three field test sites and should not be a cause for concern. Load management strategies like off peak charging should be encouraged to minimize load impacts on the distribution system.
- Simulation studies of one of the test sites were performed and the field data and the simulation results of the voltage THD were found to match within 2.9%, validating the modeling and simulation process developed during the course of this project.
- An evaluation of worst-case service configurations has been performed. These data are likely to be useful for utility planners in estimating overloads and analyzing other system phenomena for the corresponding feeder.
- The influence of EV charging on transformer temperature at one field site was studied. Temperature rise was not attributable to voltage THD but was affected rather by the extra loading on the transformer due to the EVs.
- The main cause of concern is the overloading of the distribution transformer with widespread use of EV chargers, assuming the chargers meet voluntary IWC guidelines such that voltage THD is not an issue. Still, utility service planning groups should ask for kVA and true power factor values in addition to kW values for any rectifier or other non-linear load.