PLUG-IN HYBRID ELECTRIC VEHICLE IMPACTS ON A CENTRAL
CALIFORNIA RESIDENTIAL DISTRIBUTION CIRCUIT

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ABSTRACT

Plug-in Hybrid Electric Vehicle Impacts on a Central California

Residential Distribution Circuit

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The adoption of plug-in hybrid electric vehicles (PHEV) as a means of transportation over conventionally fueled vehicles introduces new challenges to the existing infrastructure of the electrical transmission and distribution system. PHEV battery charging can represent a significant power demand that has the potential to overload electrical distribution components. This study examines the impacts of PHEV charging on household service transformers, distribution conductors and voltage levels of a Central California residential distribution system. The system is simulated using ETAP power system analysis software. Transformers are the most vulnerable to overloads, especially if PHEV charging occurs in clusters. Main feeder conductors will be overloaded if a large amount of high power, quick charging occurs. Branch conductors will not be affected by PHEV charging. Based on current PHEV market projections for the region this study shows that significant equipment overloads are not likely to occur until well after 2017.

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1 INTRODUCTION

This study analyzes the effect of plug-in hybrid electric vehicles (PHEV) on electrical distribution system components. The ability of electrical equipment to meet PHEV power demands must be examined in order to determine potential overloads. This will determine upgrade requirements needed in order to restore system reliability. The PHEV load is modeled conservatively according to Chevy Volt battery specifications [19]. In this study, battery recharging is limited to home plug-in connections. Workplace and high voltage DC commercial charging stations are still being developed and are not considered. Worst case loading scenarios are used to determine system thresholds. The worst case assumes that all specified PHEVs are plugged in and recharging at the same time. Impacts on system voltages, service transformers and conductors are noted at various PHEV penetration levels.

1.1 Market Penetration

PHEVs are becoming a more economical option compared to purely internal combustion vehicles. Influences include rising fuel prices, new and existing PHEV tax incentives and rebates, and reduced electricity costs during low demand time (time-of-use rates). By 2012, auto makers such as Fisker Karma, BYD, Toyota, Ford, Mercedes and Volvo all plan to offer PHEVs. The introduction of these PHEVs will compete with the currently available all-electric Nissan Leaf and PHEV Chevy Volt. Financial benefits, increased marketplace availability and competition, and potential for reduction in greenhouse gas (GHG) emissions make PHEVs a reasonable option for consumers looking for a new vehicle.

PHEVs are predicted to replace purchases of conventional vehicles (CV) powered by internal combustion [6]. Projections of new vehicle sales in the U.S. from 2010 to 2030 are plotted in Figure 1-1 by percentage of PHEVs, CVs, and hybrid electric vehicles (HEV) [21].

Figure 1-1: Projection of New Vehicle Sales

1.2 Environmental Benefits

The Electric Power Research Institute (EPRI) has published a study indicating that the adoption of PHEV technology significantly reduces net GHG emissions. Net GHG emissions include the carbon dioxide, methane, and nitrous oxide gases from internal combustion (tank-to-wheels), the processes of delivering gasoline to the vehicle (well-to-tank), and the generation of electricity to recharge the PHEV (well-to-wheels). EPRI compared GHG emissions of a CV and an HEV to that of a PHEV with a 20 mile all-electric driving range capacity. The power source for CVs and HEVs is gasoline.

The 20-mile PHEV is propelled by a mix of gasoline and battery stored grid energy. The GHG emissions per mile for a CV, an HEV and a 20-mile PHEV are shown in Figure 1-2. The yellow section of the bar graph (well-to-wheels) is the amount of GHGs emitted with respect to different power plant technologies used to produce the power to recharge the 20-mile PHEV battery [6].

Year 2010 comparison of PHEV 20 GHG emissions when charged entirely with electricity from specific power plant technologies (12,000 miles driven per year).

Figure 1-2: GHG Emissions by Power Source for a 20-Mile PHEV

1.3 Purchase Incentives

California offers a broad range of incentives for purchasing a PHEV. In some utility districts, electric vehicle service equipment (EVSE) is installed free of charge due to local government subsidies or company donations. Both Pacific Gas and Electric (PG&E) and Southern California Edison (SCE) offer PHEV customers reduced charging

rates during off peak hours. The California Air Resource Board (CARB) offers a \$5,000 rebate on PHEV purchases. Residents of the San Joaquin Valley Air Pollution Control District (SJVAPCD) qualify for a \$3,000 PHEV purchase rebate. Free PHEV parking is offered throughout the state.

A federal tax credit ranging from \$2,500 to \$7,500 is offered for PHEVs that utilize grid energy and have a battery capacity exceeding 4 kWh. A Federal Charging Infrastructure Tax Credit is available for up to 30% of the purchase and installation costs of qualified electric vehicle charging infrastructure acquired in 2011, with a maximum credit of \$1,000 for individuals and \$30,000 for businesses. A tax credit can be claimed for up to 50% of infrastructure cost with a maximum credit of \$2,000 for individuals and \$50,000 for businesses for infrastructure acquired in 2009 and 2010 [22].

1.4 PHEV Charging Power Demands

Plug-in electric vehicles (PEVs) can store energy from the grid in rechargeable battery packs, which vary in size depending on vehicle type. Home recharging of these batteries represents a load not before seen in significant numbers in residential power systems. Planners use a coincidence factor to scale the estimated power requirements for individual service transformers providing power to homes and apartments. The likely power demand per metered customer decreases as the number of customers connected to a particular service transformer increases. This load diversity scaling factor is used because it is unlikely that every household connected to a particular service transformer will have every electrical device turned on at the same time. This coincidence factor will need to be inverted when accounting for new electric vehicle power demand. As the

number of metered customers increases, the probability of one of them having an electric vehicle increases.

1.5 Electric Vehicle Types

Current EV technologies include all-electric or battery electric vehicles (BEVs), extended-range electric vehicles (E-REVs) and plug-in hybrid electric vehicles (PHEVs). All electric BEVs run completely off of grid energy and require the largest battery capacity. E-REVs have slightly smaller battery capacity requirements than all-electrics due to the integration of a gasoline engine used to generate electricity to maintain battery power. If sufficient battery life is available, the E-REV can run all the on-board power electronics and electric drive motor without running its gas engine. Once the battery state of charge reaches a certain threshold, the gas engine starts in order to maintain battery level.

PHEVs require the smallest battery capacity of the three and have two modes of operation defined by the U.S. Department of Energy Alternative Fuels and Advanced Vehicles Data Center. In series mode, the gas engine only provides as needed electrical support to the battery and electric motor propels the car. In parallel mode, both the electric motor and gas engine work together in direct connection to the propulsion system of the vehicle. This is the same as HEV operation, and is sometimes required to meet high speed or steep uphill climb power demands. This study examines the effect of charging the Chevy Volt PHEV which may operate in both series and parallel modes. The Chevy Volt has a 16 kWh (kilowatt-hour) battery pack which is assumed to utilize 75% of its capacity (12 kWh).

2 DISTRIBUTION CIRCUIT

The circuit being studied is a typical residential distribution section of the Central California power system. The ETAP model was created based on a generalized version of actual system data in the region.

2.1 Substation

The circuit being studied is connected to the subtransmission system of the electrical grid through a 66 to 12 kV substation shown in Figure 2-1. 12 total circuits receive power from the substation through 4 transformer banks each rated at 28 MVA (megavolt-amperes). The 12 kV side can supply a three phase short-circuit duty of 312.9 MVA, and a single-phase to ground short-circuit duty of 342.3 MVA.

Figure 2-1: Substation Diagram

2.2 Circuit Characteristics

The circuit under consideration is boxed in red and labeled “Ckt-1” in Figure 2-1 (see Figure 2-2 for expanded circuit view). It contains 1908 total metered customers made up of about 90% residential type loads, and 10% commercial and educational type loads. The main 12 kV 3-phase 4-wire feeder line consists of 1 mile of underground cable followed by 2.5 miles of overhead conductor. Each load in Figure 2-2 represents a

service transformer, and the power demands of the metered customer(s) connected to it. Voltage levels provided by service transformers include 480 V, 240 V and 120 V.

The distribution circuit configuration is radial, receiving power from a single source through the connection to the substation on the 12 kV side. Figure 2-2 is a layout of the circuit including service transformer and capacitor bank interconnection points.

Figure 2-2: Distribution Circuit Layout

Power demands for this circuit typically reach an annual maximum or peak in late August. This peak occurs during heat waves in the area which bring on heavy air conditioning load. Peak power demand is useful in determining worst case stresses on the system, and will be used in order to assess the capability of existing equipment to deliver the required energy. The three-phase power and per-phase current demands of the distribution circuit over a typical 24 hour peak utility day are plotted in Figure 2-3.

Figure 2-3: Peak Day Apparent Power and Current Curves

Peak demand usually occurs at 6pm, at which time the average per-phase current on the three-phase 12 kV main feeder line was 355 A and the apparent three-phase power was 7388 kVA. The off-peak power time is considered midnight for the circuit. At this time, the average per-phase current is down to 129 A and the apparent three-phase power demand had dropped to 2680 kVA. The actual minimum power demand occurs around 4am. Midnight is a more practical off-peak point for this study when considering slow PHEV recharge time.

2.3 Circuit Equipment

Distribution system equipment includes one circuit breaker protecting the entire line, fuses at branch lines, 232 service transformers, eight capacitor banks, and overhead (OH) and underground (UG) conductors. The circuit breaker is located at the substation and opens in the event of a short circuit anywhere on the circuit that exceeds 720 A.

The service transformers include three types and variety of sizes ranging from 5 kVA to 225 kVA. Transformer types include overhead (mounted on a power pole), padmount (installed on a concrete slab within a metal frame) and buried underground distribution (BURD, in an underground in a vault). Statistical information on service transformers by size along with number of connected customers is shown in Table 2-1 through Table 2-4. The most common service transformer sizes are 25, 50 and 75 kVA.

Table 2-1: All Service Transformers by Size

All Service Transformers							
Transformer Rating (kVA)	Count	% of Total Overhead	Statistics of Connected Customers				
			Total	Minimum	Maximum	Mean	Std. Dev.
5	1	0.43%	1	1	1	1.00	0.00
10	7	3.02%	9	1	2	1.29	0.49
15	16	6.90%	47	1	8	2.94	2.24
25	56	24.14%	281	1	16	5.02	3.08
37.5	27	11.64%	181	2	12	6.70	3.06
50	59	25.43%	509	1	20	8.63	3.35
75	53	22.84%	763	1	27	14.40	3.93
100	5	2.16%	84	12	22	16.80	3.83
150	4	1.72%	14	1	9	3.50	3.70
225	4	1.72%	19	1	10	4.75	4.11
Totals:	232	100%	1908				

Table 2-2: Overhead Service Transformers by Size

Overhead Service Transformers							
Transformer Rating (kVA)	Count	% of Total Overhead	Statistics of Connected Customers				
			Total	Minimum	Maximum	Mean	Std. Dev.
5	1	0.76%	1	1	1	1.00	0.00
10	7	5.30%	9	1	2	1.29	0.49
15	16	12.12%	47	1	8	2.94	2.24
25	53	40.15%	256	1	16	4.83	3.04
37.5	27	20.45%	181	2	12	6.70	3.06
50	25	18.94%	158	1	12	6.32	2.44
75	3	2.27%	35	10	14	11.67	2.08
Totals:	132	100.00%	687				

Table 2-3: Padmount Service Transformers by Size

Padmount Service Transformers							
Transformer Rating (kVA)	Count	% of Total Overhead	Statistics of Connected Customers				
			Total	Minimum	Maximum	Mean	Std. Dev.
25	2	3.23%	19	9	10	9.50	0.71
50	21	33.87%	209	6	20	9.95	3.14
75	30	48.39%	447	1	27	14.90	4.79
100	1	1.61%	12	12	12	12.00	0.00
150	4	6.45%	14	1	9	3.50	3.70
225	4	6.45%	19	1	10	4.75	4.11
Totals:	62	100.00%	720				

Table 2-4: BURD Service Transformers by Size

BURD Service Transformers							
Transformer Rating (kVA)	Count	% of Total Overhead	Statistics of Connected Customers				
			Total	Minimum	Maximum	Mean	Std. Dev.
25	1	2.63%	6	6	6	6.00	0.00
50	13	34.21%	142	6	16	10.92	2.47
75	20	52.63%	281	10	21	14.05	2.26
100	4	10.53%	72	15	22	18.00	3.16
Totals:	38	100.00%	501				

Transformer impedance is responsible for power loss and voltage drop. Service transformer impedances found in this distribution circuit are listed by size in Table 2-5.

Table 2-5: Service Transformer Impedance by Rating and Load Type

Transformer Size (kVA)	Commercial or Apartment Single-Phase	Residential Single-Phase	Commercial Three Phase
	Transformer Impedance (%Z)		
5	1	1	1
10	1	1	1
15	1	1	1
25	1	1	1
37.5	1	1	1
50	1	1	1
75	1.3	1.3	1
100	1.1	1.1	1.3
150	N/A	N/A	1.3
225	N/A	N/A	1.3

There are eight existing capacitor banks located throughout the circuit. Capacitor banks are used in distribution systems in order to maintain voltage levels by providing reactive volt-ampere (VAR) support. This reduces the total power transferred through

the conductors which means less current and a decrease in voltage drop and power losses along the distribution lines. The eight capacitor banks in this system are all programmed to turn on automatically under certain conditions. If the voltage at the capacitor bank connection point drops below 98.33% of rated voltage (11.8 kV) for longer than 30 seconds the banks turns on. If the voltage rises to 12 kV or higher, it turns off. Relevant capacitor bank information is found in Table 2-6.

Table 2-6: Capacitor Bank Ratings

Capacitor Bank Number	Switching Type	Configuration	Connection	Rating (kVAR)	Turn On Voltage Threshold
Cap1	Automatic	3-Ph Wye	A-B-C-N	1200	$V \leq 11.8\text{kV}$
Cap2	Automatic	3-Ph Wye	A-B-C-N	1200	$V \leq 11.8\text{kV}$
Cap3	Automatic	3-Ph Wye	A-B-C-N	450	$V \leq 11.8\text{kV}$
Cap4	Automatic	3-Ph Wye	A-B-C-N	600	$V \leq 11.8\text{kV}$
Cap5	Automatic	3-Ph Wye	A-B-C-N	900	$V \leq 11.8\text{kV}$
Cap6	Automatic	3-Ph Wye	A-B-C-N	900	$V \leq 11.8\text{kV}$
Cap7	Automatic	3-Ph Wye	A-B-C-N	900	$V \leq 11.8\text{kV}$
Cap8	Automatic	3-Ph Wye	A-B-C-N	900	$V \leq 11.8\text{kV}$

The conductors connecting the distribution network consist of high ampacity main feeder lines capable of carrying large currents, and lower ampacity lines that branch off of the main feeders with much lower current delivery requirements. Conductor ratings indicate the maximum continuous current carrying capacity for a particular conductor size and material. The conductors in this circuit can be operated beyond this rating, but not for more than eight hours. If conductor currents exceed rated values for too long, they may get too hot. This can cause underground cable insulation to break down and overhead lines to sag due to thermal elongation.

Conductor information is found in Table 2-7.

Table 2-7: Normal and Emergency Conductor Ratings

Conductor Ratings						
Conductor	Material	OH/UG	Normal Operation		Emergency Operation	
			Continuous Ampacity (A)	Continuous Load (kVA)	8 Hour Emergency Ampacity (A)	8 Hour Emergency Load (kVA)
2 CIC	Copper	UG	162	3367.11	192	3990.65
2 CLP	Aluminum	UG	139	2889.06	165	3429.46
350 CLP	Aluminum	UG	355	7378.54	427	8875.03
1000 CLP	Aluminum	UG	651	13530.78	782	16253.56
6 C	Copper	OH	135	2805.92	190	3949.08
2 A	Aluminum	OH	220	4572.61	280	5819.69
1/0 A	Aluminum	OH	280	5819.69	355	7378.54
336 A	Aluminum	OH	605	12574.69	800	16627.69

Power losses that occur within the distribution system are largely due to the impedances of the load delivering conductors. Positive and zero-sequence symmetrical impedances are listed in ohms per feet in Table 2-8. Line length is proportional to impedance, so longer lines mean higher power loss. The 1000 CLP and 336 A conductors are the longest lines, and also have by far the lowest impedances per foot. These low impedances keep I^2Z power transfer losses to a minimum.

Table 2-8: Conductor Impedances

Conductor Impedances				
Conductor	Positive Sequence		Zero Sequence	
	Resistance (ohms/foot)	Reactance (ohms/foot)	Resistance (ohms/foot)	Reactance (ohms/foot)
2 CIC	0.0003409	0.0000719	0.0005845	0.0001376
2 CLP	0.0003313	0.0000457	0.0005301	0.0001165
350 CLP	0.0000615	0.0000375	0.0000984	0.0000956
1000 CLP	0.0000230	0.0000370	0.0000339	0.0000938
6 C	0.0004188	0.0001511	0.0004721	0.0006056
4 A	0.0004241	0.0001446	0.0005665	0.0005027
1/0 A	0.0001677	0.0001140	0.0002210	0.0005884
336 A	0.0000530	0.0001159	0.0001126	0.0003183

3 ETAP MODELING

3.1 ETAP Software

The network data from section 2 describing the distribution circuit is used to recreate the system using ETAP 7.1.0 power system analysis software. ETAP provides load flow analysis, a powerful tool in determining equipment loading and voltage levels throughout the circuit. The ETAP simulation file contains a main circuit diagram and 30 sub-level circuit diagrams, shown in Appendix A. An example of the circuit hierarchy is shown in Figure 3-1 on page 14.

3.2 Infinite Bus Voltages

The simulation has to account for $V = IZ$ voltage drops along the circuit as the distance from the substation power source increases. For every change in power requirements of a circuit sub-section, the voltage drop changes and must be updated throughout the circuit. This was accomplished through iterative load flow simulations. Initially, all voltage buses were set to the rated 12 kV voltage and a load flow was run in order to determine the load for that particular circuit section. The apparent power demand and power factor data is then modeled in the next hierarchy level up as a lumped load. The change in the lumped load value caused a change in lumped load bus voltage which was then entered into the original lower level hierarchy section.

3.3 Service Transformers

A single-phase distribution service transformer model is not available with this version of ETAP. The three-phase model is used instead, with the impedances, power ratings and turns ratios entered manually to accurately model the original transformer.

Figure 3-1: ETAP Simulation Circuit Hierarchy

3.4 Static Loads

Residential, commercial, and PHEV power demands are modeled as static loads. Relevant ETAP model inputs include real and reactive power demand, phase connection, number of customers and demand factor diversity or coincidence factor. Coincidence factor which is discussed in section 1.4 is a scaling factor of the maximum power demand based on the number of customers connected to a service transformer. Coincidence factor is applied to residential loads only. Commercial loads are assumed to draw 100% of estimated power demand with no scaling based on diversity factors. Standard electric utility coincidence factors are assigned to each residential load as listed in Table 3-1.

Table 3-1: Residential Load Coincidence Factors

Number of Customers Per Transformer	1	2	3	4	5-6	7-8	9-11	>11
Coincidence Factor	100%	90%	85%	80%	75%	70%	65%	60%

ETAP allows single-phase static loads to connect to three-phase transformers by specifying phase connections. Residential loads are connected between neutral and either phase A, B or C of the service transformer low side.

3.5 Residential Demand

If a transformer serves 5 households (5 metered customers), with a maximum power demand of 7 kVA per household, coincidence factor is incorporated into load calculation as follows:

$$\frac{7kVA}{1 \text{ household}} \times 5 \text{ households} \times 0.75 = 26.25kVA$$

Typical power factors for commercial and residential loads range from 0.82 to 0.95 lagging. In order to simplify the model, power factor is set to 0.9 lagging for all static loads regardless of type. All non-EV loads are scaled down by 40% for off-peak

demand modeling. The transformer serving 5 households with a maximum power demand of 7 kVA per household has a peak demand of 26.25 kVA and an off-peak demand of 10.5 kVA.

3.6 PHEV Power Demand

According to the Society of Automobile Engineers in SAE J1772 and Article 625 of the National Electric Code, EV charging has three levels. This study only considers AC charging Level 1 and Level 2 available to residential customers. Level 3 is for high-voltage DC charging stations. Level 1 charging is defined as a single-phase, grounded 120 volt electrical receptacle, with an overcurrent rating of either 15 or 20 amperes. This charging scheme has a maximum current of 12 amperes, resulting in an apparent power consumption of 1.44 kVA. Level 2 charging requires special equipment including a dedicated electric vehicle power supply. Level 2 is also single-phase, but requires either 240 or 208 volts and has an overcurrent rating of 40 amperes. This allows a maximum current of 32 amperes and an apparent power of 7.68 kVA. Charging characteristics for Level 1 and Level 2 are described in Table 3-2 [5], [7]. A power factor of 0.9 lagging is conservatively assumed.

Table 3-2: EV AC Charging Ratings

Charging Level	Voltage (V)	Current (A)	Power Factor	Power (kVA)
1	120	12	90%	1.44
2	240	32	90%	7.680

PHEV chargers demand constant power, but are modeled in the ETAP circuit as static loads. Constant power loads demand the same power, regardless input voltage. Apparent power is proportional to voltage and current. For a constant power load, if voltage decreases, current increases according to $|S| = |V||I|$. Static loads have a

constant impedance and power that varies with voltage. Steady state voltage levels are allowed to fluctuate by $\pm 5\%$ or from 114 V to 126 V. If the voltage at the static PHEV load bus drops to 114 V, the power drawn will not accurately represent a PHEV charger. As the voltage of a constant impedance load decreases, the power also decreases, but by the voltage squared because $S = V^2/Z$. In order to account for voltage deviations, the PHEV load is multiplied by 1.11, a factor determined to be the same for both PHEV charging levels. The following calculations establish static load settings of 1.6 kVA for Level 1 charging and 8.533 kVA for Level 2 charging.

PHEV Level 1 charging power:

$$120V \times 12A = 1440VA$$

Minimum allowable voltage:

$$120V \times 95\% = 114V$$

Scaling factor for PHEV loads to account for worst case voltage sags:

$$\frac{V}{I} = Z = \frac{120V}{12A} = 10\Omega$$

$$S = \frac{V^2}{Z} = \frac{(114V)^2}{10\Omega} = 1299.6VA$$

$$\frac{1299.6VA}{1440VA} = 0.9025 \cong 0.9$$

Divide all Level 1 PEV Loads by 0.9:

$$\frac{1440VA}{0.9} = 1600VA = \mathbf{1.6kVA}$$

Following the same method for PHEV Level 2 charging power:

$$240V \times 32A = 7680VA$$

Minimum allowable voltage:

$$240V \times 95\% = 228V$$

$$\frac{V}{I} = Z = \frac{240V}{32A} = 7.5\Omega$$

$$S = \frac{V^2}{Z} = \frac{(228V)^2}{7.5\Omega} = 6931.2VA$$

$$\frac{6931.2VA}{7680VA} = 0.9025 \cong 0.9$$

$$\frac{7680VA}{0.9} = 8533VA = \mathbf{8.533kVA}$$

Full three-phase power demand of each individual PHEV is assumed at both peak and off-peak electrical demand times for the load model. All other loads will follow the load curve in Figure 2-3 on page 8.

3.7 Capacitor Banks

The capacitor bank ETAP model follows the original circuit data, with each bank three-phase wye connected with four wires at the appropriate location in the circuit. Capacitor banks must be switched in and out of service manually in ETAP, and are left off during load flow analysis unless voltage level at the bank connection point drops below 98.33% of the 12 kV rated voltage, or 11.8 kV.

3.8 Conductors

Overhead conductors are modeled in ETAP as horizontally configured 4-wire transmission lines 20 feet above ground with three feet between phases. Underground conductors are modeled as 4-wire cable bundles buried in conduit. Impedance values and ampacity limits are entered according to Table 2-8 and Table 2-7 respectively on page 12.

4 BASE CASE

4.1 Base Case Modeling

In order to establish a frame of reference from which to compare PHEV impact, the base case of the circuit is analyzed with no electric vehicles. The base case is modeled for both peak and off-peak demand. Any problems that are discovered through load flow analysis such as voltage sags, transformer overloads or conductor overloads are fixed. Once the base case is determined to be fully functional, any problems that arise with the addition of PHEVs are isolated and can be treated accordingly.

4.2 Peak Demand Voltage Support Requirements

Initial base case peak load flow results are shown in Table 4-1. Bus voltages below capacitor bank programmed limits are highlighted in yellow.

Table 4-1: Base Case Peak Load Flow without Capacitor Support

Main Circuit Bus	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor	% of Rated Voltage	Voltage (kV)
Bus 2	618	305	689.165	89.7%	99.31	11.917
Bus 3	1495	737	1666.792	89.7%	99.22	11.906
Bus 4	333	163	370.753	89.8%	99.13	11.896
Bus 5	1264	620	1407.869	89.8%	98.95	11.874
Bus 6	1047	510	1164.607	89.9%	98.90	11.868
Bus 8	1020	498	1135.079	89.9%	98.22	11.786
Bus 10	1057	517	1176.664	89.8%	98.18	11.782
Bus 12	335	163	372.551	89.9%	98.16	11.779
Substation Bus	7227	3610	8078.467	89.5%	100	12.000

The peak demand base case requires voltage support from three out of the eight capacitors installed in the system. Capacitors 6, 7 and 8 will see voltage levels below 11.8 kV (98.33% of rated 12 kV distribution voltage), and are set to turn on under this condition. The addition of these capacitors adds 2,700 kVAR to the circuit. This increases the power factor at the substation to 0.991 lagging. The addition of capacitor

banks 6, 7 and 8 raises bus voltages to appropriate levels. These capacitors will be left on for any base case scenario simulations at peak demand. Base case peak load flow results with capacitor support are shown in Table 4-2. Buses with capacitor banks connected within their lumped load model (Bus8-Load and Bus12-Load) are highlighted in green.

Table 4-2: Base Case Peak Load Flow with Capacitor Support

Main Circuit Bus	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor	% of Rated Voltage	Voltage (kV)
Bus 2	621	307	692.741	89.6%	99.54	11.945
Bus 3	1503	742	1676.178	89.7%	99.48	11.938
Bus 4	335	164	372.989	89.8%	99.43	11.932
Bus 5	1274	626	1419.490	89.8%	99.35	11.922
Bus 6	1056	518	1176.206	89.8%	99.34	11.921
Bus 8	1048	-375	1113.072	94.2%	99.36	11.923
Bus 10	1082	528	1203.955	89.9%	99.37	11.924
Bus 12	347	-1609	1645.992	21.1%	99.38	11.926
Substation Bus	7319	988	7385.385	99.1%	100	12.00

4.3 Peak Demand Equipment Overloads

A branch loading report is produced by ETAP warning of overloaded system components such as transformers, conductors, switches and fuses. Marginal alerts are set to flag components being loaded from 95% to 100% of ratings. Critical alerts flag components loaded beyond 100% of ratings. Service transformers in this distribution circuit are designed to be loaded beyond rated values. They can be loaded to 120% of their rating every day for 24 hours straight, and up to 130% of their rating for 12 hours a day, according to Table 4-3.

Table 4-3: Service Transformer Loading Limits

Daily Load Type	Maximum Loading
Intermittent Loading (12 hours per day)	130%
Continuous Loading (24 hours per day)	120%

Critical component overload alerts for the base case peak demand scenario are shown in Table 4-4. Transformers loaded beyond the 130% limit are highlighted in yellow.

Table 4-4: Base Case Peak Demand Load Flow Critical Alerts

Critical Report						
Device ID	Type	Condition	Rating	Unit	Operating	% Operating
T2-5	Transformer	Overload	0.050	MVA	0.0584	116.7
T4-7	Transformer	Overload	0.025	MVA	0.0258	103.2
T4-8	Transformer	Overload	0.025	MVA	0.0286	114.4
T5-6-14-7	Transformer	Overload	0.015	MVA	0.0217	144.9
T5-6-14-8	Transformer	Overload	0.015	MVA	0.0217	144.9
T5-6-6	Transformer	Overload	0.025	MVA	0.0213	112.5
T5-6-8	Transformer	Overload	0.025	MVA	0.0279	111.7
T5-7B-2	Transformer	Overload	0.050	MVA	0.0518	103.5
T6-1	Transformer	Overload	0.025	MVA	0.0379	151.4
T10-5-8	Transformer	Overload	0.025	MVA	0.0317	126.6
T10-7	Transformer	Overload	0.015	MVA	0.0156	104.2

Marginal component overload alerts for the base case peak demand scenario are shown in Table 4-5.

Table 4-5: Base Case Peak Demand Load Flow Marginal Alerts

Marginal Report						
Device ID	Type	Condition	Rating	Unit	Operating	% Operating
T5-7B-4	Transformer	Overload	0.075	MVA	0.0740	98.7
T6-2-11B-9	Transformer	Overload	0.025	MVA	0.0240	95.9
T10-4	Transformer	Overload	0.010	MVA	0.0969	96.9

The three service transformers loaded beyond 130% at peak demand require the most urgent replacement. Loading at such levels drastically shortens transformer life due to insulation breakdown from high operating temperatures. In order to maintain equipment reliability, these three transformers must be replaced. New transformer size is selected by the next standard size up from the peak operating demand. For example, transformer T6-1 is operating at 38 kVA, but is only rated at 25 kVA. The next commercially available size up from 38 kVA is 50 kVA. This makes all residential

service transformers loaded to less than 130% during peak demand. Table 4-6 contains the list of service transformer upgrades and new percent loading values.

Table 4-6: Service Transformer Upgrades

Upgraded Service Transformer Operation					
Device ID	Type	Upgraded Rating	Unit	Upgraded Operating	Upgraded % Operating
T5-6-14-7	Transformer	0.0250	MVA	0.022	86.95
T5-6-14-8	Transformer	0.0250	MVA	0.022	86.94
T6-1	Transformer	0.0500	MVA	0.038	75.72

4.4 Off-Peak Demand Load Flow

Load flow results for the circuit during off-peak demand are shown in Table 4-7.

Table 4-7: Base Case Off-Peak Load Flow without Capacitor Support

Main Circuit Bus	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor	% of Rated Voltage	Voltage (kV)
Bus 2	250	122	278.180	89.9%	99.73	11.968
Bus 3	603	294	670.854	89.9%	99.70	11.964
Bus 4	135	65	149.833	90.1%	99.66	11.959
Bus 5	510	250	567.979	89.8%	99.59	11.951
Bus 6	423	206	470.494	89.9%	99.57	11.948
Bus 8	420	203	466.486	90.0%	99.31	11.917
Bus 10	433	212	482.113	89.8%	99.29	11.915
Bus 12	138	67	153.405	90.0%	99.28	11.914
Substation Bus	2921	1434	3254.012	89.8%	100	12.00

The distribution circuit performs within acceptable limits during off-peak loading. No equipment is overloaded, and bus voltages are maintained above 98.33% (capacitor bank turn on threshold) without capacitor support.

5 PHEV LOADING

5.1 PHEV Circuit Loading

In this section, system level PHEV impacts are examined. These impacts include the overall load seen by the circuit with the addition of Level 1 and Level 2 PHEV charging during peak and off-peak demand times. Only residential metered customers with garages are considered to be potential PHEV users. This reduces the number of potential EV plug-in sites within the circuit to 1722 out of the total 1908 metered customers. 0% PHEV penetration refers to the base case of the circuit without the addition of PHEV loads. 100% PHEV penetration means that one PHEV per household has been added to the base case circuit model, for a total of 1722. 344 PHEVs are added to the circuit in 20% increments from 0% to 80% penetration and 346 PHEVs are added from 80% to 100% penetration in order to achieve the 1722 total as shown in Table 5-1.

Table 5-1: PHEV Penetration Levels

PHEV Penetration Level	Total PHEVs in Circuit
0%	0
20%	344
40%	688
60%	1032
80%	1376
100%	1722

It is not known when and where PHEVs will be plugged in to draw power from the grid. Current studies predict purchase behavior to follow that of hybrid electric vehicles [6]. In order to account for this unknown, three charging scenarios are simulated. Scenario one assumes one PHEV per customer, and adds PHEVs to the circuit in increments of 20% starting from plug-in locations furthest from the substation. This is

referred to as adding PHEVs from the end-of-line to the substation (EOL-Sub) [18]. Adding PHEVs from EOL-Sub represents the worst case loading situation for one PHEV per household because line losses will be at their greatest due to the conductor distance over which the added load must travel. PHEV distribution for this scenario is shown in Figure 5-1. Sections of connected PHEVs are colored green in the circuit diagrams.

Figure 5-1: PHEVs Added from End-of-Line to Substation

The opposite scenario also assumes one PHEV per customer, but populates the circuit with PHEVs from the substation to the end-of-line (Sub-EOL). Sub-EOL PHEV distribution is shown in Figure 5-2.

Figure 5-2: PHEVs Added from Substation to End-of-Line

A third scenario sets no limit to number of PHEVs per customer. This scenario contains clusters of 1, 2, 4, and 8 PHEVs per metered customer household (HH). The PHEVs are added to random lumped loads within the circuit. This random clustering of PHEVs is shown in Figure 5-3.

Figure 5-3: PHEVs Added in Random Clusters

5.1.1 Level 1 PHEV Charging During Peak Demand Time

The Level 1 peak time AC charging demand for a single PHEV is modeled as a 1.6 kVA static load with a power factor of 0.9. Load flow simulations using ETAP are performed for EOL-Sub, Sub-EOL and randomly clustered PHEV penetrations. Level 1 PHEV loads are added to the circuit from EOL-Sub with a limit of one PHEV per household. Total apparent power, real power, reactive power, and power factor for the entire circuit at the 12 kV three-phase level are recorded in Table 5-2, and plotted in Figure 5-4.

Table 5-2: Level 1 End-of-Line to Substation On-Peak Circuit Loading

Penetration Level	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor
0	7319	988	7385	99.1%
20%	7847	1265	7948	98.7%
40%	8314	1519	8452	98.4%
60%	8791	1763	8966	98.0%
80%	9261	2006	9476	97.7%
100%	9729	2245	9985	97.4%

Figure 5-4: Level 1 EOL-Sub On-Peak Circuit Loading Curve

Three-phase 12 kV peak apparent power demand follows an approximately linear path from zero to 100% PHEV penetration levels. The maximum apparent power

demand for this simulation occurs at 100% penetration when 1722 PHEVs are drawing power. The apparent power demand at this point is 9,985 kVA at 12 kV. This is not enough to overload the major components of the circuit such as the circuit breaker or main feeder lines. Circuit breaker trip settings and feeder loading limits at the three-phase 12 kV level are listed in Table 5-3.

Table 5-3: 12kV Three-Phase Loading Limits for Circuit Breaker and Feeders

Device	Settings/Ratings	
	(A)	(kVA)
Circuit Breaker Trip Setting	720	14965
80% Circuit Breaker Trip Setting	576	11972
64% Circuit Breaker Trip Setting	461	9598
Underground Main Conductor Normal Rating	651	13531
Underground Main Conductor Emergency Rating	782	16254
Overhead Main Conductor Normal Rating	605	12575
Overhead Main Conductor Emergency Rating	800	16628

9,985 kVA is 66.7% of the 14,965 kVA circuit breaker trip setting. Distribution engineers and substation operators become concerned when load approaches 64% of circuit breaker trip setting. This can affect system normal and emergency switching during load management operations. In the event of loss of service on an adjacent distribution circuit, a section of the powerless circuit may be energized through the distribution circuit still receiving power. In order to safely perform this switch or “load roll,” there must be enough remaining capacity on the circuit with power to supply the new section of load. Operators have predefined switching procedures based on historical load data and existing equipment ratings. Once a circuit is loaded past 64% of the circuit breaker trip setting, the operator may have to adopt different switching mitigation techniques. This penetration level will not overload the main feeders or trip the circuit breaker, but will still have an impact on load rolls and switching operations.

The bus voltages throughout the system need to be maintained at levels that guarantee voltages greater than 95% at utility customer service points. In order to assess the voltage impacts of PHEVs, bus voltages are recorded at the eight main buses within the ETAP model (Figure A-1). These bus voltages are recorded as a percentage of 12 kV at each penetration level in Table 5-4.

Table 5-4: Level 1 End-of-Line to Substation On-Peak Bus Voltages

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.54%	99.49%	99.45%	99.40%	99.36%	99.32%
Bus 3	99.48%	99.43%	99.38%	99.33%	99.28%	99.23%
Bus 4	99.43%	99.38%	99.32%	99.26%	99.20%	99.15%
Bus 5	99.35%	99.28%	99.20%	99.12%	99.06%	99.01%
Bus 6	99.34%	99.26%	99.17%	99.09%	99.03%	98.98%
Bus 8	99.36%	99.13%	98.95%	98.87%	98.80%	98.75%
Bus 10	99.37%	99.13%	98.94%	98.86%	98.80%	98.75%
Bus 12	99.38%	99.12%	98.94%	98.86%	98.79%	98.74%

The voltage data from Table 5-4 is plotted for each bus in Figure 5-5.

Figure 5-5: Level 1 EOL-Sub On-Peak Main Bus Voltages

Buses 8, 10 and 12 are furthest from the substation and experience the most severe voltage deviations. PHEV penetration from 0% to 40% adds significant PHEV load to these buses relative to the rest of the circuit. The steep initial drop in voltage is

due to the long length of the feeder line (0.61 miles from bus six to bus eight) between these three buses and the remainder of the circuit, and the fact that the loading is initially added at the furthest distance from the substation source. The lowest bus voltage is seen by bus 12, which drops to 98.74% or 11.8488 kV at 100% PHEV circuit penetration. This is well within the acceptable voltage range limits of $\pm 5\%$.

In the previous scenario, PHEVs are added to the circuit from EOL-Sub. The second scenario repeats the process in reverse, adding PHEVs to the circuit in the opposite direction from Sub-EOL. The resulting power demands are recorded in Table 5-5 and plotted in Figure 5-6.

Table 5-5: Level 1 Substation to End-of-Line On-Peak Circuit Loading

Penetration Level	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor
0	7319	988	7385	99.1%
20%	7795	1231	7892	98.8%
40%	8273	1477	8404	98.4%
60%	8751	1726	8920	98.1%
80%	9229	1980	9439	97.8%
100%	9714	2255	9972	97.4%

Figure 5-6: Level 1 Sub-EOL On-Peak Circuit Loading Curve

At 100% penetration, the circuit demands 9,972 kVA when populated with PHEVs from Sub-EOL, which is comparable to the 9,985 kVA demand recorded for the EOL-Sub scenario. Circuit loading for the two scenarios should be nearly equal at 100% penetration for either scenario because the number of PHEVs and the location at which they are connected within the circuit is the same. 9,972 kVA is 66.6% of the 14,965 kVA circuit breaker trip setting, and is again may affect switching methods.

Bus voltages are recorded in Table 5-6 and plotted in Figure 5-7.

Table 5-6: Level 1 Substation to End-of-Line On-Peak Bus Voltages

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.54%	99.50%	99.45%	99.41%	99.36%	99.31%
Bus 3	99.48%	99.44%	99.39%	99.34%	99.28%	99.23%
Bus 4	99.43%	99.39%	99.33%	99.27%	99.21%	99.15%
Bus 5	99.35%	99.31%	99.24%	99.16%	99.09%	99.00%
Bus 6	99.34%	99.30%	99.23%	99.15%	99.06%	98.97%
Bus 8	99.36%	99.32%	99.25%	99.17%	98.98%	98.74%
Bus 10	99.37%	99.33%	99.26%	99.18%	98.99%	98.74%
Bus 12	99.38%	99.33%	99.26%	99.18%	98.99%	98.73%

Figure 5-7: Level 1 Sub-EOL On-Peak Main Bus Voltages

Buses 8, 10 and 12 again experience the most significant voltage deviations. The steep voltage drop occurs at penetration levels from 60% to 100% for these buses in this loading scenario. This range of penetration levels corresponds to added load localized to buses 8, 10 and 12. Bus 12 again sees the lowest voltage of 98.73%, which is within acceptable limits.

Random PHEV clusters are likely to occur within the residential distribution circuit. It is important to be able to predict the response of the system to such a case. The random clustering scenario adds PHEV load to buses 3, 5 and 10. The power demands of the circuit are recorded in Table 5-7 and plotted in Figure 5-8.

Table 5-7: Level 1 Randomly Clustered On-Peak Circuit Loading

Penetration Level	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor
0	7319	988	7385	99.1%
20%	7794	1241	7892	98.8%
40%	8322	1500	8456	98.4%
60%	8798	1754	8971	98.1%
80%	9255	2014	9472	97.7%
100%	9693	2278	9957	97.3%

Figure 5-8: Level 1 Randomly Clustered On-Peak Circuit Loading Curve

At 100% penetration, the circuit demands 9,957 kVA for random PHEV population, which is comparable to apparent power demands of the previous two scenarios. Circuit loading should be slightly less at 100% penetration levels due to the heavy concentration of PHEV load added to buses three and five, which are much closer to the substation, reducing line losses. 9,957 kVA is 66.5% of the 14,965 kVA circuit breaker trip setting, and is again may affect switching methods. Bus voltages are recorded in Table 5-8 and plotted in Figure 5-9.

Table 5-8: Level 1 Randomly Clustered On-Peak Bus Voltages

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.54%	99.50%	99.45%	99.40%	99.36%	99.32%
Bus 3	99.48%	99.44%	99.38%	99.33%	99.28%	99.23%
Bus 4	99.43%	99.38%	99.33%	99.26%	99.21%	99.15%
Bus 5	99.35%	99.28%	99.23%	99.15%	99.07%	99.00%
Bus 6	99.34%	99.27%	99.21%	99.13%	99.05%	98.97%
Bus 8	99.36%	99.29%	99.08%	99.01%	98.93%	98.85%
Bus 10	99.37%	99.30%	99.08%	99.00%	98.92%	98.85%
Bus 12	99.38%	99.31%	99.08%	99.01%	98.93%	98.85%

Figure 5-9: Level 1 Randomly Clustered On-Peak Main Bus Voltages

5.1.2 Analysis of Level 1 PHEV Charging During Peak Demand

The total apparent power demand of the circuit for the three PHEV population scenarios is combined for comparison in Figure 5-10.

Figure 5-10: Level 1 Peak Demand Load Curves

The EOL-Sub load curve is consistently higher due to the location and order in which PHEV load is added and simulated. The Sub-EOL curve has a more linear characteristic, with slightly lower values than the EOL-Sub curve. Together the curves make an envelope that represents the loading boundaries for PHEV penetrations. This is

confirmed by observing the load flow results of the randomly clustered PHEVs. Points on the graph corresponding to PHEVs connected in random clusters fall within the boundaries of the EOL-Sub and Sub-EOL curves. This means that apparent power demand does not depend heavily on where PHEV load is added within the distribution circuit. Approximate load curves can be determined using any of the three methods.

No feeders are overloaded and circuit breakers are not tripped at 100% PHEV penetration for any population scenario. Due to the linearity of the loading curves, the data can be extrapolated out to determine PHEV penetration levels that will cause overloads. An extrapolation of the loading curves is shown in Figure 5-11.

Figure 5-11: Extrapolated Level 1 On-Peak Circuit Loading Curve

According to Figure 5-11, Level 1 charging will reach critical loading points at the penetration levels listed in Table 5-9.

Table 5-9: Overload Penetration Levels for Level 1 On-Peak Charging

Component	Level 1 PHEV Penetration to Overload/Trip
Circuit Breaker Trip	292%
80% Circuit Breaker Trip	177%
64% Circuit Breaker Trip	84%
Overhead Main Conductor Normal Rating	200%
Overhead Main Conductor Emergency Rating	357%

As previously discovered, the 64% circuit breaker trip loading level is reached before complete PHEV population at 84% penetration or a little less than one PHEV per household. The next critical point is the 80% of circuit breaker trip loading level, reached at 177% PHEV penetration, or just under two PHEVs per household. The circuit breaker will trip at 292% PHEV penetration for Level 1 on-peak charging, which is about three PHEVs per household. The main overhead feeder line is loaded to rated value at two PHEVs per household, and emergency rating is reached at three and a half PHEVs per household.

5.1.3 Level 2 PHEV Charging During Peak Demand Time

On-peak Level 2 AC charging demand is modeled as an 8.533 kVA static load with a power factor of 0.9 for each PHEV. Load flow simulations are performed for the worst case EOL-Sub PHEV population scenario. This will produce the most conservative results due to higher line losses for PHEV placement.

Level 2 charging causes capacitor banks to turn on in response to sagging voltage levels. The circuit loading is determined for two capacitor support scenarios. One scenario involves initial capacitor support but no added support as PHEV load is added. The second scenario adds capacitor support as voltage drops below the capacitor bank

threshold set at 98.33% of rated voltage. The circuit loading results for both scenarios are recorded in Table 5-10 and Table 5-11 respectively.

Table 5-10: Level 2 On-Peak Loading with Minimal Capacitor Support

Penetration Level	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor	Capacitors Banks On
0	7319	988	7385.385	99.1%	6, 7, 8
20%	9848	2395	10135.045	97.2%	6, 7, 8
40%	12310	3810	12886.124	95.5%	6, 7, 8
60%	14778	5174	15657.572	94.4%	6, 7, 8
80%	17232	6531	18428.125	93.5%	6, 7, 8
100%	19709	7897	21232.223	92.8%	6, 7, 8

Table 5-11: Level 2 On-Peak Loading with Maximum Capacitor Support

Penetration Level	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor	Capacitors Banks On
0	7319	988	7385.385	99.1%	6, 7, 8
20%	9848	2395	10135.045	97.2%	6, 7, 8
40%	12300	2948	12648.348	97.2%	5, 6, 7, 8
60%	14762	3248	15115.097	97.7%	3, 4, 5, 6, 7, 8
80%	17248	2200	17387.740	99.2%	1, 2, 3, 4, 5, 6, 7, 8
100%	19721	3540	20036.203	98.4%	1, 2, 3, 4, 5, 6, 7, 8

The circuit requires full capacitor support by 60% PHEV penetration due to voltage sags caused by the significant addition of Level 2 charging load. The total apparent power demand required by the circuit is 21,232 kVA for on-peak Level 2 charging at 100% PHEV penetration with only initial capacitor support. The total apparent power demand is 20,036 kVA for on-peak Level 2 charging at 100% PHEV penetration with full support from all connected capacitor banks. This decreases the power delivery requirements of the substation by 1,196 kVA. This indicates that capacitors within the distribution circuit can reduce strain on the overall system. This reduction in power delivery will also decrease line losses.

The apparent power demand of the circuit with both limited initial and as needed capacitor support is plotted in Figure 5-12, and loading alerts are listed in Table 5-12.

Figure 5-12: Level 2 On-Peak Circuit Loading

Table 5-12: Overload Penetration Levels for Level 2 On-Peak Charging

Component	PHEV Penetration to Overload/Trip	
	Initial Capacitor Support	As Needed Capacitor Support
Circuit Breaker Trip	54.8%	58.8%
80% Circuit Breaker Trip	33.2%	34.3%
64% Circuit Breaker Trip	15.3%	15.3%
Overhead Main Conductor Normal Rating	37.6%	39.7%
Overhead Main Conductor Emergency Rating	66.8%	73.2%

The main bus voltages for the circuit with only initial capacitor support are shown in Table 5-13 and plotted in Figure 5-13.

Table 5-13: Level 2 On-Peak Bus Voltages with Initial Capacitor Support

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.54%	99.30%	99.05%	98.81%	98.58%	98.34%
Bus 3	99.48%	99.21%	98.93%	98.65%	98.38%	98.12%
Bus 4	99.43%	99.11%	98.79%	98.47%	98.16%	97.89%
Bus 5	99.35%	98.94%	98.52%	98.11%	97.74%	97.48%
Bus 6	99.34%	98.89%	98.43%	98.01%	97.64%	97.37%
Bus 8	99.36%	98.20%	97.18%	96.75%	96.38%	96.12%
Bus 10	99.37%	98.14%	97.11%	96.68%	96.31%	96.04%
Bus 12	99.38%	98.10%	97.07%	96.64%	96.27%	96.00%

Figure 5-13: Level 2 On-Peak Bus Voltages with Initial Capacitor Support

The main buses of the distribution system maintain voltage levels above the 95% allowable minimum for PHEV penetration levels up to 100%. Voltages at buses 8, 10 and 12 reach levels of nearly 96% of 12 kV at 100% PHEV penetration. Due to additional voltage drops across branch feeders and service transformers, customers connected downstream of these buses may see voltages below the 95% utility limit.

Main bus voltages are shown in Table 5-14. Capacitors are turned on as needed at 40%, 60% and 80% as previously shown in Table 5-11 on page 37. This added support increases voltage levels as shown in Figure 5-14. Bus 12 reaches a voltage level of 96.58% of rated at 100% PHEV penetration and will likely keep customer voltages above the minimum voltage threshold.

Table 5-14: Level 2 On-Peak Bus Voltages with as Needed Capacitor Support

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.54%	99.30%	99.13%	98.98%	98.94%	98.69%
Bus 3	99.48%	99.21%	99.01%	98.84%	98.80%	98.53%
Bus 4	99.43%	99.11%	98.89%	98.69%	98.65%	98.38%
Bus 5	99.35%	98.94%	98.65%	98.40%	98.30%	98.03%
Bus 6	99.34%	98.89%	98.58%	98.31%	98.21%	97.94%
Bus 8	99.36%	98.20%	97.33%	97.06%	96.96%	96.69%
Bus 10	99.37%	98.14%	97.26%	96.99%	96.89%	96.62%
Bus 12	99.38%	98.10%	97.22%	96.95%	96.84%	96.58%

Figure 5-14: Level 2 On-Peak Bus Voltages with as Needed Capacitor Support

5.1.4 Level 1 PHEV Charging During Off-Peak Demand Time

Off-peak Level 1 AC charging demand is modeled again as a 1.6 kVA static load with a power factor of 0.9 for each PHEV. Off-peak demand time occurs at midnight according to Figure 2-3 on page 8. Load flow simulations are performed for the worst case EOL-Sub PHEV population scenario. The circuit loading results are listed in Table 5-15 and extrapolated out in Figure 5-15.

Table 5-15: Level 1 Off-Peak Circuit Loading

Penetration Level	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor
0	2921	1434	3254.0124	89.77%
20%	3415.8	1681.6	3807.2965	89.74%
40%	3910.6	1929.2	4360.5805	89.70%
60%	4405.4	2176.8	4913.8646	89.67%
80%	4900.2	2424.4	5467.1486	89.64%
100%	5395	2672	6020.4326	89.61%

Figure 5-15: Extrapolated Level 1 EOL-Sub Off-Peak Circuit Loading Curve

As shown in Figure 5-15, 64% of circuit breaker trip loading is not reached until PHEV penetration levels exceed two vehicles plugged in per household. The loading alerts are shown in Table 5-16.

Table 5-16: Overload Penetration Levels for Level 1 Off-Peak Charging

Component	Level 1 PHEV Penetration to Overload/Trip
Circuit Breaker Trip	423%
80% Circuit Breaker Trip	315%
64% Circuit Breaker Trip	229%
Overhead Main Conductor Normal Rating	337%
Overhead Main Conductor Emergency Rating	469%

Level 1 off-peak PHEV loading does not require capacitor bank voltage support.

The main bus voltages are recorded in Table 5-17 and plotted in Figure 5-16.

Table 5-17: Level 1 Off-Peak Bus Voltages

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.73%	99.68%	99.64%	99.59%	99.55%	99.50%
Bus 3	99.70%	99.64%	99.59%	99.54%	99.49%	99.43%
Bus 4	99.66%	99.60%	99.54%	99.48%	99.42%	99.36%
Bus 5	99.59%	99.51%	99.43%	99.35%	99.29%	99.23%
Bus 6	99.57%	99.48%	99.39%	99.31%	99.25%	99.20%
Bus 8	99.31%	99.10%	98.91%	98.82%	98.75%	98.69%
Bus 10	99.29%	99.08%	98.89%	98.80%	98.73%	98.66%
Bus 12	99.28%	99.07%	98.87%	98.78%	98.71%	98.64%

Figure 5-16: Level 1 EOL-Sub Off-Peak Bus Voltages

5.1.5 Level 2 Off-Peak PHEV Charging

Off-peak Level 2 AC charging demand is modeled again as an 8.533 kVA static load with a power factor of 0.9 for each PHEV. Load flow simulations are performed for the worst case EOL-Sub PHEV population scenario. The circuit loading results are listed in Table 5-18 and plotted in Figure 5-17.

Table 5-18: Level 2 Off-Peak Loading with Capacitor Support

Penetration Level	Real Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor
0	2921	1434	3254.012446	89.77%
20%	5510	1888	5824.486587	94.60%
40%	8080	1478	8214.066228	98.37%
60%	10663	2840	11034.7256	96.63%
80%	13227	3303	13633.1705	97.02%
100%	15824	3647	16238.82955	97.45%

Figure 5-17: Level 2 EOL-Sub Off-Peak Circuit Loading

PHEV penetration circuit loading alert levels are shown in Table 5-19. Capacitor support shifts the circuit breaker trip PHEV penetration level by nearly 10%, allowing a greater number of PHEVs on the circuit.

Table 5-19: Overload Penetration Levels for Level 2 Off-Peak Charging

Component	PHEV Penetration to Overload/Trip	
	No Capacitor Support	Capacitor Support
Circuit Breaker Trip	81%	90%
80% Circuit Breaker Trip	60%	67%
64% Circuit Breaker Trip	44%	50%
Overhead Main Conductor Normal Rating	65%	72%
Overhead Main Conductor Emergency Rating	93%	105%

The main bus voltages for the circuit without capacitor support are recorded in Table 5-20 and plotted in Figure 5-18.

Table 5-20: Level 2 Off-Peak Bus Voltages with no Capacitor Support

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.73%	99.50%	99.25%	98.95%	98.70%	98.49%
Bus 3	99.70%	99.40%	99.05%	98.75%	98.50%	98.29%
Bus 4	99.66%	99.25%	98.85%	98.55%	98.30%	98.07%
Bus 5	99.59%	99.09%	98.69%	98.29%	98.00%	97.66%
Bus 6	99.57%	98.99%	98.59%	98.19%	97.90%	97.55%
Bus 8	99.31%	97.95%	97.00%	96.55%	96.20%	95.96%
Bus 10	99.29%	97.91%	96.95%	96.52%	96.17%	95.87%
Bus 12	99.28%	97.86%	96.92%	96.49%	96.15%	95.81%

Figure 5-18: Level 2 Off-Peak Bus Voltages with no Capacitor Support

The main bus voltages for the circuit with capacitor support are recorded in Table 5-21 and plotted in Figure 5-19.

Table 5-21: Level 2 Off-Peak Bus Voltages with Capacitor Support

Main Circuit Bus	Main Circuit Percent Voltage at Penetration Level					
	0%	20%	40%	60%	80%	100%
Bus 2	99.73%	99.56%	99.46%	99.22%	99.05%	98.89%
Bus 3	99.70%	99.50%	99.39%	99.11%	98.92%	98.75%
Bus 4	99.66%	99.43%	99.31%	98.98%	98.77%	98.61%
Bus 5	99.59%	99.30%	99.14%	98.73%	98.48%	98.36%
Bus 6	99.57%	99.26%	99.09%	98.65%	98.42%	98.30%
Bus 8	99.31%	98.52%	98.25%	97.81%	97.57%	97.45%
Bus 10	99.29%	98.46%	98.20%	97.76%	97.52%	97.40%
Bus 12	99.28%	98.41%	98.17%	97.73%	97.50%	97.37%

Figure 5-19: Level 2 Off-Peak Bus Voltages with Capacitor Support

5.2 PHEV Service Transformer Loading

Individual service transformers directly providing power to customer households are susceptible to overloads under PHEV loading scenarios. These transformers are selected in the distribution design process based on traditional residential loading. They would be at the highest risk of overloading if multiple PHEVs customers were connected

to the same transformer and simultaneously recharging their vehicles at Level 2. A critical loading report generated in ETAP is shown for a section of the circuit at the end of the line (Bus12-Load in Figure A-1 on page 59) in Table 5-22. This section of the distribution circuit has nine transformers serving residential household customers. If one PHEV per household is being charged at Level 2 during peak demand time, every transformer will be loaded beyond the 130% utility equipment limit. These overloads also increase voltage drop across the transformer due to core saturation, and greatly reduce the voltage on the customer low side to levels below 95% of rated voltage.

Table 5-22: Level 2 On-Peak Loading for Bus12-Load

Critical Report						
Device ID	Type	Condition	Rating	Unit	Operating	% Operating
Bus12-11	Bus	Under Voltage	0.208	kV	0.196	94.3
Bus12-13	Bus	Under Voltage	0.208	kV	0.196	94.1
Bus12-15	Bus	Under Voltage	0.208	kV	0.196	94.1
Bus12-19	Bus	Under Voltage	0.208	kV	0.196	94.0
Bus12-21	Bus	Under Voltage	0.208	kV	0.195	94.0
Bus12-23	Bus	Under Voltage	0.208	kV	0.197	94.8
Bus12-4	Bus	Under Voltage	0.208	kV	0.197	94.9
Bus12-7	Bus	Under Voltage	0.208	kV	0.196	94.3
Bus12-9	Bus	Under Voltage	0.208	kV	0.195	93.9
T12-1	Transformer	Overload	0.015	MVA	0.024	162.2
T12-2	Transformer	Overload	0.025	MVA	0.056	225.2
T12-3	Transformer	Overload	0.025	MVA	0.065	260.2
T12-4	Transformer	Overload	0.038	MVA	0.088	235.5
T12-5	Transformer	Overload	0.038	MVA	0.097	257.8
T12-6	Transformer	Overload	0.005	MVA	0.012	231.0
T12-7	Transformer	Overload	0.075	MVA	0.176	234.9
T12-8	Transformer	Overload	0.050	MVA	0.129	257.5
T12-9	Transformer	Overload	0.100	MVA	0.179	179.2

Service transformer T12-3 is overloaded, operating at 260.2% of its rated value. This also causes a drop in voltage at the customer bus Bus12-9 to 93.9%. Upgrading the service transformer to a larger size will fix both of these issues. Circuit diagrams of this section of the system with load flow results before and after a transformer upgrade from

25 kVA to 75 kVA are displayed in Figure 5-20. A complete list of service transformers and predicted loading for PHEV penetration levels up to 100% for Level 1 and Level 2 charging at peak and off-peak demand times is given in Appendix B.

Figure 5-20: Loading Flow Prior to (left) and after (right) Upgrade

5.3 PHEV Branch Conductor Loading

The branch and tap conductors connecting the main feeder to service transformers are not overloaded in any PHEV loading scenario. Level 2 charging during peak demand time with 100% PHEV penetration does not load these conductors close to rated ampacities. No upgrades are required of the branch conductors.

5.4 PHEV Loading Results

The existing eight capacitor banks installed throughout the circuit provide sufficient voltage support for all PHEV demands. PHEV Level 2 loading during peak demand will reduce main bus voltages near the end of the distribution line to about 96.5% if PHEV penetration levels reach 100%. This is still above the minimum voltage of 95%

guaranteed by the utility. However, due to overloaded service transformers, the voltage the customer will see may fall to as low as 93.9% as previously shown in Table 5-22. Upgrading the service transformer will restore the low side voltage to above 95%.

Capacitor banks support voltage levels throughout the distribution system, but also alleviate substation power demands. A capacitor bank provides VAR to the system, reducing apparent power delivery requirements from the substation. The VAR demand in this circuit is due to the 0.9 lagging power factor of the PHEV chargers and typical household loads. Capacitor banks offset this VAR demand, allowing a greater number PHEVs to draw power from the system without overloading the circuit breaker.

The minimum number of PHEVs to overload the continuous rating of the main distribution overhead feeder conductor is 648 for on-peak Level 2 charging. Table 5-23 contains the numbers of PHEVs that cause critical circuit loading.

Table 5-23: Number of PHEVs to Cause Critical Loading

Component	Charging Level 1		Charging Level 2	
	Off-Peak	On-Peak	Off-Peak	On-Peak
	Number of PHEVs on Circuit			
Feeder Overload (Emergency)	8077	6148	1809	1261
CB Trip	7285	5029	1550	944
Feeder Overload (Normal)	5804	3444	1240	648
80% CB Trip	5425	3048	1154	572
64% CB Trip	3944	1447	861	264

The emergency eight hour conductor rating far exceeds the circuit breaker trip setting. It is possible to increase the trip setting of the circuit breaker to accommodate new PHEV load. Circuit breaker settings are beyond the scope of this study because they would take into account overall substation loading which includes 11 other distribution circuits.

6 PHEV IMPACT LIKELIHOOD

6.1 System Level Impacts

PHEV penetration levels are predicted to range from 2000 – 5000 by 2017 in the California Central Valley city considered in this study [11]. The average number of people per regional household in the year 2000 was determined by the U.S. Census Bureau to be 2.91. Probable PHEV penetration levels are calculated as follows.

$$\text{Persons per household} = 2.91 \cong 3 \text{ persons/household}$$

$$\text{Total Population} = 120,000 \text{ persons in region}$$

$$\text{Number of PHEV Households} = 1722$$

Minimum Market Projections:

Minimum Projected PHEVs per household:

$$\frac{2000 \text{ PHEVs}}{120,000 \text{ people}} \times \frac{3 \text{ people}}{1 \text{ household}} = \frac{1 \text{ PHEV}}{20 \text{ Households}}$$

Minimum Projected PHEVs for area:

$$\frac{2000 \text{ PHEVs}}{120,000 \text{ people}} \times \frac{3 \text{ people}}{1 \text{ household}} \times 1722 \text{ households} = 86.1 \text{ PHEVs}$$

$$\frac{86.1 \text{ PHEVs}}{1722 \text{ households}} = 5\% \text{ Penetration}$$

Maximum Market Projections:

Maximum Projected PHEVs per household:

$$\frac{5000 \text{ PHEVs}}{120,000 \text{ people}} \times \frac{3 \text{ people}}{1 \text{ household}} = \frac{1 \text{ PHEV}}{8 \text{ Households}}$$

Maximum Projected PHEVs for area:

$$\frac{5000 \text{ PHEVs}}{120,000 \text{ people}} \times \frac{3 \text{ people}}{1 \text{ household}} \times 1722 \text{ households} = 215.25 \text{ PHEVs}$$

$$\frac{215.25 \text{ PHEVs}}{1722 \text{ households}} = \mathbf{12.5\% \text{ Penetration}}$$

According to the above calculations, the maximum PHEV penetration for the distribution circuit under study will be 12.5% by 2017. Table 6-1 reiterates the critical PHEV penetration levels that place the system at risk or into a vulnerable state of loading.

Table 6-1: Critical PHEV Penetration Levels

Component	Charging Level 1		Charging Level 2	
	Off-Peak	On-Peak	Off-Peak	On-Peak
	PHEV Penetration Level			
CB Trip	423.00%	292.00%	90.00%	54.80%
Feeder Overload (Normal)	337.00%	200.00%	72.00%	37.60%
80% CB Trip	315.00%	177.00%	67.00%	33.20%
64% CB Trip	229.00%	84.00%	50.00%	15.30%

A PHEV penetration of 12.5% is not high enough to overload system level distribution components such as the main feeder or circuit breaker. The lowest penetration level of concern is 15.3%, and the highest anticipated 12.5% PHEV penetration is below it. This 15.3% PHEV penetration alert level only represents circuit loading of 64% of circuit breaker trip and not an overload point. This means that switching operations may be altered, but no main equipment will be damaged. Service transformer overloads may occur at a 12.5% penetration. It is unknown where PHEV customers will be located throughout the circuit. If enough PHEV customers are connected to the same service transformer, 12.5% penetration may overload it.

7 FUTURE WORK

7.1 Stochastic Analysis

It is not known whether PHEVs will penetrate the market as predicted. There is no historical record of widespread adoption of electric vehicle technology upon which to predict future market outcomes. In such a case, stochastic analysis may provide realistic predictions based on current available data. The National Household Travel Survey (NHTS) performed a study of U.S. driving behavior in 2001. This study included California drivers. The probability density function and distribution for miles driven per vehicle in California is shown in Figure 7-1. Assuming PHEVs will not alter driving behavior, this distribution can be applied to determine PHEV charging behavior, and energy requirements at plug-in time.

Figure 7-1: Vehicle Mile Driven in California [23]

The amount of daily miles driven for a PHEV from Figure 7-1, combined with the likely time of home arrival in Figure 7-2, energy demands in Figure 7-3, and power demands in Figure 7-4, likely PHEV impacts can be evaluated. This would be a less severe loading scenario than considered in this study, because it is very unlikely that every PHEV owner will be recharging their vehicles battery at home at the same time.

Figure 7-2: Plug-in Time Distribution [12]

Figure 7-3: Chevy Volt Battery Charging Energy Demands [12]

Figure 7-4: Chevy Volt Battery Charging Power Demands [12]

7.2 Single-Phase Service Transformer Modeling

All the household service transformers on this distribution circuit are actually single-phase. The connection is made on the transformer high side between two lines of the three-phase distribution feeder. The transformer low side is center tapped to provide with 120 or 240 volts to the customer. The available ETAP simulation software does not have a single-phase transformer model. Transformer model options include three-phase two-winding and three-winding transformers. Three-phase, two-winding transformers were used in this study, and actual single-phase transformer data was substituted into the three-phase model. Modeling household service transformers as three-phase does not accurately represent the distribution circuit being analyzed. An improvement to this study would use single-phase service transformers to match the original circuit and account for unbalanced single-phase power demands, and phase loading imbalance.

7.3 Service Transformer Loss-of-Life Analysis

The component most vulnerable to being overloaded is the service transformer, as discovered in this study. Overloading a transformer can shorten its effective life span due to the breakdown of insulation from heating. Transformers should be upgraded according to which will fail first. Loss-of-life analysis of each transformer for likely loading will properly assess such failures. Procedures for such analysis are found in the IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

7.4 Smart Meter Load Sharing

Load management will be vital in dealing with PHEV charging. On-board PHEV chargers can program in delays so that if the vehicle is plugged in at peak demand time, it will wait for off-peak to begin charging. Smart meters can manage PHEV load in order to prevent overloads. Service transformer loading, number of PHEVs connected, and remaining battery capacity can be in the inputs to a load sharing smart meter algorithm to evenly distribute the charging load.

7.5 Charger Harmonics and Power Quality

PHEV chargers may have detrimental effects on grid power quality. Chargers rectify AC grid power to supply the PHEV DC battery packs. This process draws non-linear current from the grid. Chargers without harmonic filtering or power factor correction will introduce voltage and current harmonics onto the distribution system. Harmonic generation for different charger types should be quantified. The harmonic impact on the power quality of the system can be analyzed in accordance to IEEE Standard 519, (IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems).

8 CONCLUSION

California emissions standards, environmental benefits and financial incentives are moving the state's transportation fleet towards electrification. As EVs replace conventional internal combustion vehicles, PHEVs are the likely bridge between the two technologies. PHEVs represent a significant load previously unseen to the electric grid. In the unlikely event of a worst case scenario in which all PHEV charging occurs during peak demand time, overloads will be seen at the substation circuit breaker and on the main feeder lines at market penetration levels well below 100%. If 648 PHEVs are connected for Level 2 charging during peak demand time, the main 12 kV three-phase overhead feeder will be overloaded. Level 2 charging capacity doubles to 1240 PHEVs if charge time is shifted to midnight. Level 1 charging will not overload the main overhead feeder or circuit breaker until at least 3444 PHEVs (two per household) are being charged during peak demand time. Level 1 charging capacity increases by a factor of 1.7 to 5804 PHEVs (over three per household) if charge time is shifted to midnight. Individual service transformers feeding PHEV customers are most likely to see overloads. These overloads will be a function of plug-in time and location and have yet to be fully quantified. Conductors branching off the main feeder are oversized for this circuit and will not be overloaded by PHEV charging.

BIBLIOGRAPHY

- [1] Bass, R.; Harley, R.; Lambert, F.; Rajasekaran, V.; Pierce, J., "Residential harmonic loads and EV charging," *Power Engineering Society Winter Meeting, 2001. IEEE*, vol. 2, pp. 803-808, 2001.
- [2] Berisha, S.H.; Karady, G.G.; Ahmad, R.; Hobbs, R.; Karner, D., "Current harmonics generated by electric vehicle battery chargers," *Power Electronics, Drives and Energy Systems for Industrial Growth, 1996., Proceedings of the 1996 International Conference on*, vol. 1, pp. 584-589, 8-11 Jan 1996.
- [3] Danilov, D.; Notten, P.H.L., "Adaptive battery management systems for the new generation of electrical vehicles," *Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE*, pp. 317-320, 7-10 Sept. 2009.
- [4] Dyke, K.J.; Schofield, N.; Barnes, M., "The impact of transport electrification on electrical networks," *Industrial Electronics, IEEE Transactions on*, vol. 57, no. 12, pp. 3917-3926, Dec. 2010.
- [5] Earley, M.W.; Sargent, J.S. (2011). National Electrical Code Handbook. Quincy, MA: National Fire Protection Association.
- [6] Electric Power Research Institute, Natural Resources Defense Council and Charles Clark Group, (23 July 2007). "Environmental Assessment of Plug-In Hybrid Electric Vehicles." Retrieved from <http://my.epri.com/portal>
- [7] Electric Vehicle Conductive Charge Coupler, SAE J1772, Recommended Practice, Draft Document in Progress 2009.
- [8] Farmer, C.; Hines, P.; Dowds, J.; Blumsack, S., "Modeling the impact of increasing PHEV loads on the distribution infrastructure," *System Sciences (HICSS), 2010 43rd Hawaii International Conference on*, pp. 1-10, 5-8 Jan. 2010.
- [9] Gonder, J.; Simpson, A., "Measuring and reporting fuel economy of plug-in hybrid electric vehicles," *22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-22), Yokohama, Japan, 23-28 October 2006*.
- [10] Green, R.C.; Lingfeng Wang; Alam, M., "The impact of plug-in hybrid electric vehicles on distribution networks: a review and outlook," *Power and Energy Society General Meeting, 2010 IEEE*, pp. 1-8, 25-29 July 2010.
- [11] KEMA, Inc. and ISO/RTO Council, (2010), "Assessment of plug-in electric vehicle integration with ISO/RTO Systems." Retrieved from http://www.isorto.org/site/c.jhKQIZPBImE/b.2604461/k.6151/Documents_and_Issues.htm

- [12] Maitra, A.; Kook, K.S.; Giumento, A.; Taylor, J.; Brooks, D.; Alexander, M.; Duvall, M., "Evaluation of PEV loading characteristics of Hydro-Quebec's distribution system operations," 24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-24), Stavanger, Norway, 13-16 May 2009.
- [13] Maitra, A.; Kook, K.S.; Taylor, J.; Giumento, A., "Grid impacts of plug-in electric vehicles on Hydro Quebec's distribution system," *Transmission and Distribution Conference and Exposition, 2010 IEEE PES*, pp. 1-7, 19-22 April 2010.
- [14] Maitra, A.; Taylor, J.; Brooks, D.; Alexander, M.; Duvall, M., "Integrating plug-in- electric vehicles with the distribution system," *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, pp. 1-5, 8-11 June 2009.
- [15] Meliopoulos, S.; Meisel, J.; Cokkinides, J., "Power system level impacts of plug-in hybrid vehicles," Power Systems Engineering Research Center (October 2009). Retrieved from http://www.pserc.wisc.edu/documents/general_information/presentations/pserc_seminars/5psercsemin/
- [16] Onar, O.C.; Khaligh, A., "Grid interactions and stability analysis of distribution power network with high penetration of plug-in hybrid electric vehicles," *Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE*, pp. 1755-1762, 21-25 Feb. 2010.
- [17] Poch, L.; Mahalik, M.; Jianhui Wang; Vyas, A., "Impacts of plug-in hybrid electric vehicles on the electric power system in the western United States," *Power and Energy Society General Meeting, 2010 IEEE*, pp. 1-7, 25-29 July 2010.
- [18] Richardson, P.; Flynn, D.; Keane, A., "Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems," *Power and Energy Society General Meeting, 2010 IEEE*, pp. 1-6, 25-29 July 2010.
- [19] Shengnan Shao.; Pipattanasomporn, M.; Rahman, S., "Challenges of PHEV penetration to the residential distribution network," *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, pp. 1-8, 26-30 July 2009.
- [20] Taylor, J.; Maitra, A.; Alexander, M.; Brooks, D.; Duvall, M., "Evaluations of plug-in electric vehicle distribution system impacts," *Power and Energy Society General Meeting, 2010 IEEE*, pp. 1-6, 25-29 July 2010.
- [21] Taylor, J.; Maitra, A.; Alexander, M.; Brooks, D.; Duvall, M., "Evaluation of the impact of plug-in electric vehicle loading on distribution system operations," *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, pp. 1-6, 26-30 July 2009.

- [22] U.S. Department of Energy - Energy Efficiency and Renewable Energy Alternative Fuels and Advanced Vehicles Data Center, "Federal and state incentives and laws." Retrieved from <http://www.afdc.energy.gov/afdc/laws/matrix/tech> (14 April 2011).
- [23] U.S. Department of Transportation, Federal Highway Administration, 2001 National Household Travel Survey (NHTS). Retrieved from <http://nhts.ornl.gov/download.shtml>
- [24] Wirasingha, S.G.; Schofield, N.; Emadi, A., "Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility," *Vehicle Power and Propulsion Conference, 2008. VPPC '08. IEEE*, pp. 1-8, 3-5 Sept. 2008.
- [25] Wu, D.; Aliprantis, D. C.; Gkritza, K., "Electric energy and power consumption by light-duty plug-in electric vehicles," *Power Systems, IEEE Transactions on*, vol. 26, no. 2, pp. 738-746, May 2011.

APPENDIX A: ETAP CIRCUIT MODEL

Figure A-1: Main Circuit One-Line Diagram

Figure A-3: Bus 3 Sub-Circuit One-Line Diagram

Figure A-4: Bus 3-24 Sub-Circuit One-Line Diagram

Figure A-5: Bus 3-25A Sub-Circuit One-Line Diagram

Figure A-6: Bus 3-25B Sub-Circuit One-Line Diagram

Figure A-7: Bus 4 Sub-Circuit One-Line Diagram

Figure A-8: Bus 5 Sub-Circuit One-Line Diagram

Figure A-9: Bus 5-6 Sub-Circuit One-Line Diagram

Figure A-10: Bus 5-6-14 Sub-Circuit One-Line Diagram

Figure A-11: Bus 5-7A Sub-Circuit One-Line Diagram

Figure A-12: Bus 5-7B Sub-Circuit One-Line Diagram

Figure A-13: Bus 5-21 Sub-Circuit One Line-Diagram

Figure A-14: Bus 6 Sub-Circuit One-Line Diagram

Figure A-16: Bus 6-2 Sub-Circuit One-Line Diagram

Figure A-17: Bus 6-2-11A Sub-Circuit One-Line Diagram

Figure A-18: Bus 6-2-11B Sub-Circuit One-Line Diagram

Figure A-19: Bus 6-16A Sub-Circuit One-Line Diagram

Figure A-20: Bus 6-16B Sub-Circuit One-Line Diagram

Figure A-21: Bus 8 Sub-Circuit One-Line Diagram

Figure A-22: Bus 8-12 Sub-Circuit One-Line Diagram

Figure A-24: Bus 8-12-21-21 Sub-Circuit One-Line Diagram

Figure A-26: Bus 10 Sub-Circuit One-Line Diagram

Figure A-27: Bus 10-5 Sub-Circuit One-Line Diagram

Figure A-28: Bus 10-24A Sub-Circuit One-Line Diagram

Figure A-29: Bus 10-24B Sub-Circuit One-Line Diagram

Figure A-30: Bus 12 Sub-Circuit One-Line Diagram

Figure A-31: Bus 12-16 Sub-Circuit One-Line Diagrams

APPENDIX B: SERVICE TRANSFORMER LOADING

Service transformer loading is calculated for PHEV penetration levels up to 100% in order to determine which are most vulnerable to overload. The transformer rating, number of customers taking service from it, peak apparent power demand, charging and penetration level are entered into the equation as follows for Level 1 and Level 2 charging. Any transformer loaded beyond 130% is at greater risk of failure and replacement should be considered.

$$\text{Load} = \frac{\text{Peak Demand} + \text{PHEV Load} \times \text{Penetration Level} \times \text{Customers Connected}}{\text{Transformer Rating}}$$

Table B-1: Level 1 On-Peak Service Transformer Loading

Level 1 Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T2-5	50	20	120.0	125.8	131.5	137.3	143.0	148.8	154.6	160.3	166.1	171.8	177.6
T3-5	50	14	92.4	96.4	100.5	104.5	108.5	112.6	116.6	120.6	124.7	128.7	132.7
T3-25A-6	50	14	92.4	96.4	100.5	104.5	108.5	112.6	116.6	120.6	124.7	128.7	132.7
T4-7	25	9	105.3	110.5	115.7	120.9	126.0	131.2	136.4	141.6	146.8	152.0	157.1
T4-8	25	10	117.0	122.8	128.5	134.3	140.0	145.8	151.6	157.3	163.1	168.8	174.6
T5-6-14-3	15	4	96.0	99.8	103.7	107.5	111.4	115.2	119.0	122.9	126.7	130.6	134.4
T5-6-14-7	25	8	89.6	94.2	98.8	103.4	108.0	112.6	117.2	121.9	126.5	131.1	135.7
T5-6-14-8	25	8	89.6	94.2	98.8	103.4	108.0	112.6	117.2	121.9	126.5	131.1	135.7
T5-6-6	25	12	115.2	122.1	129.0	135.9	142.8	149.8	156.7	163.6	170.5	177.4	184.3
T5-6-7	37.5	12	86.4	91.0	95.6	100.2	104.8	109.4	114.0	118.7	123.3	127.9	132.5
T5-6-8	25	11	114.4	120.7	127.1	133.4	139.7	146.1	152.4	158.8	165.1	171.4	177.8
T5-7A-2	37.5	11	95.3	99.6	103.8	108.0	112.2	116.5	120.7	124.9	129.1	133.3	137.6
T5-7A-3	37.5	11	95.3	99.6	103.8	108.0	112.2	116.5	120.7	124.9	129.1	133.3	137.6
T5-7B-2	50	16	105.6	110.2	114.8	119.4	124.0	128.6	133.2	137.9	142.5	147.1	151.7
T5-7B-4	75	21	100.8	104.8	108.9	112.9	116.9	121.0	125.0	129.0	133.1	137.1	141.1
T6-2-5	37.5	12	96.0	100.6	105.2	109.8	114.4	119.0	123.6	128.3	132.9	137.5	142.1
T6-2-11B-6	37.5	12	96.0	100.6	105.2	109.8	114.4	119.0	123.6	128.3	132.9	137.5	142.1
T6-2-11B-9	25	7	98.0	102.0	106.1	110.1	114.1	118.2	122.2	126.2	130.3	134.3	138.3
T10-5-8	25	10	130.0	135.8	141.5	147.3	153.0	158.8	164.6	170.3	176.1	181.8	187.6
T10-7	15	4	106.7	110.5	114.3	118.2	122.0	125.9	129.7	133.5	137.4	141.2	145.1

Table B-2: Level 2 On-Peak Service Transformer Loading

Level 2 Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T2-2	75	14	61.6	75.9	90.3	104.6	118.9	133.3	147.6	162.0	176.3	190.6	205.0
T2-3	75	11	57.2	68.5	79.7	91.0	102.3	113.5	124.8	136.0	147.3	158.6	169.8
T2-4	75	19	91.2	110.7	130.1	149.6	169.0	188.5	207.9	227.4	246.8	266.3	285.8
T2-5	50	20	120.0	150.7	181.4	212.2	242.9	273.6	304.3	335.0	365.8	396.5	427.2
T3-5	50	14	92.4	113.9	135.4	156.9	178.4	199.9	221.4	242.9	264.4	285.9	307.4
T3-6	75	14	67.2	81.5	95.9	110.2	124.5	138.9	153.2	167.6	181.9	196.2	210.6
T3-7	75	14	67.2	81.5	95.9	110.2	124.5	138.9	153.2	167.6	181.9	196.2	210.6
T3-8	50	12	93.6	112.0	130.5	148.9	167.3	185.8	204.2	222.6	241.1	259.5	277.9
T3-24-1	50	6	49.5	58.7	67.9	77.1	86.4	95.6	104.8	114.0	123.2	132.4	141.7
T3-24-2	75	14	61.6	75.9	90.3	104.6	118.9	133.3	147.6	162.0	176.3	190.6	205.0
T3-24-3	50	9	64.4	78.2	92.0	105.8	119.6	133.5	147.3	161.1	174.9	188.8	202.6
T3-24-4	75	10	47.7	57.9	68.1	78.4	88.6	98.9	109.1	119.3	129.6	139.8	150.1
T3-24-5	75	13	57.2	70.5	83.8	97.1	110.4	123.8	137.1	150.4	163.7	177.0	190.3
T3-24-6	75	11	52.4	63.7	75.0	86.2	97.5	108.8	120.0	131.3	142.5	153.8	165.1
T3-24-7	75	13	57.2	70.5	83.8	97.1	110.4	123.8	137.1	150.4	163.7	177.0	190.3
T3-24-8	75	15	66.0	81.4	96.7	112.1	127.4	142.8	158.2	173.5	188.9	204.2	219.6
T3-24-9	75	14	61.6	75.9	90.3	104.6	118.9	133.3	147.6	162.0	176.3	190.6	205.0
T3-24-10	75	16	70.4	86.8	103.2	119.6	135.9	152.3	168.7	185.1	201.5	217.9	234.2
T 3-25B-1	50	10	78.0	93.4	108.7	124.1	139.4	154.8	170.2	185.5	200.9	216.2	231.6
T 3-25B-2	50	7	58.8	69.6	80.3	91.1	101.8	112.6	123.3	134.1	144.8	155.6	166.3
T 3-25B-3	50	8	67.2	79.5	91.8	104.1	116.4	128.6	140.9	153.2	165.5	177.8	190.1
T 3-25B-4	50	11	78.7	95.5	112.4	129.3	146.2	163.1	180.0	196.9	213.8	230.7	247.6
T3-25A-7	50	10	71.5	86.9	102.2	117.6	132.9	148.3	163.7	179.0	194.4	209.7	225.1
T3-25A-8	75	14	61.6	75.9	90.3	104.6	118.9	133.3	147.6	162.0	176.3	190.6	205.0
T3-25A-9	50	12	79.2	97.6	116.1	134.5	152.9	171.4	189.8	208.2	226.7	245.1	263.5
T3-25A-10	50	6	49.5	58.7	67.9	77.1	86.4	95.6	104.8	114.0	123.2	132.4	141.7
T3-25A-11	50	10	71.5	86.9	102.2	117.6	132.9	148.3	163.7	179.0	194.4	209.7	225.1
T3-25A-6	50	14	92.4	113.9	135.4	156.9	178.4	199.9	221.4	242.9	264.4	285.9	307.4
T3-25A-1	75	19	83.6	103.1	122.5	142.0	161.4	180.9	200.3	219.8	239.2	258.7	278.2
T3-25A-4	75	14	61.6	75.9	90.3	104.6	118.9	133.3	147.6	162.0	176.3	190.6	205.0
T3-25A-5	50	12	79.2	97.6	116.1	134.5	152.9	171.4	189.8	208.2	226.7	245.1	263.5
T3-25A-2	50	8	61.6	73.9	86.2	98.5	110.8	123.0	135.3	147.6	159.9	172.2	184.5
T3-25A-3	50	8	61.6	73.9	86.2	98.5	110.8	123.0	135.3	147.6	159.9	172.2	184.5
T4-7	25	9	105.3	132.9	160.6	188.2	215.9	243.5	271.2	298.8	326.5	354.1	381.8
T4-8	25	10	117.0	147.7	178.4	209.2	239.9	270.6	301.3	332.0	362.8	393.5	424.2
T4-9	50	12	79.2	97.6	116.1	134.5	152.9	171.4	189.8	208.2	226.7	245.1	263.5
T4-10	50	10	71.5	86.9	102.2	117.6	132.9	148.3	163.7	179.0	194.4	209.7	225.1
T4-11	75	15	72.0	87.4	102.7	118.1	133.4	148.8	164.2	179.5	194.9	210.2	225.6
T5-6-2	25	7	88.2	109.7	131.2	152.7	174.2	195.7	217.2	238.7	260.2	281.7	303.2
T5-6-3	25	6	81.0	99.4	117.9	136.3	154.7	173.2	191.6	210.0	228.5	246.9	265.3

Table B-3: Level 2 On-Peak Service Transformer Loading

Level 2 Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T5-6-14-1	25	6	81.0	99.4	117.9	136.3	154.7	173.2	191.6	210.0	228.5	246.9	265.3
T5-6-14-2	37.5	9	70.2	88.6	107.1	125.5	143.9	162.4	180.8	199.2	217.7	236.1	254.5
T5-6-14-3	15	4	96.0	116.5	137.0	157.4	177.9	198.4	218.9	239.4	259.8	280.3	300.8
T5-6-14-4	15	3	76.5	91.9	107.2	122.6	137.9	153.3	168.7	184.0	199.4	214.7	230.1
T5-6-14-5	25	4	57.6	69.9	82.2	94.5	106.8	119.0	131.3	143.6	155.9	168.2	180.5
T5-6-14-6	25	7	88.2	109.7	131.2	152.7	174.2	195.7	217.2	238.7	260.2	281.7	303.2
T5-6-14-7	25	8	89.6	114.2	138.8	163.3	187.9	212.5	237.1	261.6	286.2	310.8	335.4
T5-6-14-8	25	8	89.6	114.2	138.8	163.3	187.9	212.5	237.1	261.6	286.2	310.8	335.4
T5-6-6	25	12	115.2	152.1	188.9	225.8	262.7	299.5	336.4	373.2	410.1	447.0	483.8
T5-6-7	37.5	12	86.4	111.0	135.6	160.1	184.7	209.3	233.9	258.4	283.0	307.6	332.2
T5-6-8	25	11	114.4	148.2	182.0	215.8	249.6	283.4	317.2	350.9	384.7	418.5	452.3
T5-7A-1	75	11	47.7	58.9	70.2	81.5	92.7	104.0	115.3	126.5	137.8	149.0	160.3
T5-7A-2	37.5	11	95.3	117.9	140.4	162.9	185.4	208.0	230.5	253.0	275.6	298.1	320.6
T5-7A-3	37.5	11	95.3	117.9	140.4	162.9	185.4	208.0	230.5	253.0	275.6	298.1	320.6
T5-7A-4	50	9	64.4	78.2	92.0	105.8	119.6	133.5	147.3	161.1	174.9	188.8	202.6
T5-7A-5	37.5	5	55.0	65.2	75.5	85.7	96.0	106.2	116.4	126.7	136.9	147.2	157.4
T5-7B-1	75	14	67.2	81.5	95.9	110.2	124.5	138.9	153.2	167.6	181.9	196.2	210.6
T5-7B-2	50	16	105.6	130.2	154.8	179.3	203.9	228.5	253.1	277.6	302.2	326.8	351.4
T5-7B-3	50	9	70.2	84.0	97.8	111.7	125.5	139.3	153.1	167.0	180.8	194.6	208.4
T5-7B-4	75	21	100.8	122.3	143.8	165.3	186.8	208.3	229.8	251.3	272.8	294.3	315.8
T5-7B-5	75	14	67.2	81.5	95.9	110.2	124.5	138.9	153.2	167.6	181.9	196.2	210.6
T5-3	75	16	76.8	93.2	109.6	126.0	142.3	158.7	175.1	191.5	207.9	224.3	240.6
T5-4	75	16	76.8	93.2	109.6	126.0	142.3	158.7	175.1	191.5	207.9	224.3	240.6
T5-5	75	15	72.0	87.4	102.7	118.1	133.4	148.8	164.2	179.5	194.9	210.2	225.6
T5-6	75	17	81.6	99.0	116.4	133.8	151.2	168.6	186.0	203.5	220.9	238.3	255.7
T5-7	75	19	91.2	110.7	130.1	149.6	169.0	188.5	207.9	227.4	246.8	266.3	285.8
T5-21-1	75	13	57.2	70.5	83.8	97.1	110.4	123.8	137.1	150.4	163.7	177.0	190.3
T5-21-2	75	15	66.0	81.4	96.7	112.1	127.4	142.8	158.2	173.5	188.9	204.2	219.6
T5-21-3	75	10	47.7	57.9	68.1	78.4	88.6	98.9	109.1	119.3	129.6	139.8	150.1
T5-21-4	75	12	52.8	65.1	77.4	89.7	102.0	114.2	126.5	138.8	151.1	163.4	175.7
T5-21-5	100	15	49.5	61.0	72.5	84.1	95.6	107.1	118.6	130.1	141.7	153.2	164.7
T5-21-6	50	9	64.4	78.2	92.0	105.8	119.6	133.5	147.3	161.1	174.9	188.8	202.6
T5-21-7	50	10	71.5	86.9	102.2	117.6	132.9	148.3	163.7	179.0	194.4	209.7	225.1
T5-8	25	3	51.0	60.2	69.4	78.6	87.9	97.1	106.3	115.5	124.7	133.9	143.2
T6-1-1	50	7	68.6	79.4	90.1	100.9	111.6	122.4	133.1	143.9	154.6	165.4	176.1
T6-1-2	75	16	89.6	106.0	122.4	138.8	155.1	171.5	187.9	204.3	220.7	237.1	253.4
T6-1-3	75	17	88.4	105.8	123.2	140.6	158.0	175.4	192.8	210.3	227.7	245.1	262.5
T6-1-4	50	10	78.0	93.4	108.7	124.1	139.4	154.8	170.2	185.5	200.9	216.2	231.6
T6-1-5	75	15	78.0	93.4	108.7	124.1	139.4	154.8	170.2	185.5	200.9	216.2	231.6
T6-1-6	100	12	57.6	66.8	76.0	85.2	94.5	103.7	112.9	122.1	131.3	140.5	149.8

Table B-4: Level 2 On-Peak Service Transformer Loading

Level 2 Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T6-2-5	37.5	12	96.0	120.6	145.2	169.7	194.3	218.9	243.5	268.0	292.6	317.2	341.8
T6-2-1	10	1	55.0	62.7	70.4	78.0	85.7	93.4	101.1	108.8	116.4	124.1	131.8
T6-2-2	10	1	55.0	62.7	70.4	78.0	85.7	93.4	101.1	108.8	116.4	124.1	131.8
T6-2-11B-1	25	3	56.1	65.3	74.5	83.7	93.0	102.2	111.4	120.6	129.8	139.0	148.3
T6-2-11B-3	37.5	5	55.0	65.2	75.5	85.7	96.0	106.2	116.4	126.7	136.9	147.2	157.4
T6-2-11B-4	37.5	6	66.0	78.3	90.6	102.9	115.2	127.4	139.7	152.0	164.3	176.6	188.9
T6-2-11B-5	25	7	88.2	109.7	131.2	152.7	174.2	195.7	217.2	238.7	260.2	281.7	303.2
T6-2-11B-6	37.5	12	96.0	120.6	145.2	169.7	194.3	218.9	243.5	268.0	292.6	317.2	341.8
T6-2-11B-7	37.5	5	50.0	60.2	70.5	80.7	91.0	101.2	111.4	121.7	131.9	142.2	152.4
T6-2-11B-8	25	5	75.0	90.4	105.7	121.1	136.4	151.8	167.2	182.5	197.9	213.2	228.6
T6-2-11B-9	25	7	98.0	119.5	141.0	162.5	184.0	205.5	227.0	248.5	270.0	291.5	313.0
T6-2-11A-1	50	6	40.5	49.7	58.9	68.1	77.4	86.6	95.8	105.0	114.2	123.4	132.7
T6-2-11A-2	75	14	61.6	75.9	90.3	104.6	118.9	133.3	147.6	162.0	176.3	190.6	205.0
T6-2-11A-5	50	10	71.5	86.9	102.2	117.6	132.9	148.3	163.7	179.0	194.4	209.7	225.1
T6-2-11A-6	75	11	52.4	63.7	75.0	86.2	97.5	108.8	120.0	131.3	142.5	153.8	165.1
T6-2-11A-3	75	13	57.2	70.5	83.8	97.1	110.4	123.8	137.1	150.4	163.7	177.0	190.3
T6-2-11A-4	25	6	81.0	99.4	117.9	136.3	154.7	173.2	191.6	210.0	228.5	246.9	265.3
T6-1	50	13	78.0	98.0	117.9	137.9	157.9	177.8	197.8	217.8	237.7	257.7	277.7
T6-4	50	7	58.8	69.6	80.3	91.1	101.8	112.6	123.3	134.1	144.8	155.6	166.3
T6-16B-1	25	5	82.5	97.9	113.2	128.6	143.9	159.3	174.7	190.0	205.4	220.7	236.1
T6-16B-5	25	4	70.4	82.7	95.0	107.3	119.6	131.8	144.1	156.4	168.7	181.0	193.3
T6-16B-2	25	4	70.4	82.7	95.0	107.3	119.6	131.8	144.1	156.4	168.7	181.0	193.3
T6-16B-3	50	7	53.9	64.7	75.4	86.2	96.9	107.7	118.4	129.2	139.9	150.7	161.4
T8-2	75	15	72.0	87.4	102.7	118.1	133.4	148.8	164.2	179.5	194.9	210.2	225.6
T8-3	50	12	86.4	104.8	123.3	141.7	160.1	178.6	197.0	215.4	233.9	252.3	270.7
T8-4	75	12	57.6	69.9	82.2	94.5	106.8	119.0	131.3	143.6	155.9	168.2	180.5
T8-12-1	50	8	67.2	79.5	91.8	104.1	116.4	128.6	140.9	153.2	165.5	177.8	190.1
T8-12-2	50	6	54.0	63.2	72.4	81.6	90.9	100.1	109.3	118.5	127.7	136.9	146.2
T8-12-21-1	25	4	83.2	95.5	107.8	120.1	132.4	144.6	156.9	169.2	181.5	193.8	206.1
T8-12-21-2	25	3	66.3	75.5	84.7	93.9	103.2	112.4	121.6	130.8	140.0	149.2	158.5
T8-12-21-3	15	2	78.0	88.2	98.5	108.7	119.0	129.2	139.4	149.7	159.9	170.2	180.4
T8-12-10	37.5	4	51.2	59.4	67.6	75.8	84.0	92.2	100.4	108.5	116.7	124.9	133.1
T8-12-11	37.5	4	51.2	59.4	67.6	75.8	84.0	92.2	100.4	108.5	116.7	124.9	133.1
T8-12-21-5	25	3	71.4	80.6	89.8	99.0	108.3	117.5	126.7	135.9	145.1	154.3	163.6
T8-12-21-4	37.5	4	59.7	67.9	76.1	84.3	92.5	100.7	108.9	117.1	125.3	133.5	141.7
T8-12-21-6	50	7	53.9	64.7	75.4	86.2	96.9	107.7	118.4	129.2	139.9	150.7	161.4
T8-12-21-7	37.5	4	55.5	63.7	71.9	80.0	88.2	96.4	104.6	112.8	121.0	129.2	137.4
T8-12-21-8	37.5	5	65.0	75.2	85.5	95.7	106.0	116.2	126.4	136.7	146.9	157.2	167.4
T8-12-21-9	50	8	72.8	85.1	97.4	109.7	122.0	134.2	146.5	158.8	171.1	183.4	195.7
T8-12-21-10	25	4	76.8	89.1	101.4	113.7	126.0	138.2	150.5	162.8	175.1	187.4	199.7

Table B-5: Level 2 On-Peak Service Transformer Loading

Level 2 Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T8-12-21-21-2	37.5	4	59.7	67.9	76.1	84.3	92.5	100.7	108.9	117.1	125.3	133.5	141.7
T8-12-21-21-3	25	4	83.2	95.5	107.8	120.1	132.4	144.6	156.9	169.2	181.5	193.8	206.1
T8-12-21-21-4	15	2	96.0	106.2	116.5	126.7	137.0	147.2	157.4	167.7	177.9	188.2	198.4
T8-12-21-21-6	25	3	61.2	70.4	79.6	88.8	98.1	107.3	116.5	125.7	134.9	144.1	153.4
T8-12-21-21-7	25	4	76.8	89.1	101.4	113.7	126.0	138.2	150.5	162.8	175.1	187.4	199.7
T8-12-21-21-8	25	3	71.4	80.6	89.8	99.0	108.3	117.5	126.7	135.9	145.1	154.3	163.6
T8-12-21-21-10-2	25	4	89.6	101.9	114.2	126.5	138.8	151.0	163.3	175.6	187.9	200.2	212.5
T8-12-21-21-10-3	50	5	60.0	67.7	75.4	83.0	90.7	98.4	106.1	113.8	121.4	129.1	136.8
T8-12-21-21-10-7	25	3	71.4	80.6	89.8	99.0	108.3	117.5	126.7	135.9	145.1	154.3	163.6
T8-5	75	15	60.0	75.4	90.7	106.1	121.4	136.8	152.2	167.5	182.9	198.2	213.6
T8-6	50	11	71.5	88.4	105.3	122.2	139.1	156.0	172.9	189.8	206.7	223.6	240.5
T8-7	75	16	64.0	80.4	96.8	113.2	129.5	145.9	162.3	178.7	195.1	211.5	227.8
T8-8	75	13	52.0	65.3	78.6	91.9	105.2	118.6	131.9	145.2	158.5	171.8	185.1
T8-9	100	19	57.0	71.6	86.2	100.8	115.4	130.0	144.6	159.1	173.7	188.3	202.9
T10-1	75	14	44.8	59.1	73.5	87.8	102.1	116.5	130.8	145.2	159.5	173.8	188.2
T10-2	25	7	88.2	109.7	131.2	152.7	174.2	195.7	217.2	238.7	260.2	281.7	303.2
T10-5-3	50	6	49.5	58.7	67.9	77.1	86.4	95.6	104.8	114.0	123.2	132.4	141.7
T10-5-4	25	3	61.2	70.4	79.6	88.8	98.1	107.3	116.5	125.7	134.9	144.1	153.4
T10-5-5	25	3	61.2	70.4	79.6	88.8	98.1	107.3	116.5	125.7	134.9	144.1	153.4
T10-5-6	15	3	93.5	108.9	124.2	139.6	154.9	170.3	185.7	201.0	216.4	231.7	247.1
T10-5-7	25	4	70.4	82.7	95.0	107.3	119.6	131.8	144.1	156.4	168.7	181.0	193.3
T10-5-8	25	10	130.0	160.7	191.4	222.2	252.9	283.6	314.3	345.0	375.8	406.5	437.2
T10-5-10	25	4	70.4	82.7	95.0	107.3	119.6	131.8	144.1	156.4	168.7	181.0	193.3
T10-3	50	9	70.2	84.0	97.8	111.7	125.5	139.3	153.1	167.0	180.8	194.6	208.4
T10-8	10	1	65.0	72.7	80.4	88.0	95.7	103.4	111.1	118.8	126.4	134.1	141.8
T10-7	15	4	106.7	127.1	147.6	168.1	188.6	209.1	229.5	250.0	270.5	291.0	311.5
T10-6	25	3	56.1	65.3	74.5	83.7	93.0	102.2	111.4	120.6	129.8	139.0	148.3
T10-5	15	3	93.5	108.9	124.2	139.6	154.9	170.3	185.7	201.0	216.4	231.7	247.1
T10-4	10	2	99.0	114.4	129.7	145.1	160.4	175.8	191.2	206.5	221.9	237.2	252.6
T10-9	37.5	10	86.7	107.1	127.6	148.1	168.6	189.1	209.5	230.0	250.5	271.0	291.5
T10-10	50	9	58.5	72.3	86.1	100.0	113.8	127.6	141.4	155.3	169.1	182.9	196.7
T10-24A-1	50	7	58.8	69.6	80.3	91.1	101.8	112.6	123.3	134.1	144.8	155.6	166.3
T10-24A-2	50	6	54.0	63.2	72.4	81.6	90.9	100.1	109.3	118.5	127.7	136.9	146.2
T10-24A-3	25	5	82.5	97.9	113.2	128.6	143.9	159.3	174.7	190.0	205.4	220.7	236.1
T10-24A-4	75	17	74.8	92.2	109.6	127.0	144.4	161.8	179.2	196.7	214.1	231.5	248.9
T10-24A-5	50	11	78.7	95.5	112.4	129.3	146.2	163.1	180.0	196.9	213.8	230.7	247.6
T10-24A-6	75	15	72.0	87.4	102.7	118.1	133.4	148.8	164.2	179.5	194.9	210.2	225.6
T10-24A-7	50	10	78.0	93.4	108.7	124.1	139.4	154.8	170.2	185.5	200.9	216.2	231.6
T10-24A-8	75	16	76.8	93.2	109.6	126.0	142.3	158.7	175.1	191.5	207.9	224.3	240.6
T10-24A-9	50	8	67.2	79.5	91.8	104.1	116.4	128.6	140.9	153.2	165.5	177.8	190.1

Table B-6: Level 2 On-Peak Service Transformer Loading

Level 2 Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T10-24A-10	50	11	85.8	102.7	119.6	136.5	153.4	170.3	187.2	204.1	221.0	237.9	254.8
T10-24A-11	75	12	57.6	69.9	82.2	94.5	106.8	119.0	131.3	143.6	155.9	168.2	180.5
T10-24B-1	50	7	53.9	64.7	75.4	86.2	96.9	107.7	118.4	129.2	139.9	150.7	161.4
T10-24B-2	75	14	61.6	75.9	90.3	104.6	118.9	133.3	147.6	162.0	176.3	190.6	205.0
T10-24B-3	25	6	81.0	99.4	117.9	136.3	154.7	173.2	191.6	210.0	228.5	246.9	265.3
T10-24B-4	25	5	90.0	105.4	120.7	136.1	151.4	166.8	182.2	197.5	212.9	228.2	243.6
T10-24B-6	37.5	4	51.2	59.4	67.6	75.8	84.0	92.2	100.4	108.5	116.7	124.9	133.1
T10-24B-8	75	10	52.0	62.2	72.5	82.7	93.0	103.2	113.4	123.7	133.9	144.2	154.4
T10-24B-7	25	4	70.4	82.7	95.0	107.3	119.6	131.8	144.1	156.4	168.7	181.0	193.3
T10-24B-9	25	6	90.0	108.4	126.9	145.3	163.7	182.2	200.6	219.0	237.5	255.9	274.3
T10-24B-10	37.5	8	82.1	98.5	114.9	131.3	147.7	164.1	180.4	196.8	213.2	229.6	246.0
T12-1	15	2	66.0	76.2	86.5	96.7	107.0	117.2	127.4	137.7	147.9	158.2	168.4
T12-2	25	5	82.5	97.9	113.2	128.6	143.9	159.3	174.7	190.0	205.4	220.7	236.1
T12-3	25	6	90.0	108.4	126.9	145.3	163.7	182.2	200.6	219.0	237.5	255.9	274.3
T12-4	37.5	8	82.1	98.5	114.9	131.3	147.7	164.1	180.4	196.8	213.2	229.6	246.0
T12-5	37.5	9	85.8	104.2	122.7	141.1	159.5	178.0	196.4	214.8	233.3	251.7	270.1
T12-6	5	1	90.0	105.4	120.7	136.1	151.4	166.8	182.2	197.5	212.9	228.2	243.6
T12-7	75	16	83.2	99.6	116.0	132.4	148.7	165.1	181.5	197.9	214.3	230.7	247.0
T12-8	50	12	86.4	104.8	123.3	141.7	160.1	178.6	197.0	215.4	233.9	252.3	270.7
T12-9	100	16	62.4	74.7	87.0	99.3	111.6	123.8	136.1	148.4	160.7	173.0	185.3
T12-16-1	25	5	75.0	90.4	105.7	121.1	136.4	151.8	167.2	182.5	197.9	213.2	228.6
T12-16-2	37.5	8	82.1	98.5	114.9	131.3	147.7	164.1	180.4	196.8	213.2	229.6	246.0
T12-16-3	37.5	5	60.0	70.2	80.5	90.7	101.0	111.2	121.4	131.7	141.9	152.2	162.4
T12-16-4	50	7	58.8	69.6	80.3	91.1	101.8	112.6	123.3	134.1	144.8	155.6	166.3

Table B-7: Level 1 Off-Peak Service Transformer Loading

Level 1 Off-Peak Transformer Loading													
Penetration Level:			0 %	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

No service transformers were overloaded during off-peak demand time from 0% to 100% PHEV loading.

Table B-8: Level 2 Off-Peak Service Transformer Loading

Level 2 Off-Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T2-2	75	14	24.6	39.0	53.3	67.6	82.0	96.3	110.7	125.0	139.3	153.7	168.0
T2-3	75	11	22.9	34.1	45.4	56.7	67.9	79.2	90.5	101.7	113.0	124.3	135.5
T2-4	75	19	36.5	55.9	75.4	94.8	114.3	133.8	153.2	172.7	192.1	211.6	231.0
T2-5	50	20	48.0	78.7	109.4	140.2	170.9	201.6	232.3	263.0	293.8	324.5	355.2
T3-5	50	14	37.0	58.5	80.0	101.5	123.0	144.5	166.0	187.5	209.0	230.5	252.0
T3-6	75	14	26.9	41.2	55.6	69.9	84.2	98.6	112.9	127.2	141.6	155.9	170.2
T3-7	75	14	26.9	41.2	55.6	69.9	84.2	98.6	112.9	127.2	141.6	155.9	170.2
T3-8	50	12	37.4	55.9	74.3	92.7	111.2	129.6	148.0	166.5	184.9	203.3	221.8
T3-24-2	75	14	24.6	39.0	53.3	67.6	82.0	96.3	110.7	125.0	139.3	153.7	168.0
T3-24-3	50	9	25.7	39.6	53.4	67.2	81.0	94.9	108.7	122.5	136.3	150.2	164.0
T3-24-5	75	13	22.9	36.2	49.5	62.8	76.1	89.4	102.8	116.1	129.4	142.7	156.0
T3-24-6	75	11	21.0	32.2	43.5	54.8	66.0	77.3	88.6	99.8	111.1	122.3	133.6
T3-24-7	75	13	22.9	36.2	49.5	62.8	76.1	89.4	102.8	116.1	129.4	142.7	156.0
T3-24-8	75	15	26.4	41.8	57.1	72.5	87.8	103.2	118.6	133.9	149.3	164.6	180.0
T3-24-9	75	14	24.6	39.0	53.3	67.6	82.0	96.3	110.7	125.0	139.3	153.7	168.0
T3-24-10	75	16	28.2	44.5	60.9	77.3	93.7	110.1	126.5	142.8	159.2	175.6	192.0
T 3-25B-1	50	10	31.2	46.6	61.9	77.3	92.6	108.0	123.4	138.7	154.1	169.4	184.8
T 3-25B-2	50	7	23.5	34.3	45.0	55.8	66.5	77.3	88.0	98.8	109.5	120.3	131.0
T 3-25B-3	50	8	26.9	39.2	51.5	63.7	76.0	88.3	100.6	112.9	125.2	137.5	149.8
T 3-25B-4	50	11	31.5	48.4	65.3	82.1	99.0	115.9	132.8	149.7	166.6	183.5	200.4
T3-25A-7	50	10	28.6	44.0	59.3	74.7	90.0	105.4	120.8	136.1	151.5	166.8	182.2
T3-25A-8	75	14	24.6	39.0	53.3	67.6	82.0	96.3	110.7	125.0	139.3	153.7	168.0
T3-25A-9	50	12	31.7	50.1	68.5	87.0	105.4	123.8	142.3	160.7	179.1	197.6	216.0
T3-25A-11	50	10	28.6	44.0	59.3	74.7	90.0	105.4	120.8	136.1	151.5	166.8	182.2
T3-25A-6	50	14	37.0	58.5	80.0	101.5	123.0	144.5	166.0	187.5	209.0	230.5	252.0
T3-25A-1	75	19	33.4	52.9	72.4	91.8	111.3	130.7	150.2	169.6	189.1	208.5	228.0
T3-25A-4	75	14	24.6	39.0	53.3	67.6	82.0	96.3	110.7	125.0	139.3	153.7	168.0
T3-25A-5	50	12	31.7	50.1	68.5	87.0	105.4	123.8	142.3	160.7	179.1	197.6	216.0
T3-25A-2	50	8	24.6	36.9	49.2	61.5	73.8	86.1	98.4	110.7	122.9	135.2	147.5
T3-25A-3	50	8	24.6	36.9	49.2	61.5	73.8	86.1	98.4	110.7	122.9	135.2	147.5
T4-7	25	9	42.1	69.8	97.4	125.1	152.7	180.4	208.0	235.7	263.3	291.0	318.6
T4-8	25	10	46.8	77.5	108.2	139.0	169.7	200.4	231.1	261.8	292.6	323.3	354.0
T4-9	50	12	31.7	50.1	68.5	87.0	105.4	123.8	142.3	160.7	179.1	197.6	216.0
T4-10	50	10	28.6	44.0	59.3	74.7	90.0	105.4	120.8	136.1	151.5	166.8	182.2
T4-11	75	15	28.8	44.2	59.5	74.9	90.2	105.6	121.0	136.3	151.7	167.0	182.4
T5-6-2	25	7	35.3	56.8	78.3	99.8	121.3	142.8	164.3	185.8	207.3	228.8	250.3
T5-6-3	25	6	32.4	50.8	69.3	87.7	106.1	124.6	143.0	161.4	179.9	198.3	216.7
T5-6-14-1	25	6	32.4	50.8	69.3	87.7	106.1	124.6	143.0	161.4	179.9	198.3	216.7
T5-6-14-2	37.5	9	28.1	46.5	64.9	83.4	101.8	120.2	138.7	157.1	175.5	194.0	212.4
T5-6-14-3	15	4	38.4	58.9	79.4	99.8	120.3	140.8	161.3	181.8	202.2	222.7	243.2

Table B-9: Level 2 Off-Peak Service Transformer Loading

Level 2 Off-Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T5-6-14-4	15	3	30.6	46.0	61.3	76.7	92.0	107.4	122.8	138.1	153.5	168.8	184.2
T5-6-14-5	25	4	23.0	35.3	47.6	59.9	72.2	84.5	96.8	109.1	121.3	133.6	145.9
T5-6-14-6	25	7	35.3	56.8	78.3	99.8	121.3	142.8	164.3	185.8	207.3	228.8	250.3
T5-6-14-7	25	8	35.8	60.4	85.0	109.6	134.1	158.7	183.3	207.9	232.4	257.0	281.6
T5-6-14-8	25	8	35.8	60.4	85.0	109.6	134.1	158.7	183.3	207.9	232.4	257.0	281.6
T5-6-6	25	12	46.1	82.9	119.8	156.7	193.5	230.4	267.3	304.1	341.0	377.9	414.7
T5-6-7	37.5	12	34.6	59.1	83.7	108.3	132.9	157.4	182.0	206.6	231.2	255.7	280.3
T5-6-8	25	11	45.8	79.6	113.3	147.1	180.9	214.7	248.5	282.3	316.1	349.9	383.7
T5-7A-1	75	11	19.1	30.3	41.6	52.9	64.1	75.4	86.7	97.9	109.2	120.4	131.7
T5-7A-2	37.5	11	38.1	60.7	83.2	105.7	128.2	150.8	173.3	195.8	218.4	240.9	263.4
T5-7A-3	37.5	11	38.1	60.7	83.2	105.7	128.2	150.8	173.3	195.8	218.4	240.9	263.4
T5-7A-4	50	9	25.7	39.6	53.4	67.2	81.0	94.9	108.7	122.5	136.3	150.2	164.0
T5-7B-1	75	14	26.9	41.2	55.6	69.9	84.2	98.6	112.9	127.2	141.6	155.9	170.2
T5-7B-2	50	16	42.2	66.8	91.4	116.0	140.5	165.1	189.7	214.3	238.8	263.4	288.0
T5-7B-3	50	9	28.1	41.9	55.7	69.6	83.4	97.2	111.0	124.8	138.7	152.5	166.3
T5-7B-4	75	21	40.3	61.8	83.3	104.8	126.3	147.8	169.3	190.8	212.4	233.9	255.4
T5-7B-5	75	14	26.9	41.2	55.6	69.9	84.2	98.6	112.9	127.2	141.6	155.9	170.2
T5-3	75	16	30.7	47.1	63.5	79.9	96.3	112.6	129.0	145.4	161.8	178.2	194.6
T5-4	75	16	30.7	47.1	63.5	79.9	96.3	112.6	129.0	145.4	161.8	178.2	194.6
T5-5	75	15	28.8	44.2	59.5	74.9	90.2	105.6	121.0	136.3	151.7	167.0	182.4
T5-6	75	17	32.6	50.0	67.5	84.9	102.3	119.7	137.1	154.5	171.9	189.3	206.7
T5-7	75	19	36.5	55.9	75.4	94.8	114.3	133.8	153.2	172.7	192.1	211.6	231.0
T5-21-1	75	13	22.9	36.2	49.5	62.8	76.1	89.4	102.8	116.1	129.4	142.7	156.0
T5-21-2	75	15	26.4	41.8	57.1	72.5	87.8	103.2	118.6	133.9	149.3	164.6	180.0
T5-21-4	75	12	21.1	33.4	45.7	58.0	70.3	82.6	94.8	107.1	119.4	131.7	144.0
T5-21-5	100	15	19.8	31.3	42.8	54.4	65.9	77.4	88.9	100.4	112.0	123.5	135.0
T5-21-6	50	9	25.7	39.6	53.4	67.2	81.0	94.9	108.7	122.5	136.3	150.2	164.0
T5-21-7	50	10	28.6	44.0	59.3	74.7	90.0	105.4	120.8	136.1	151.5	166.8	182.2
T6-1-1	50	7	27.4	38.2	48.9	59.7	70.4	81.2	92.0	102.7	113.5	124.2	135.0
T6-1-2	75	16	35.8	52.2	68.6	85.0	101.4	117.8	134.1	150.5	166.9	183.3	199.7
T6-1-3	75	17	35.4	52.8	70.2	87.6	105.0	122.4	139.8	157.2	174.6	192.0	209.4
T6-1-4	50	10	31.2	46.6	61.9	77.3	92.6	108.0	123.4	138.7	154.1	169.4	184.8
T6-1-5	75	15	31.2	46.6	61.9	77.3	92.6	108.0	123.4	138.7	154.1	169.4	184.8
T6-2-5	37.5	12	38.4	63.0	87.6	112.1	136.7	161.3	185.9	210.4	235.0	259.6	284.2
T6-2-11B-4	37.5	6	26.4	38.7	51.0	63.3	75.6	87.8	100.1	112.4	124.7	137.0	149.3
T6-2-11B-5	25	7	35.3	56.8	78.3	99.8	121.3	142.8	164.3	185.8	207.3	228.8	250.3
T6-2-11B-6	37.5	12	38.4	63.0	87.6	112.1	136.7	161.3	185.9	210.4	235.0	259.6	284.2
T6-2-11B-8	25	5	30.0	45.4	60.7	76.1	91.4	106.8	122.2	137.5	152.9	168.2	183.6
T6-2-11B-9	25	7	39.2	60.7	82.2	103.7	125.2	146.7	168.2	189.7	211.2	232.7	254.2
T6-2-11A-2	75	14	24.6	39.0	53.3	67.6	82.0	96.3	110.7	125.0	139.3	153.7	168.0

Table B-10: Level 2 Off-Peak Service Transformer Loading

Level 2 Off-Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T6-2-11A-5	50	10	28.6	44.0	59.3	74.7	90.0	105.4	120.8	136.1	151.5	166.8	182.2
T6-2-11A-6	75	11	21.0	32.2	43.5	54.8	66.0	77.3	88.6	99.8	111.1	122.3	133.6
T6-2-11A-3	75	13	22.9	36.2	49.5	62.8	76.1	89.4	102.8	116.1	129.4	142.7	156.0
T6-2-11A-4	25	6	32.4	50.8	69.3	87.7	106.1	124.6	143.0	161.4	179.9	198.3	216.7
T6-1	50	13	31.2	51.2	71.1	91.1	111.1	131.0	151.0	171.0	190.9	210.9	230.9
T6-4	50	7	23.5	34.3	45.0	55.8	66.5	77.3	88.0	98.8	109.5	120.3	131.0
T6-16B-1	25	5	33.0	48.4	63.7	79.1	94.4	109.8	125.2	140.5	155.9	171.2	186.6
T6-16B-5	25	4	28.2	40.4	52.7	65.0	77.3	89.6	101.9	114.2	126.5	138.8	151.0
T6-16B-2	25	4	28.2	40.4	52.7	65.0	77.3	89.6	101.9	114.2	126.5	138.8	151.0
T8-2	75	15	28.8	44.2	59.5	74.9	90.2	105.6	121.0	136.3	151.7	167.0	182.4
T8-3	50	12	34.6	53.0	71.4	89.9	108.3	126.7	145.2	163.6	182.0	200.4	218.9
T8-4	75	12	23.0	35.3	47.6	59.9	72.2	84.5	96.8	109.1	121.3	133.6	145.9
T8-12-1	50	8	26.9	39.2	51.5	63.7	76.0	88.3	100.6	112.9	125.2	137.5	149.8
T8-12-21-1	25	4	33.3	45.6	57.9	70.1	82.4	94.7	107.0	119.3	131.6	143.9	156.2
T8-12-21-3	15	2	31.2	41.4	51.7	61.9	72.2	82.4	92.6	102.9	113.1	123.4	133.6
T8-12-21-9	50	8	29.1	41.4	53.7	66.0	78.3	90.6	102.8	115.1	127.4	139.7	152.0
T8-12-21-10	25	4	30.7	43.0	55.3	67.6	79.9	92.2	104.4	116.7	129.0	141.3	153.6
T8-12-21-21-3	25	4	33.3	45.6	57.9	70.1	82.4	94.7	107.0	119.3	131.6	143.9	156.2
T8-12-21-21-4	15	2	38.4	48.6	58.9	69.1	79.4	89.6	99.8	110.1	120.3	130.6	140.8
T8-12-21-21-7	25	4	30.7	43.0	55.3	67.6	79.9	92.2	104.4	116.7	129.0	141.3	153.6
T8-12-21-21-10-2	25	4	35.8	48.1	60.4	72.7	85.0	97.3	109.6	121.9	134.1	146.4	158.7
T8-5	75	15	24.0	39.4	54.7	70.1	85.4	100.8	116.2	131.5	146.9	162.2	177.6
T8-6	50	11	28.6	45.5	62.4	79.3	96.2	113.1	130.0	146.9	163.8	180.7	197.6
T8-7	75	16	25.6	42.0	58.4	74.8	91.1	107.5	123.9	140.3	156.7	173.1	189.4
T8-8	75	13	20.8	34.1	47.4	60.7	74.0	87.4	100.7	114.0	127.3	140.6	153.9
T8-9	100	19	22.8	37.4	52.0	66.6	81.2	95.8	110.4	124.9	139.5	154.1	168.7
T10-1	75	14	17.9	32.3	46.6	60.9	75.3	89.6	103.9	118.3	132.6	146.9	161.3
T10-2	25	7	35.3	56.8	78.3	99.8	121.3	142.8	164.3	185.8	207.3	228.8	250.3
T10-5-6	15	3	37.4	52.8	68.1	83.5	98.8	114.2	129.6	144.9	160.3	175.6	191.0
T10-5-7	25	4	28.2	40.4	52.7	65.0	77.3	89.6	101.9	114.2	126.5	138.8	151.0
T10-5-8	25	10	52.0	82.7	113.4	144.2	174.9	205.6	236.3	267.0	297.8	328.5	359.2
T10-5-10	25	4	28.2	40.4	52.7	65.0	77.3	89.6	101.9	114.2	126.5	138.8	151.0
T10-3	50	9	28.1	41.9	55.7	69.6	83.4	97.2	111.0	124.8	138.7	152.5	166.3
T10-7	15	4	42.7	63.1	83.6	104.1	124.6	145.1	165.5	186.0	206.5	227.0	247.5
T10-5	15	3	37.4	52.8	68.1	83.5	98.8	114.2	129.6	144.9	160.3	175.6	191.0
T10-4	10	2	39.6	55.0	70.3	85.7	101.0	116.4	131.8	147.1	162.5	177.8	193.2
T10-9	37.5	10	34.7	55.1	75.6	96.1	116.6	137.1	157.5	178.0	198.5	219.0	239.5
T10-10	50	9	23.4	37.2	51.0	64.9	78.7	92.5	106.3	120.2	134.0	147.8	161.6
T10-24A-1	50	7	23.5	34.3	45.0	55.8	66.5	77.3	88.0	98.8	109.5	120.3	131.0
T10-24A-3	25	5	33.0	48.4	63.7	79.1	94.4	109.8	125.2	140.5	155.9	171.2	186.6

Table B-11: Level 2 Off-Peak Service Transformer Loading

Level 2 Off-Peak Transformer Loading													
Penetration Level:			0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Equip #	Rating (kVA)	# of Connected Customers	% Operating										
T10-24A-4	75	17	29.9	47.3	64.7	82.1	99.6	117.0	134.4	151.8	169.2	186.6	204.0
T10-24A-5	50	11	31.5	48.4	65.3	82.1	99.0	115.9	132.8	149.7	166.6	183.5	200.4
T10-24A-6	75	15	28.8	44.2	59.5	74.9	90.2	105.6	121.0	136.3	151.7	167.0	182.4
T10-24A-7	50	10	31.2	46.6	61.9	77.3	92.6	108.0	123.4	138.7	154.1	169.4	184.8
T10-24A-8	75	16	30.7	47.1	63.5	79.9	96.3	112.6	129.0	145.4	161.8	178.2	194.6
T10-24A-9	50	8	26.9	39.2	51.5	63.7	76.0	88.3	100.6	112.9	125.2	137.5	149.8
T10-24A-10	50	11	34.3	51.2	68.1	85.0	101.9	118.8	135.7	152.6	169.5	186.4	203.3
T10-24A-11	75	12	23.0	35.3	47.6	59.9	72.2	84.5	96.8	109.1	121.3	133.6	145.9
T10-24B-2	75	14	24.6	39.0	53.3	67.6	82.0	96.3	110.7	125.0	139.3	153.7	168.0
T10-24B-3	25	6	32.4	50.8	69.3	87.7	106.1	124.6	143.0	161.4	179.9	198.3	216.7
T10-24B-4	25	5	36.0	51.4	66.7	82.1	97.4	112.8	128.2	143.5	158.9	174.2	189.6
T10-24B-7	25	4	28.2	40.4	52.7	65.0	77.3	89.6	101.9	114.2	126.5	138.8	151.0
T10-24B-9	25	6	36.0	54.4	72.9	91.3	109.7	128.2	146.6	165.0	183.5	201.9	220.3
T10-24B-10	37.5	8	32.9	49.2	65.6	82.0	98.4	114.8	131.2	147.5	163.9	180.3	196.7
T12-2	25	5	33.0	48.4	63.7	79.1	94.4	109.8	125.2	140.5	155.9	171.2	186.6
T12-3	25	6	36.0	54.4	72.9	91.3	109.7	128.2	146.6	165.0	183.5	201.9	220.3
T12-4	37.5	8	32.9	49.2	65.6	82.0	98.4	114.8	131.2	147.5	163.9	180.3	196.7
T12-5	37.5	9	34.3	52.8	71.2	89.6	108.0	126.5	144.9	163.3	181.8	200.2	218.6
T12-6	5	1	36.0	51.4	66.7	82.1	97.4	112.8	128.2	143.5	158.9	174.2	189.6
T12-7	75	16	33.3	49.7	66.0	82.4	98.8	115.2	131.6	148.0	164.4	180.7	197.1
T12-8	50	12	34.6	53.0	71.4	89.9	108.3	126.7	145.2	163.6	182.0	200.4	218.9
T12-9	100	16	25.0	37.2	49.5	61.8	74.1	86.4	98.7	111.0	123.3	135.6	147.8
T12-16-1	25	5	30.0	45.4	60.7	76.1	91.4	106.8	122.2	137.5	152.9	168.2	183.6
T12-16-2	37.5	8	32.9	49.2	65.6	82.0	98.4	114.8	131.2	147.5	163.9	180.3	196.7
T12-16-4	50	7	23.5	34.3	45.0	55.8	66.5	77.3	88.0	98.8	109.5	120.3	131.0