

Effects of Large-Scale Penetration of Electric Vehicles on the
Distribution Network and Mitigation by Demand Side
Management

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Abstract

For the purpose of this study, data for low voltage distribution transformer loading in small communities in Maryland was collected from a local electric utility company. Specifically, analysis was done on three distribution transformers on their system. Each of these transformers serves at least one electric vehicle (EV) owner. Of the three transformers analyzed, Transformer 2 serves eight residential homes and has the highest risk of experiencing an overload if all customers purchase at least one EV. Transformer 2 has a nameplate rating of 25kVA (22.5kW assuming a 0.9 power factor).

With one EV owner, Transformer 2 has a peak load of 46.82kW during the study period between August 4 and August 17, 2013. When seven additional EVs of different types were added in a simulated scenario, the peak load for Transformer 2 increased from 46.82kW to 89.76kW, which is outside the transformer thermal limit. With the implementation of TOU pricing, the peak load was reduced to 56.71kW from 89.76kW. By implementing a combination of TOU pricing and appliance cycling through demand side management (DSM), the peak load was further reduced to 52.27kW.

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1 Introduction

1.1 Motivation for research

In 2011, the Electric Power Research Institute (EPRI) developed three scenarios to forecast the impacts of low, medium, and high projected rates of plug-in electric vehicle adoption between 2010 and 2030 [1]. The low scenario is patterned after electric vehicle sales performance between 2000 and 2008 and predicts total electric vehicle sales in the United States of 600,000 vehicles in 2015, 3.1 million by 2020, and slightly fewer than 15 million by 2030. The medium scenario is based on electric vehicle sales combined with announced manufacturer plans for more models and increased production volume. The medium scenario projects 1.2 million electric vehicles by 2015, 5.8 million by 2020, and nearly 35 million by 2030. The high scenario is an optimistic view of electric vehicle adoption and forecasts 2.4 million electric vehicles by 2015, 12 million by 2020, and over 65 million by 2030 [1]. In addition, the Obama Administration stated a goal of 1,000,000 plug-in hybrid electric vehicles in the United States by 2015 [2]. It is not clear whether or not this goal or projections will be met. However, as the penetration of plug-in hybrid electric vehicles (PHEVs) and plug-in electric vehicles (EVs) continues to increase, it is best to study the impact of a projected influx of a significant number of EVs on the electric grid.

An EV is a vehicle which utilizes rechargeable batteries, or another energy storage device, which can be restored to full charge using electricity [2]. A PHEV combines a conventional propulsion system with an electric propulsion system [2]. Therefore, a PHEV has a significantly longer driving range than that of a solely battery-powered electric vehicle. The use of EVs and PHEVs has many benefits, with the most important being the reduction of air

pollution synonymous with the use of gasoline-powered vehicles. EVs will result in even less greenhouse gas emissions than gasoline-powered vehicles if the electricity used to charge them is from a renewable source such as wind or solar. In a comprehensive environmental assessment of electric transportation, the Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC) examined the greenhouse gas emissions and air quality impacts of plug-in hybrid electric vehicles (PHEV). EPRI and NRDC researchers concluded that PHEVs recharged by electricity produced by efficient combustion, non-emitting, or renewable generation technologies will emit significantly lower fuel-cycle greenhouse gas emissions than either conventional or hybrid vehicles [3]. Global warming is a serious environmental concern and the United States among other countries seeks to reduce greenhouse gas emissions. Over the past 100 years, the average global temperature has increased by 0.7 degrees Celsius and the concentration of greenhouse gases (GHG) in the atmosphere has exceeded the pre-industrial level [4]. Global carbon emissions from fossil fuels have significantly increased since 1900. Emissions increased by over 16 times between 1900 and 2008 and by about 1.5 times between 1990 and 2008 [5].

Existing technical solutions to the present energy system include higher efficiency, increased reliance on renewable sources, deployment of new energy technologies such as the use of EVs, and policies to accelerate the adoption of new technologies [6]. The main limitation of EVs is the chemical battery technology which currently has limited range. Also, battery recharge could take several hours compared to gasoline refueling which takes a few minutes. Large-scale penetration of electric vehicles would require increasing the performance of car batteries, as well as great changes in infrastructure of the power distribution system, automobile industry, and in the power generation industry [6].

There have been studies done to understand the impact of EVs on existing electric generation facilities. As of 2008, the transportation industry was using the second highest amount of energy of all other sectors in the world at 27.3% as shown in Table 1 below [6]. With the transportation industry consuming so much energy compared to other sectors, electric generation facilities may need to be expanded to support a higher EV penetration.

Table 1: 2008 World Energy Use per Sector. Source: J. Goldemberg, *Energy, What Everyone Needs to Know*, New York: Oxford University Press, Inc., 2012. Used under fair use, 2014

Sector	Million toe	%
Industry	2,435	28.8
Transport	2,299	27.3
Residential	2,024	24.0
Commercial and public services	0.693	8.2
Other (agriculture, forestry, etc.)	0.323	3.8
Non-energy use	0.747	8.9
Total	8.428	100.0

Another important part of the electric grid to study is the distribution network. With more customers charging EVs in their homes, there is a risk of overloading low voltage distribution transformers if proper demand side management or strategic distribution planning is not implemented. More attention needs to be paid to the distribution network’s ability to support EVs, especially in states where the government is taking steps to encourage a higher EV penetration rate. In the State of Maryland for example, legislators have set in motion financial investments, tax incentives and Public Service Commission (PSC) directives to encourage and accommodate electric vehicle market expansion in the state [7].

Since 2011, Maryland legislators have passed several bills into law to encourage EV expansion in the state. Maryland Senate Bill 176 established a Maryland (MD) Electric Vehicle Infrastructure Council representing a broad spectrum of EV stakeholders. Among

other goals, the mission of the Council is to "develop an action plan to facilitate the rapid and seamless integration of electric vehicles into the State's transportation network" [7].

MD Senate Bill 179 requires the PSC to establish a pilot program for electric customers to recharge electric vehicles during off-peak hours, with a commencement date on or before June 30, 2013. In addition the bill requires the program to include certain incentives for the residential customers to increase the efficiency and reliability of the electric distribution system and to lower electricity use at times of high demand. One of the incentives cited by the bill is "Time-of-Day Pricing of Electricity" [7].

In addition, the Maryland Energy Administration has allocated \$600,000 in American Recovery and Reinvestment Act funds to help in the development and integration of electric transportation by investing in 65 electric charging stations throughout the Baltimore-Washington DC Metropolitan Area [7].

Based on these incentives put in place by the Maryland State legislators, it is obvious that the State's government is intent on having a robust EV market. Therefore, it is important to study the potential impacts of this robust EV market on the electric power distribution network of the state.

1.2 Objective

This research will analyze the potential effects of a large-scale penetration of EVs on the Maryland electric power distribution system by modeling and analyzing the low voltage distribution transformer load profiles of sample communities in Maryland. The worst case peak forecasts of the transformers due to a higher EV penetration will be analyzed. The effects of implementing efficient price incentives for EV customers to plug in during non-congested distribution periods will also be analyzed.

2 Literature Review

2.1 Related Research

As mentioned previously, there have been studies done to understand the impact of EVs on existing electric generation facilities. Authors in [8] conclude that most U.S. regions would need to build additional generation capacity to meet the added electric demand when EVs are charged during the evening peak hours. This is because most vehicle users will most likely charge their vehicles when convenient, as opposed to waiting for power grid off-peak periods.

In recent years, more studies have also been done to understand the impact of EVs on the electric distribution network. Authors in [9] point out that there is a high possibility of spatially variable EV penetration in residential areas. The EV penetration rate pattern is expected to vary with household demographic and socioeconomic attributes such as income, travel distance, age, household size, and education [9]. EV penetration is likely to be initiated in urban environments [10]. The typical concept of EV includes urban driving only, where the full battery charge is sufficient for medium-range routes of 50–100 miles [11]. However, PHEVs can be used in rural and mixed communities.

Due to these patterns, there may be specific points along some electric distribution lines that face congestion because of EV recharging and the electric grid substations will be more sensitive to the usage patterns of a few customers. Hence in a region, the overall electric generation and grid capacity may be under-utilized. However, if too many consumers on a given circuit or low voltage distribution transformer recharge their plug-in vehicles simultaneously, it could increase peak electric demand locally causing system disruptions and require upgrading of the electric distribution infrastructure [9].

According to [9], while the national impact is shown to be manageable, local distribution network analysis is required in order to investigate the impact of localized concentrations of EVs. Authors in [10] agree that voltage fluctuation is one of the possible implications which may arise with the addition of EVs in distribution networks. Authors in [12], [13], [14], and [15] further analyze the impacts of EV charging on the distribution grid in terms of power losses and voltage deviations, and evaluate demand response with customer choice. An algorithm for intelligent home energy management and demand response analysis is discussed by the authors in [16].

In this study, actual customer use data from a local utility in Maryland is used to analyze the impacts of EV penetration on the electric distribution system in the state, especially the impact on low voltage distribution transformers and distribution cable. By addressing the significance of the impact of a high penetration of EVs on Maryland's distribution system, this study could provide a foundation for the identification of future planning needs and electricity rate structure in the state. The concept of using EV batteries as a power source to feed power back into the electric grid during emergency periods was not studied as part of this research.

2.2 Apparent Technical Issues

2.2.1 Operating Issues

When charging electric vehicles in residential homes, these act as loads on the electric distribution network. A number of operating issues could arise including the following:

- i. **Voltage Drop:** When charging electric vehicles, the voltage profile of the distribution network will be affected [10]. Voltage drop is the difference of voltage between two points. A voltage drop occurs due to the impedance of a conductor and the flow of current across the conductor.

Allowable voltage variations at the customer’s meter are established by the American National Standards Institute (ANSI) standards and by Public Service Commission (PSC) regulations. For example, the voltage limits for 120V secondary distribution circuits in Maryland is $\pm 5\%$ of the nominal single phase voltage of 120 V. Table 2 below summarizes the allowable voltage limits for each standard distribution voltage found in the State of Maryland:

Table 2: Maryland Distribution Voltage Limits. Source: COMAR 20.50.07.02 Voltage Limits, Maryland Public Service Commission [Online]. Available: <http://www.dsd.state.md.us/comar/comar.aspx>. [Accessed January 10, 2014]. Used under fair use, 2014

Standard Voltage (V)	Minimum Voltage (V)	Maximum Voltage (V)
120	114	126
120/208	114/197	126/219
120/240	114/228	126/252
208	197	219
240	216	252
240/416	228/395	252/437
240/480	228/456	252/504
265/460	238/414	278/483
277/480	249/432	291/504
440	396	462
460	414	483
480	432	504
600	540	630

While charging EVs, the load increase on the network may cause a voltage drop. In a circuit with constant resistance, the voltage drop is proportional to the current flowing in the circuit. See Equation 1, Equation 2 and Equation 3.

Equation 1: Voltage Equation [17]

$$V = I \times R$$

Where:

V = Voltage measured in volts

I = Current flowing in circuit measured in amperes

R = Resistance of circuit measured in ohms

Equation 2: Single Phase Voltage Drop Calculation [18]

$$\text{Voltage Drop} = 2 \times D \times I \times R$$

$$\text{Percent Voltage Drop} = \frac{\text{Voltage Drop}}{\text{Source Voltage}} \times 100\%$$

Equation 3: Three Phase Voltage Drop Calculation [18]

$$\text{Voltage Drop} = \sqrt{3} \times D \times I \times R$$

$$\text{Percent Voltage Drop} = \frac{\text{Voltage Drop}}{\text{Source Voltage}} \times 100\%$$

Where:

D = One way length of the power line in feet

R = Resistance factor in ohms/feet

I = Load current in amperes

Note that in a single-phase system, the voltage between line conductors is 2 times the phase conductor to neutral voltage [19]. In a three-phase system, the voltage between line conductors is $\sqrt{3}$ times the phase conductor to neutral voltage [20]. Source voltage refers to the voltage of the branch circuit at the source of power. Typical distribution source voltages found in the State Maryland are seen in column 1 of Table 2 above.

For example, the voltage drop in a 100-foot single phase power line of #10 copper conductors supplied from a 120 V source, with 1.2 ohms per 1000-foot electrical resistance, and a current of 10 amperes can be calculated as follows:

$$\text{Voltage Drop} = \frac{2 \times 100 \text{ ft} \times 1.2 \Omega \times 10 \text{ A}}{1,000 \text{ ft}} = 2.4 \text{ V}$$

$$\text{Percent Voltage Drop} = \frac{2.4 \text{ V}}{120 \text{ V}} \times 100\% = 2\%$$

If an electric vehicle is added to this circuit, the percent voltage drop would increase due to an increase in resistance.

- ii. **Distribution Transformer Thermal Limits:** A transformer is a voltage changing device composed of a primary and secondary winding and interlinked by a magnetic core [21]. The core material is often a laminated iron core [22]. The coil that receives the electrical input energy is called the primary winding, while the output coil is the secondary winding. An alternating electric current flowing through the primary winding of a transformer generates an electromagnetic field in its surroundings and a varying magnetic flux in the core of the transformer [22]. This magnetic flux generates a varying electromotive force in the secondary winding by electromagnetic induction, resulting in a voltage across the output terminals [22]. If a load is connected across the secondary winding, a current flows through the secondary winding drawing power from the primary winding and the transformer's power source [22].

Using Faraday's induction law, the voltage induced across the secondary coil may be calculated as follows:

Equation 4: Faraday's Induction Law for Transformer Secondary Winding [22]

$$V_s = E_s = N_s \frac{d\Phi}{dt}$$

Where:

V_s = the instantaneous voltage

N_s = the number of turns in the secondary coil

$\frac{d\Phi}{dt}$ = the derivative of the magnetic flux through one turn of the coil

Since the same magnetic force passes through both the primary and secondary coils in an ideal transformer, the instantaneous voltage across the primary windings can also be calculated as follows:

Equation 5: Faraday's Induction Law for Transformer Primary Winding [22]

$$V_P = E_P = N_P \frac{d\Phi}{dt}$$

Using Equation 4 and Equation 5, the ratio of electromagnetic force induced across each winding can be derived:

$$\frac{V_P}{V_S} = \frac{E_P}{E_S} = \frac{N_P}{N_S}$$

In addition to the electromagnetic induction process, a load serving transformer also goes through a thermal process driven by heat [21]. This heat is generated by no-load and load losses.

- a) **Load Losses:** Load losses in a transformer are due to the electric resistance of the windings and stray losses. The magnitude of energy lost from the resistive action of the winding conductor to the flow of electric current is derived by the formula I^2R , and is considered the main source of heat generation in a transformer [21]. Stray losses occur due to the winding leakage field and due to high currents of the internal structural parts of the transformer [21].
- b) **No-load Losses:** When an energized transformer has no loads connected to it, it behaves similar to a highly inductive element. The alternating excitation current is drawn from the system, producing an alternating mutual flux in the primary winding of the transformer [21].

Induced voltage produced by the alternating flux results in undesirable currents within the transformer laminations called eddy currents [21]. The energy from eddy currents is lost. The alternating magnetization of the transformer core also causes the iron core molecules to align with the changing field. The energy lost from successive reversal of magnetization in the transformer core is called hysteresis loss [21].

Heat produced by transformer losses can negatively impact the life span of the transformer insulation. To absorb heat from the transformer windings, core, and structural parts, oil is used as the cooling and insulating medium. In low voltage distribution transformers, the tank surface is used to dissipate heat to the atmosphere. This is done by the natural circulation of the oil through the windings, which is externally cooled by natural air [21]. This method of transformer cooling is known as the Oil Natural Air Natural (ONAN) cooling method [23].

The IEEE Standard C57.91-1995 states that under a continuous ambient temperature of 30°C, the maximum hottest-spot winding temperature should not exceed 110°C [24]. If the hottest-spot temperature is allowed to go beyond 110°C, the transformer insulation will deteriorate at a faster than normal rate. Per IEEE C57.91-1995, experimental evidence indicates that the aging of insulation is part of a chemical process, which is impacted by temperature as shown in an adaptation of the Arrhenius reaction rate theory below [25].

Equation 6: Transformer Insulation Calculated Life [25]

$$\text{Per Unit Life} = A.e^{\left(\frac{B}{\Theta H + 273}\right)}$$

Where

- ΘH is the winding hottest-spot temperature, °C
- A is a constant
- B is a constant
- E is the base of the natural logarithm

The use of this equation focuses on temperature as the principal variable affecting transformer thermal life. The IEEE C57.91-1995 Standard translates this equation on a per unit life basis as shown in the revised equation and curve below.

Equation 7: Transformer Insulation Calculated Life, with constants [25]

$$\text{Per Unit Life} = 9.8 \times 10^{-18} \cdot e^{\left(\frac{15,000}{\Theta H + 273}\right)}$$

Where

ΘH is the winding hottest-spot temperature, °C

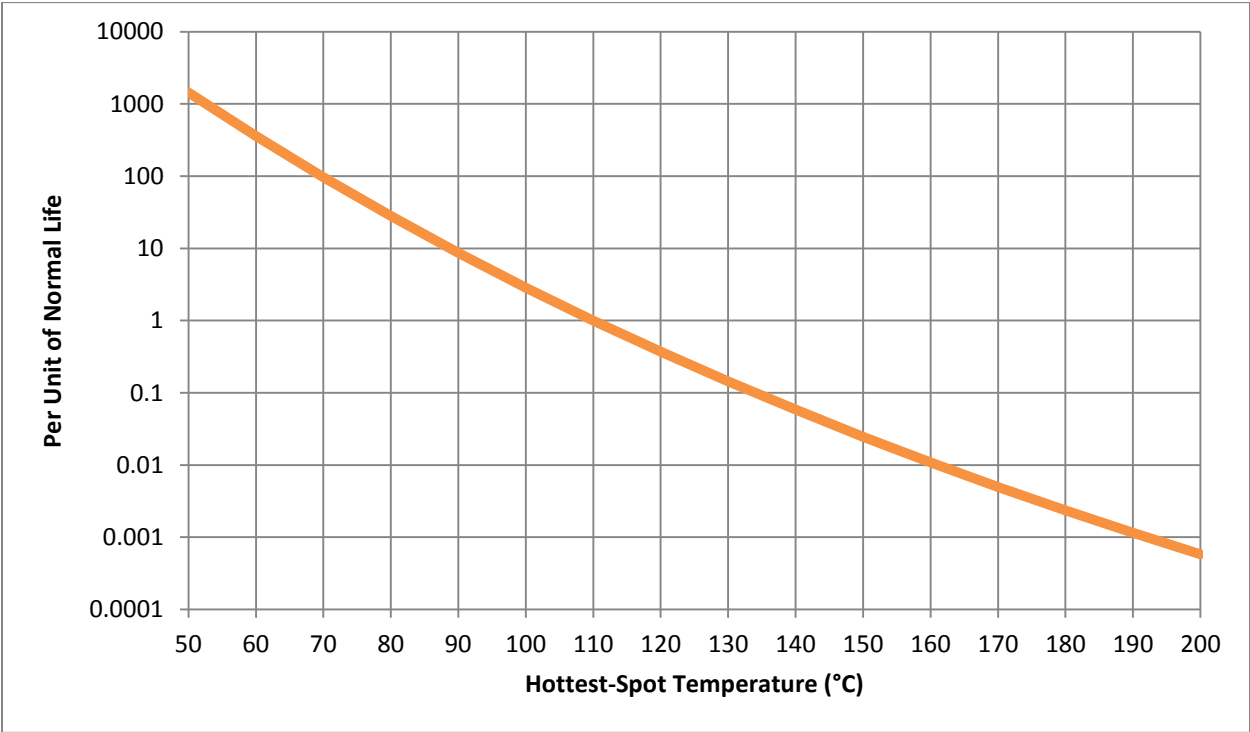


Figure 1: Transformer Insulation Life

According to the curve in Figure 1, the rate of aging is accelerated beyond normal for winding hottest-spot temperatures above a reference temperature of 110 °C (or 230°F) and is reduced below normal for winding hottest-spot temperatures below 110°C (or 230°F).

The permissible loading of transformers for normal life expectancy depends on the design of the particular transformer, its temperature rise at the rated load, temperature of the cooling medium, duration of the overloads, the load factor, and the altitude above sea level if air is used as the cooling medium [26]. The dielectric strength of transformers that depend in whole or in part upon air for insulation decreases as the altitude increases due to the effect of decreased air density [27]. Transformers are designed and rated by manufacturers on the basis of 55°C or 65°C rise above the ambient temperature as determined by average winding [26]. In actual operation, the hottest-spot temperature should be used as the loading limitation rather than the average winding temperature rise [26]. Transformers may be operated continuously at hottest-spot temperatures up to 95°C for 55°C rated transformers, or 110°C for 65°C rated transformers [26].

According to authors in [26], for normal life expectancy and at a daily average ambient temperature of 30°C, the permissible load on a transformer should be 100% of its rated nameplate kVA for a self-cooled transformer. Based on calculations, authors in [26] also believe that using the maximum permissible top-oil temperature as a guide, a self-cooled transformer should not exceed 200% of its rated nameplate kVA depending on the temperature of the top-oil.

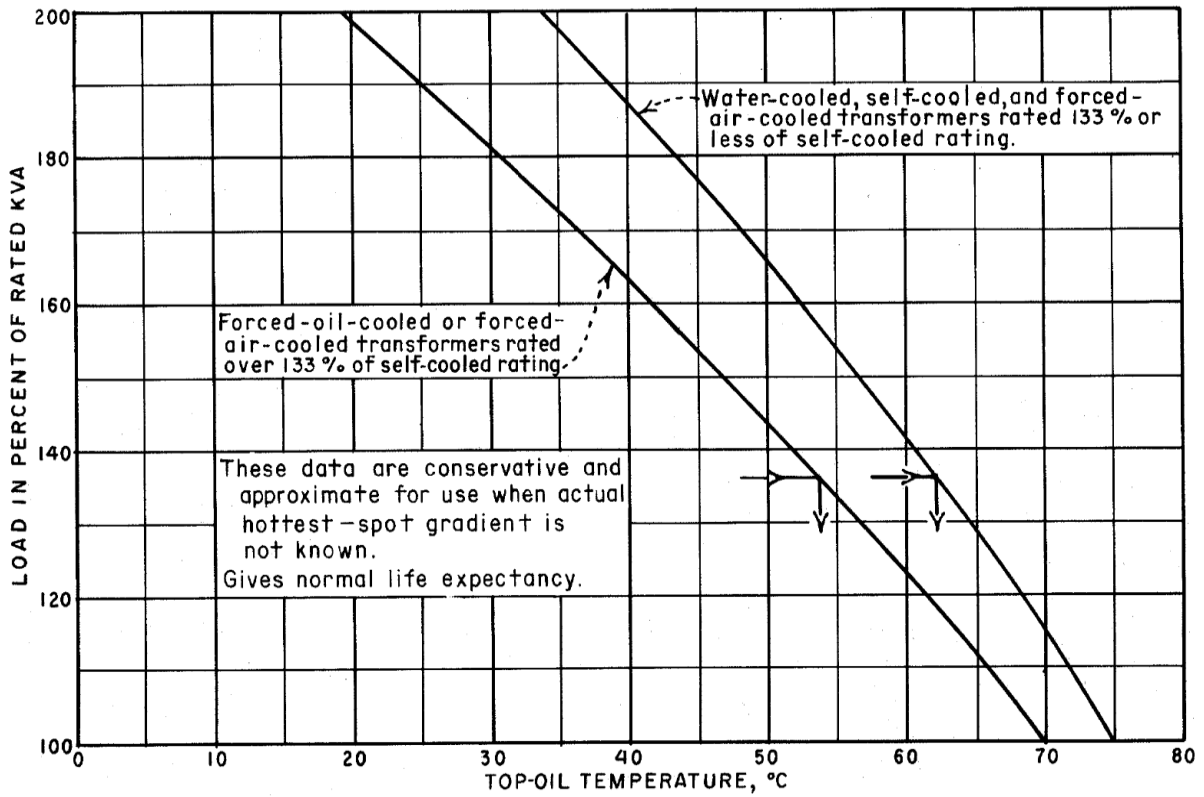


Figure 2: Maximum permissible top-oil temperature for overload conditions for transformers with 55°C average winding rise
 Source: "Permissible Loading of Oil-Immersed Transformers and Regulators," Facilities Engineering Branch, United States Department of the Interior Bureau of Reclamation, Denver, 2000. Used under fair use, 2014

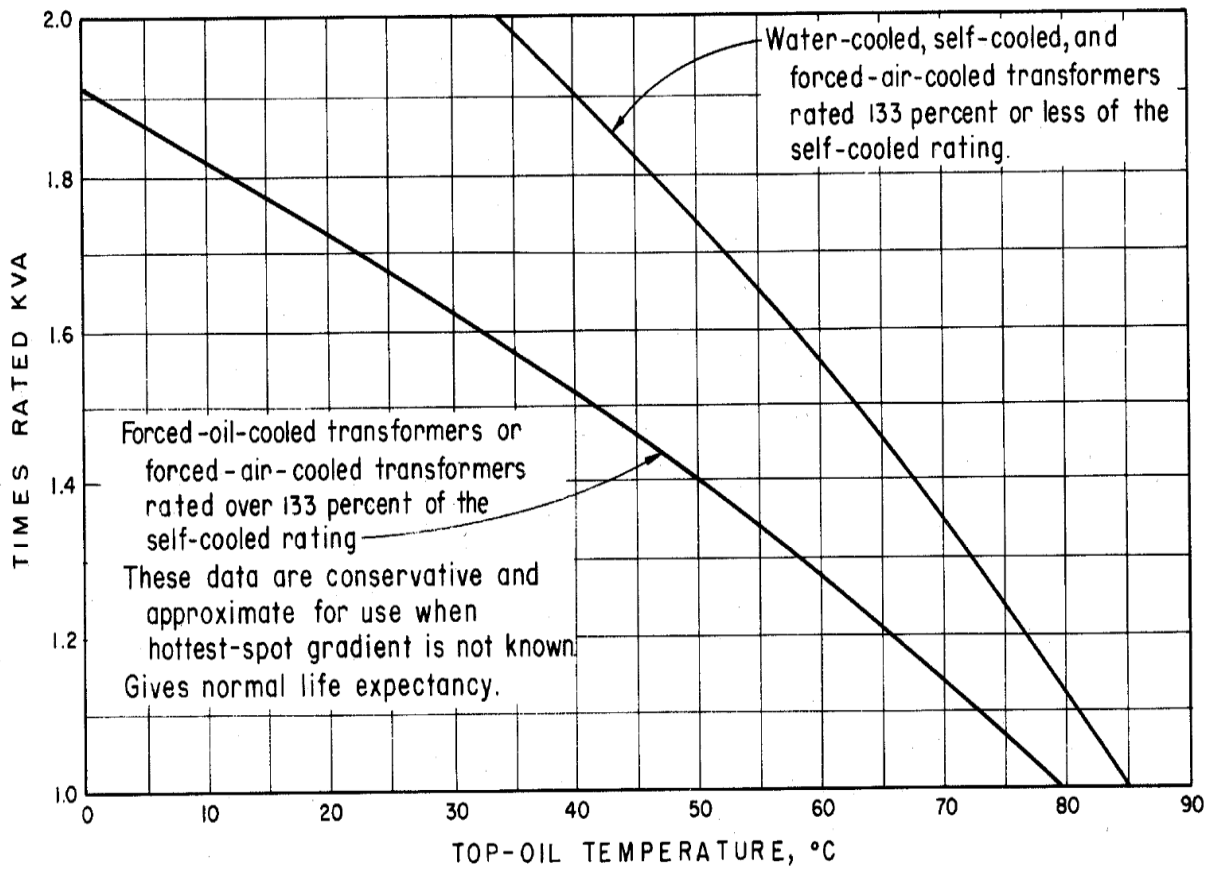


Figure 3: Maximum permissible top-oil temperature for overload conditions for transformers with 65°C average winding rise. Source: "Permissible Loading of Oil-Immersed Transformers and Regulators," Facilities Engineering Branch, United States Department of the Interior Bureau of Reclamation, Denver, 2000. Used under fair use, 2014

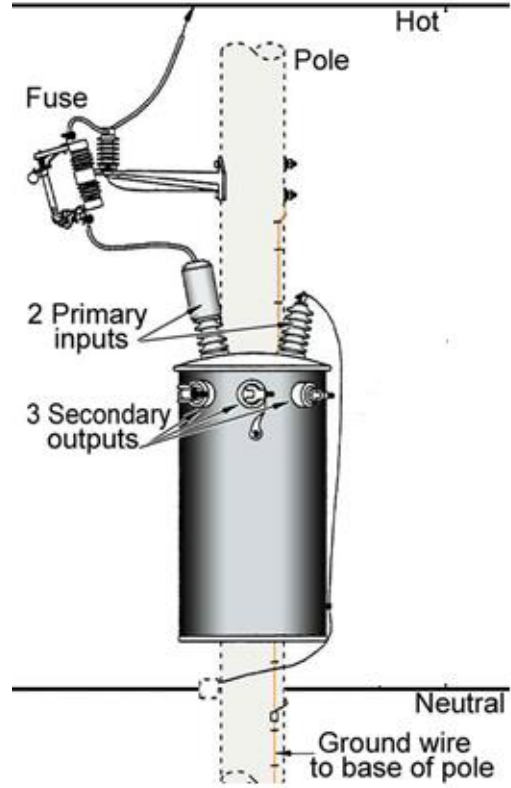
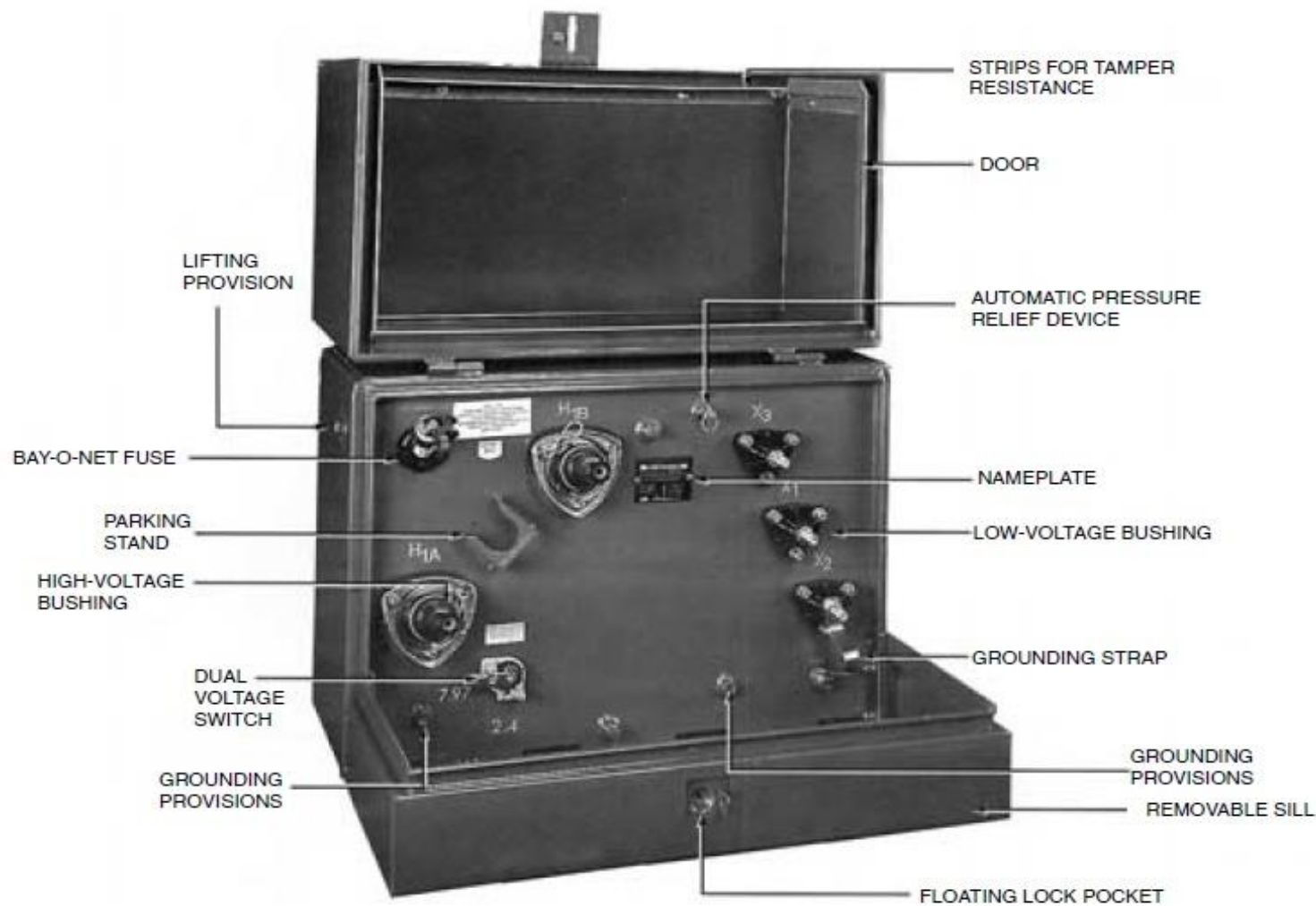


Figure 4: Single-Phase Pole-mount Distribution Transformer. Sources: "Transformers," [Online]. Available: <http://en.wikipedia.org/wiki/Transformer>. [Accessed 19 February 2014]. "Inside an electric distribution transformer," [Online]. Available: <http://waterheatertimer.org/See-inside-main-breaker-box.html>. [Accessed 9 April 2014]. Used under fair use, 2014



Figure 5: Single-Phase Pad-mount Distribution Transformer. Source: "Central Moloney Inc. - Transformers," [Online]. Available: http://www.centramoloneyinc.com/transformers/single_phase_pad_mount.aspx. [Accessed 9 April 2014]. Used under fair use, 2014



Single-phase pad-mounted distribution transformer. *Courtesy Cooper Power Systems*

Figure 6: Parts of a single-phase pad-mount distribution transformer. Source: "Single-Phase Pad-mount Distribution Transformer," Cooper Power Systems, 2005. Used under fair use, 2014

As opposed to a pole-mounted transformer pictured in Figure 4, a pad-mount transformer, pictured in Figure 5, is mounted on the ground and supplies underground residential customers. Unlike a single-phase pole-mounted transformer which has an external fuse, a single phase pad-mounted transformer comes with a standard Bayonet fuse. The current sensing Bayonet fuse link is used to protect the distribution pad-mount transformers from damaging currents and failed apparatus.

The distribution transformers used in this study are self-cooled pad-mount transformers with name-plate ratings of 25kVA and 50 kVA. Load limits for these transformers range from 173% to 183% of the name-plate rating. The 173% load limit for a self-cooled 25kVA transformer is based on a 65°C average winding rise and a maximum permissible top oil temperature of about 50°C (or 122°F) [26]. 173% of 25kVA is 43.25kVA, or 38.93kW. See Equation 8. In this study, a 0.9 power factor is assumed for all calculations.

Equation 8

$$P = S \times P.F.$$

$$P = 43.25kVA \times 0.9 = 38.93kW$$

Where

P = Real Power in Kilowatts (kW)

S = Apparent Power in Kilovolt-amps (kVA)

$P.F.$ = Power Factor

The 183% load limit for a self-cooled 50kVA transformer is based on a 65°C average winding rise and a maximum permissible top oil temperature of about 45°C (or 113°F) [26]. The load limits for the transformers are also based on loading and utilization curves that pre-date the adoption of EVs. When these loading limits are exceeded, the transformer insulation will

deteriorate at a faster rate and the normal life of the transformer is reduced.

- iii. **Distribution Feeder Thermal Limits:** A large penetration of EVs will cause a load increase on the distribution network. Larger amounts of current will need to be fed through the distribution substations and cables, and this may result in cable overloads. In a properly designed system, this only applies in extreme operating conditions of maximum load and maximum EV penetration

2.2.2 Planning Implications

Distribution planners will have to take into consideration these operating issues while developing both short- and long-term system development plans. Close monitoring of peak load forecasts, line and equipment capabilities is required to avoid overloading facilities.

Based on operating data and the loading of distribution transformers and feeders during peak and off-peak periods, distribution transformer and feeder upgrades may need to be considered. However, before implementing these upgrades, the advantages of time-of-use (TOU) pricing and other forms of demand side management may help offset these operating issues and planners would also have to consider this strategy. Justifications for demand side management include avoiding transformer damage and loss of power to customers which may take a long time to restore.

2.3 Residential Electric Distribution Network

The alternating current (AC) electric system in the United States (U.S.) consists mainly of the electric generation system, transmission system, and the distribution system as shown in Figure 7 below.

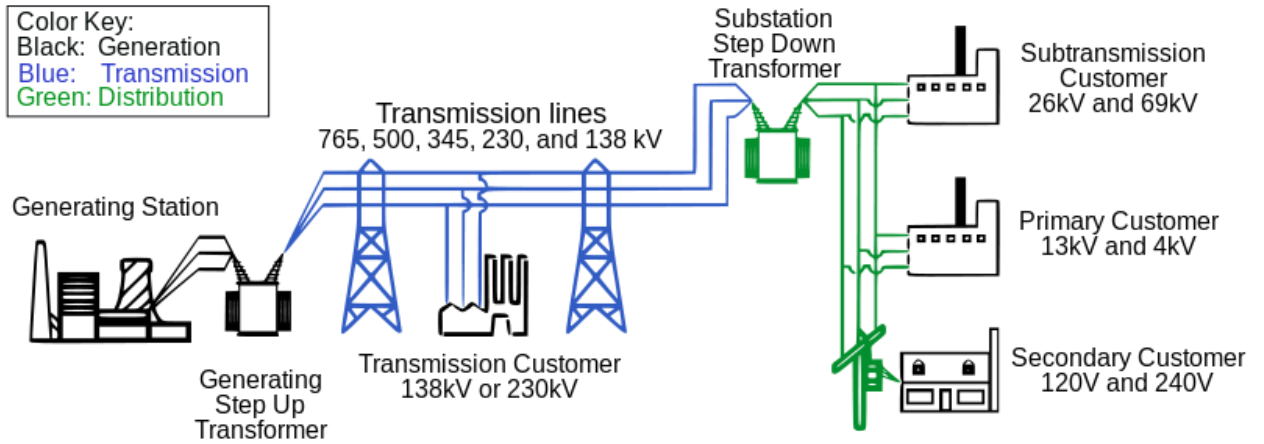


Figure 7: Simplified Diagram of a U.S. AC Electric System. Source: "Final Report on the August 14, 2003 Blackout in the United States and Canada," United States Department of Energy, 2004. Used under fair use, 2014

Although a range of voltage classes can be found in the U.S. as shown in Figure 7, not all voltage classes are found in all states. In the State of Maryland, the distribution voltage classes utilized are summarized in Table 2.



Figure 8: Block Diagram of the Electric Power System

The electric facilities that connect the transmission system to the customer's equipment are collectively called the distribution system. An electric distribution system normally consists of a distribution substation, distribution feeder circuits, switches, protective equipment, primary circuits, distribution transformers, secondary circuits, and services [17]. A distribution planning engineer is tasked with conducting studies and developing plans for the modification of the distribution system to continually ensure electric customers have adequate, safe, and reliable electric service at the lowest possible costs.

In most sections of the Maryland electric distribution network, the 34.5kV sub-transmission circuits leaving the distribution master substations serve as the source to the 13.2 kV primary circuits. The sub-transmission circuits transmit power from the master substations to distribution substations. The 13.2 kV distribution feeders in Maryland are 4-wire multi-grounded wye connected circuits that distribute power to end-use customers. A typical feeder supplies hundreds of distribution step-down transformers that provide secondary voltage to residential, commercial and industrial customers. The 4-wire multi-grounded wye connected system means that the circuit consists of three high voltage phase wires A, B, and C, and a common neutral that is connected to ground at multiple points. The phase-to-neutral voltage is 7.62 kV, and the phase-to-phase voltage is 13.2 kV.

The function of the low voltage distribution transformer is to step-down the voltage of the primary circuits to the utilization secondary voltage required to supply customers.

2.4 Demand Side Management

Demand response is typically any reactive or preventive method used to reduce, flatten, or shift peak demand [28], and these actions are normally taken at the customer side of the electric meter. To participate in these initiatives or programs, customers are normally offered savings incentives. This paper will focus on Time-of-Use (TOU) Pricing and appliance cycling as forms of demand side management (DSM). Appliance cycling simply refers to the cycling of customer appliances during peak or emergency periods. For example, customers could voluntarily sign up for air-conditioner or home heater cycling during peak or emergency periods. The idea, as it

relates to the charging of EVs, would be to educate customers on not using home heaters or air conditioners while charging EVs, or on reducing their use during this period. Alternatively, there could be an automatic setting to switch off the heating system or air conditioning unit in the home once an EV starts to charge.

Time-Of-Use (TOU) pricing, as regards to electricity usage, is essentially charging customers more or less for electricity depending on the time of day. Utilities that implement TOU pricing will typically charge customers more for electricity during the peak electricity usage periods determined by the utility planners, and less for electricity during off-peak hours of the day [7]. Although time-of-use (TOU) electricity pricing is generally seen as an effective way to provide an economic incentive for EV drivers to charge their vehicles during off-peak hours, thereby minimizing the cost of electricity and reducing stress on the grid, there is no guarantee that EV owners will strictly not charge their vehicles during peak hours. Some consumer research indicates that consumers are generally receptive to the idea of off-peak charging given a reasonable economic incentive [29]. However, one has to consider that electricity is so much less expensive than gasoline in most areas of the U.S., and that EV drivers may still choose to charge at peak electricity rates to ensure their vehicle is sufficiently charged [29].

2.4.1 Time-Of-Use Pricing in Maryland

Based on information from the Maryland Public Service Commission [30], electric utilities in Maryland include Baltimore Gas and Electric (BGE), Choptank, Delmarva, Pepco, Potomac Edison, and SMECO amongst others. Of the electric utility companies in Maryland, at least one utility has an optional time-of-use pricing program available to residential customers.

BGE's Time-of-Use Pricing Program

Time of Use Pricing (TOU) is a program provided by BGE in which the supply portion of a customer's electric bill will vary based on the time of day the energy is consumed [31].

Electricity supply rates vary based on the time of day or night, day of the week, and season of the year electricity is used. TOU prices include generation and transmission charges, but do not include a delivery service charge which is constant. Under BGE's program, there are three different periods as follows:

- **On-Peak:** This is when electricity is most expensive. In the summer, the on-peak period is weekdays from 10 a.m. to 8 p.m. In the winter, the on-peak period is weekdays from 7 a.m. to 11 a.m. and 5 p.m. to 9 p.m. [31].
- **Intermediate Peak:** During this period, electricity is less expensive than during the on-peak hours. In the summer, the intermediate-peak period is weekdays from 7 a.m. to 10 a.m. and 8 p.m. to 11 p.m. In the winter, the intermediate-peak period is weekdays from 11 a.m. to 5 p.m. [31].
- **Off-Peak:** This is when electricity is least expensive. In the summer, the off-peak period is weekdays from 11 p.m. to 7 a.m. In the winter, the off-peak period is weekdays from 9 p.m. to 7 a.m. Saturdays, Sundays, and designated major holidays (New Year's Day, President's Day, Good Friday, Memorial Day, Independence Day, Labor Day, Thanksgiving, Christmas and Mondays following any of those holidays that fall on a Sunday) are always considered off-peak periods [31].

BGE's TOU program is optional to all residential customers, and all commercial customers who have a monthly demand less than 60 kW. Larger commercial customers with a monthly demand greater than 60 kW are automatically enrolled in the program.

Table 3: BGE Current Residential Market-Priced Service Rate Components, 2014. Source: "Standard Offer Service, Electric Retail," Baltimore Gas & Electric Company, Baltimore, 2014. Used under fair use, 2014

Residential	Period	Generation Rate				Transmission Rate	Total SOS Rate
		Energy Rate (¢/kWh)	Fixed Admin. Charge (¢/kWh)	Applicable Taxes	Total Generation Rate (¢/kWh)	Transmission Rate (¢/kWh)	Total Rate (¢/kWh)
Schedule R (Same rate all the time)	June 1 – Sept. 30, 2014	7.709	0.400	0.018	8.127	0.802	8.929
	Oct. 1, 2013 – May 31, 2014	8.510	0.400	0.014	8.924	0.802	9.726
Schedule RL (Time of Use Rates)	June 1 – Sept. 30, 2014 On-Peak	10.257	0.400	0.023	10.680	0.706	11.386
	June 1 – Sept. 30, 2014 Inter.-Peak	6.653	0.400	0.015	7.068	0.706	7.774
	June 1 – Sept. 30, 2014 Off-Peak	6.289	0.400	0.015	6.704	0.706	7.410
	Oct. 1, 2013 – May 31, 2014 On-Peak	10.597	0.400	0.017	11.014	0.706	11.720
	Oct. 1, 2013 – May 31, 2014 Inter.-Peak	9.469	0.400	0.015	9.884	0.706	10.590
	Oct. 1, 2013 – May 31, 2014 Off-Peak	7.212	0.400	0.012	7.624	0.706	8.330
Schedule EV (For Electric Vehicles)	June 1 – Sept. 30, 2014 On-Peak	12.778	0.400	0.029	13.207	2.360	15.567
	June 1 – Sept. 30, 2014 Off-Peak	5.124	0.400	0.012	5.536	-	5.536
	Oct. 1, 2013 – May 31, 2014 On-Peak	18.82	0.400	0.029	19.249	3.086	22.335
	Oct. 1, 2013 – May 31, 2014 Off-Peak	4.919	0.400	0.008	5.327	-	5.327

Table 3 above shows the BGE Standard Offer Service rates that went into effect in January 2014. Schedule R is used for residential customers who do not sign up for TOU rates, while schedule RL is used for those who sign up for TOU rates. Schedule EV is used for electric vehicles. It can be seen that for the EV-TOU rates, the summer peak rate is almost triple the off-peak rate. The winter peak rate is more than four times the off-peak rate.

2.5 Electric Vehicle Loading

The term electric-drive vehicle describes any vehicle where the propulsion system contains one or more electric motors that contribute toward providing the motive force to drive the vehicle [29]. Electric drive vehicles include electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles. Plug-in electric vehicles (PEVs) are electric-drive vehicles with the capability to recharge using grid electricity [1]. PEVs include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). As mentioned earlier, a BEV is solely powered by its battery system while a PHEV adds a combustion engine to allow extended driving even with a fully depleted battery.

2.5.1 Electric Vehicle Charging Classes

There are officially two classes of AC charging methods for electric vehicles as defined by SAE J1772-2012 [32]. SAE J1772 is the standard for the general physical, electrical, functional and performance requirements to facilitate charging of EV/PHEV vehicles in North America. An earlier version of SAE J1772, released in 2010, defined AC Level 1 and AC Level 2 charge levels and specified conductive charge coupler and electrical interfaces for AC Level 1 and AC Level 2 charging [32]. The 2012 revision of the standard incorporates DC charging where DC Level 1 and DC Level 2 charge levels, charge coupler and electrical interfaces are defined. This paper will focus on the AC charging classes which will most likely be utilized in residential homes. As stated in the SAE J1772 Charging Configurations and Ratings Methodology report [33], the AC charging classes and their operational characteristics are as follows:

- **AC Level 1:** 120 V AC single-phase, 12-A or 15-A continuous current. This charging level is designed to allow an electric vehicle plug into the common 120 V AC receptacle. EPRI concludes that Level 1 charging generates the fewest distribution system impacts [1].

- **AC Level 2:** 240 V AC single-phase, 80-A maximum continuous current. This level provides a faster rate of charge than AC Level 1. The estimated charge time for an EV will vary based on the capacity of the vehicle on-board charger. Higher power Level 2 charging generates the strongest system impacts and is typically not required for most customer charging scenarios [1].

The table below summarizes the typical electric outlets that can be found in a typical home.

Table 4: Home Electric Outlets. Source: "Tesla Motors - Electric Vehicle Charging," [Online]. Available: <http://www.teslamotors.com/charging#/outlet>. [Accessed 5 April 2014]. Used under fair use, 2014

Outlet	Description	Volts/Amps	Kilowatts
NEMA 5-15	Standard Outlet	110 V / 12 A	1.4 kW
NEMA 5-20	Newer Standard Outlet	110 V / 15 A	1.8 kW
NEMA 14-50	RVs and Campsites	240 V / 40 A	10 kW
NEMA 6-50	Welding Equipment	240 V / 40 A	10 kW
NEMA 10-30	Older Dryers	240 V / 24 A	5.8 kW
NEMA 14-30	Newer Dryers	240 V / 24 A	5.8 kW

2.5.2 Electric Vehicles and Residential Charging

To assess the effects of EV loading on an electric distribution network, the following key parameters would need to be known:

- The number of EVs in the service territory
- The number of EVs owned by each residential customer
- The types of EVs and the level of charging capability

The battery specifications analyzed in this paper are those for the Nissan LEAF, Chevy Volt, Tesla Model S, and Toyota Prius PHEV.

In the year 2011, the typical residential non-heat customer in Central Maryland had a whole-house load without EV of 3.49kW coincident with PJM RTO system peaks [7]. From data in Table 4, the residential charging power levels for EVs could vary from 1.4 kW to 10 kW. EVs could potentially add an average of approximately 4 kW to the residence peak load, almost doubling the whole-house electric load during system peak levels.

Table 5 summarizes the key assumptions for EV residential charging loads used in this study.

Table 5: Assumptions for Electric Vehicle Loads – Residential Home Charging

EV	Type	Battery Capacity	Battery Type	Battery Range	Total Range	Home Charging Voltage (V)	Home Charging Current (A)	Home EV Load (kW)	0 - 100% Charging Time (Actual charge times may vary)
2013 Tesla Model S [34]	EV	85 kWh	Lithium- ion	265 miles (EPA)	265 miles (EPA)	120, 240 V	12A/15A, 24 A/40 A	1.4/1.8, 5.8/10	About 9 hours for 10 kW charging source
2012 Chevy Volt [35]	PHEV	16 kWh	Lithium- ion	35 miles (EPA)	380 miles (EPA)	120, 240 V	15 A, 24 A	1.8, 5.8	About 10 - 12 hours for 120 V/15 A , about 4 hours for 240 V/24A source
2013 Toyota Prius Two [36]	PHEV	4.4 kWh	Lithium- ion	11 miles (EPA)	530 miles	120, 240 V	15 A, 24 A	1.8, 5.8	About 3 hours for 120 V and 1.5 hours for 240 V
2012 Nissan LEAF [37] [38]	EV	24 kWh	Lithium- ion	73 miles (EPA)	73 miles (EPA)	120, 240 V	15 A, 30 A/40 A	1.4, 3.3/6.6	About 4 hours for 240 V/40 A, 8 hours for 240V/30A, and 22 hours on 120 V/15A outlets

2.6 Electric Utility Assumptions

2.6.1 Transformer Voltage Regulation

As mentioned earlier, data for this research was supplied by an electric utility. Based on information supplied by the utility, Table 6 below summarizes the voltage regulation of the sample transformers used in this study at a utilization voltage of 240V.

Table 6: Transformer voltage regulation at power factor

Transformer Size (kVA)	Percent Regulation at 0.9 Power Factor
25	1.35 %
50	1.23 %

The voltage regulation of a transformer is the percent change in output voltage from no-load to full-load, relative to rated output voltage. In order to give representative values for regulation, the utility performed calculations using the average value of load losses for transformers purchased from all manufacturers through 1992. Voltage regulation is used in voltage drop calculations. For example, if a 25 kVA pad-mount, single-phase 7620 volt to 120/240 volt transformer is loaded to 20 kVA at 0.9 power factor, the transformer has a voltage drop of:

$$\frac{20kVA}{25kVA} \times 1.35\% = 1.08\%$$

The 1.35% factor is taken from Table 6 above.

2.6.2 Cable Voltage Regulation

Cable voltage regulation refers to the percent change in the voltage magnitude from no-load to full-load measured at the receiving end of the cable. In order to give representative values for cable voltage regulation, the utility performed calculations for a 10kVA load at a distance of

100 feet from the source for different service voltages and power factors. For loads other than 10kVA and at distances other than 100 feet, the relationship in Equation 9 must be employed.

Equation 9

$$\% \text{ V. D.} = \frac{\text{Distance}}{100 \text{ feet}} \times \frac{\text{Load (kVA)}}{10 \text{ kVA}} \times \% \text{ Voltage Regulation}$$

Where

Distance = distance from source in feet

Based on information supplied by the utility, Table 7 below summarizes the voltage regulation of the secondary distribution cables used in this study at a utilization voltage of 240V.

Table 7: Secondary cable voltage regulation at power factor, per 10kVA per 10 feet

Cable	Set-up	Percent Regulation at 0.9 Power Factor
350 Aluminum	Underground	0.2400%
4/0 Aluminum	Underground	0.3717%

2.6.3 Transformer Load Limits

Table 8 shows the maximum allowable transformer load limits prescribed by the utility. The load limits are expressed as a percent of the nameplate rating of the transformer. Based on data supplied by the utility, the maximum allowable loading for the 25kVA transformers is 173% of the nameplate rating both during the summer and winter. The maximum allowable loading for the 50kVA transformer is 175% of its nameplate rating during the summer, and 183% of its nameplate rating during the winter. The summer and winter loading limits differ for the 50 kVA transformer due to thermal considerations. During the winter, there is a lower ambient

temperature which enables a more effective cooling process for the transformers. Therefore, the allowable loading during the winter is sometimes higher than that allowed during the summer.

Table 8: Maximum Allowable Transformer Loading for Single-Phase Unbanked Transformers

Transformer Size (kVA)	Summer Load Limit (% of Nameplate)	Winter Load Limit (% of Nameplate)
Pad-mounted Transformers		
25	173	173
50	175	183

For a single phase nominal voltage of 120/240V, the voltage limits at the customer’s meter is $\pm 5\%$ of the nominal voltage as established by the Maryland PSC [39]. For this utility, at peak conditions, the input voltage to the low voltage distribution transformer is maintained at 1.01p.u. of the nominal voltage in the worst case scenario. In order to comply with the PSC standard, the utility design standards only allow for a total voltage drop of 6% across the low voltage distribution transformer and secondary cables at peak conditions.

3 Case Studies and Results

Hourly customer electric usage data for 3 sample transformers was gotten from a Maryland Utility, for 8/4/2013 through 8/17/2013. The transformers included two 25 kVA and one 50 kVA pad-mount single-phase transformers. During this period, outside temperature ranged between 52°F and 86°F. To determine hourly transformer load, hourly customer load was summed up for all customers on each transformer.

A smart meter is a digital meter that eliminates the need for manual meter reading. These advanced digital infrastructures enable two-way capabilities for communicating information, controlling equipment, and distributing energy [40]. Smart meters typically have two digital radios using the Zigbee system [41]. One of these radios communicates with the utility and the second is intended to communicate with devices inside the customer's home. Using these smart meters, it is easier for utilities to monitor customer power usage. 100% of the customers supplied by the transformers in this study have smart meters. Therefore, it was possible to obtain their hourly electricity usage information. All analysis was done using Microsoft Excel.

Transformer base loads were analyzed to determine if and when EV customers were charging their vehicles. To determine the worst case loading impacts of a large scale EV penetration, one simulated EV was placed at each home of non-EV customers. Simulated EV load is based on data in Table 5. Transformer loading impact was analyzed for EV charging during traditional on-peak and off-peak hours. The effect of appliance cycling as a form of DSM was also analyzed. Again, all analysis was done using Microsoft Excel. More details are provided in Section 3.2.

Finally, secondary distribution cable loading and voltage drop were analyzed.

3.1 Sample Transformers

Two 25 kVA, and one 50 kVA, pad-mount single-phase distribution transformers that serve three different communities in Maryland, USA were selected for this study. Currently, each transformer serves one EV customer each. The residential customers supplied by these transformers are provided 120/240-volt single-phase secondary service.

Table 9: Sample transformers

Transformer #	# of homes served	# EV Customers	Transf. Capacity (kVA)	Transf. Capacity (kW)	Design	Primary Voltage (V)	Secondary Voltage (V)
1	5	1	25	22.5	Padmount	7620	120/240
2	8	1	25	22.5	Padmount	7620	120/240
3	5	1	50	45.0	Padmount	7620	120/240

Table 9 above shows the specifications for the distribution transformers selected.

3.1.1 Transformer 1

Transformer 1 is a single phase 25 kVA pad-mounted transformer that steps down 7620 V primary voltage to 120/240 V secondary service. This transformer serves five homes, one of which owns an electric vehicle. The home sizes range from 2,200 square feet to 3,400 square feet.

Table 10: Transformer 1 Customer Summary

Customers	EV?	Building Type	Base area of building (Square feet)	# Stories	Smart Meter?
C1	Yes	Residential	3,343	2.0	Yes
C2	No	Residential	2,296	2.0	Yes
C3	No	Residential	3,352	2.0	Yes
C4	No	Residential	2,688	2.0	Yes
C5	No	Residential	3,096	2.0	Yes

Customer 1, with an electric vehicle

This customer purchased a Toyota Prius plug-in hybrid early 2013. The figure below shows the summary of the daily load profile for this customer on sample days in August 2013.

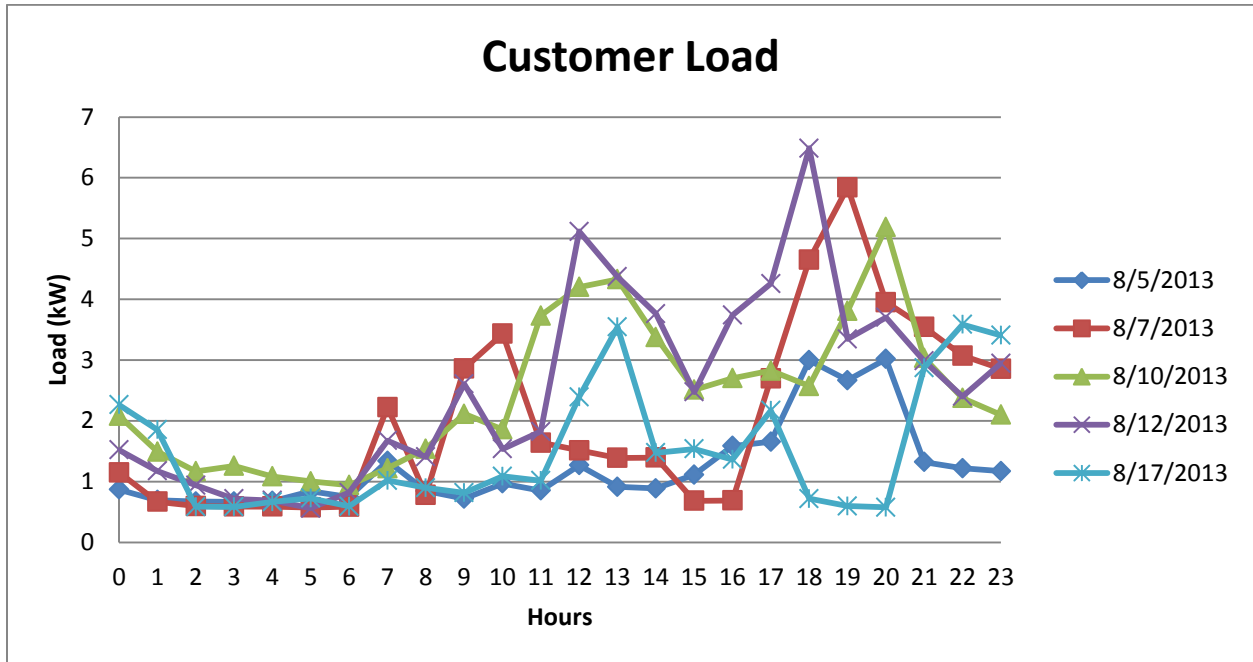


Figure 9: Transformer 1, Customer 1 Daily Load Profiles August 2013

From Figure 9, it can be seen that on some days, there is a sudden increase in electric usage of about 2 kW. Since a Toyota Prius plug-in vehicle can be charged on 1.8 kW or higher, it can be assumed that the customer was charging the vehicle during these times. For example, on 8/7/2013 at 8 a.m., there is an increase of about 2 kW usage which lasts for about 3 hours. The same usage is seen on 8/12/2013 at 11 a.m. A Toyota Prius plug-in hybrid vehicle can be charged from 0% to 100% drawing 1.8 kW for 3 hours, or 5.8 kW for 1.5 hours.

3.1.1.1 Transformer 1 Peak Analysis

Since Transformer 1 supplies five customers who have smart meters installed, the peak electricity usage times can be easily determined by adding the load for all customers. Figure 10

below shows the daily load profile for transformer 1 on select days in August 2013 during which the outside temperature ranged between 52°F and 86°F. The peak usage of about 20 kW is seen on 8/12/2013 around 7 p.m.

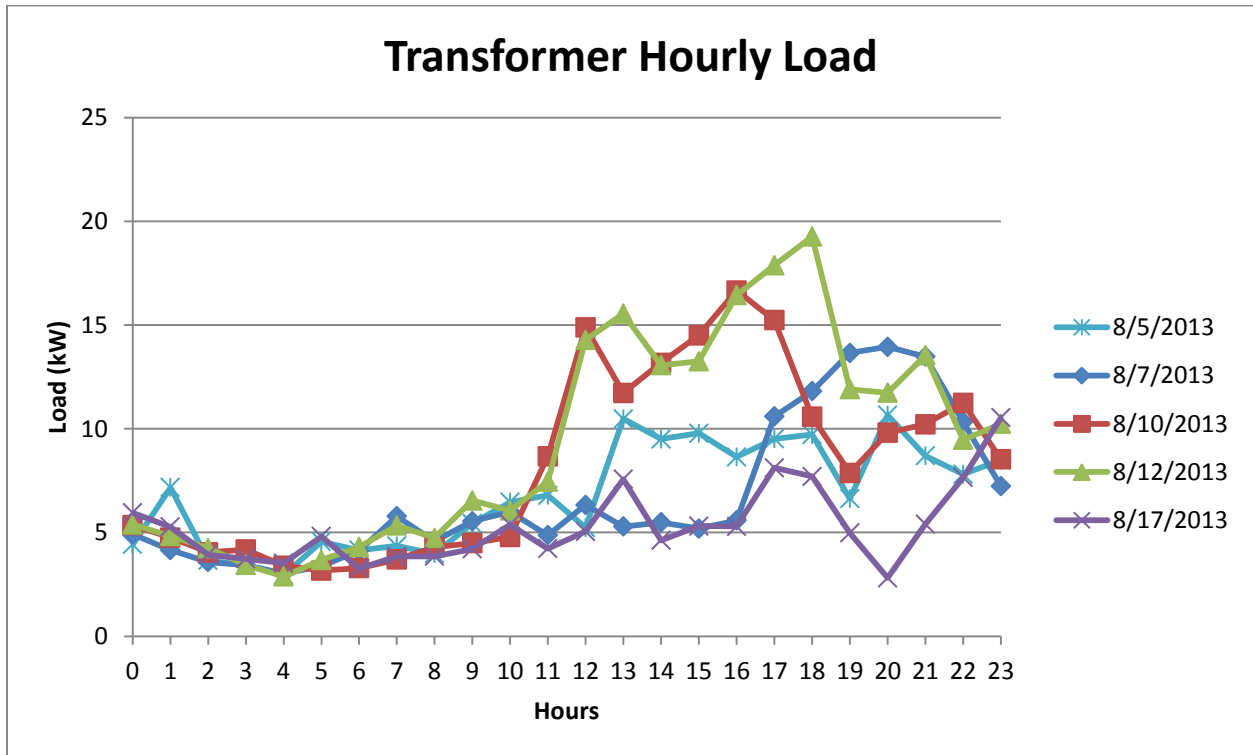


Figure 10: Transformer 1 Daily Load Profiles August 2013

It should be noted that temperature does have an impact on electric power demand. For example, higher temperatures during the summer cause customers to use fans and air conditioners which increase power demand. The use of heating systems during the winter also increases power demand. To demonstrate this effect, below is a plot of the temperature, as well as the load on transformer 1, on 8/12/2013.

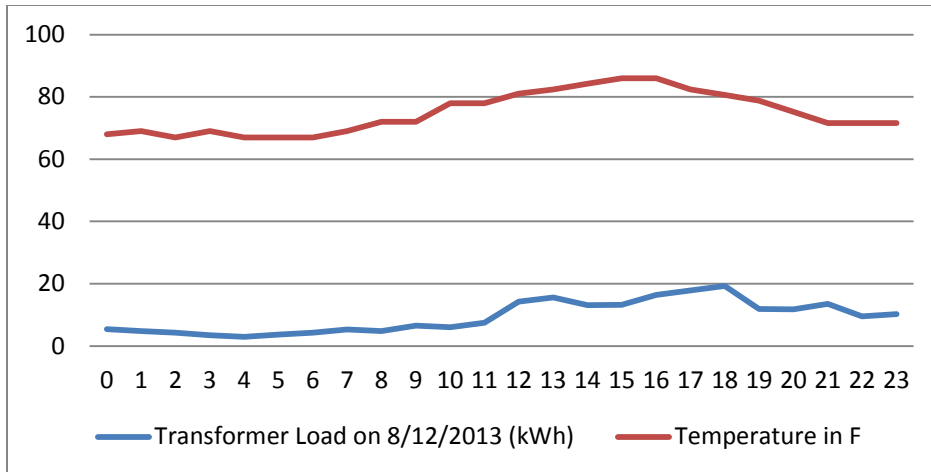


Figure 11: Effect of Temperature on Transformer 1 Load on 8/12/2013

It can be seen from Figure 11 that temperature has a direct effect on the electric power demand on transformer 1. Because it is summer, the higher the temperature, the higher the demand and vice versa. This is because customers are putting on air conditioners and other cooling systems as temperature starts to rise. If the maximum allowable loading of the transformer is exceeded during the summer, the chance of transformer failure is higher due to higher temperatures, reduced heat transfer from the transformer to its surrounding environment (or reduced cooling), and increase in the winding hottest-spot temperature of the transformer.

3.1.2 Transformer 2

Transformer 2 is a single phase 25 kVA pad-mounted transformer that steps down 7620 V primary voltage to 120/240 V secondary service. This transformer serves eight homes, one of which owns an electric vehicle. The home sizes range from 2,800 square feet to 3,800 square feet.

Table 11: Transformer 2 Customer Summary

Customers	EV?	Building Type	Base area of building (Square feet)	# Stories	Smart Meter?
C1	Yes	Residential	3,790	2.0	Yes
C2	No	Residential	2,932	2.0	Yes
C3	No	Residential	3,340	2.0	Yes
C4	No	Residential	2,888	2.0	Yes
C5	No	Residential	3,296	2.0	Yes
C6	No	Residential	2,864	2.0	Yes
C7	No	Residential	3,112	2.0	Yes
C8	No	Residential	2,932	2.0	Yes

Customer 1, with an electric vehicle

This customer purchased a Nissan Leaf early 2013. The figure below shows the summary of the daily load profile for this customer on sample days in August 2013.

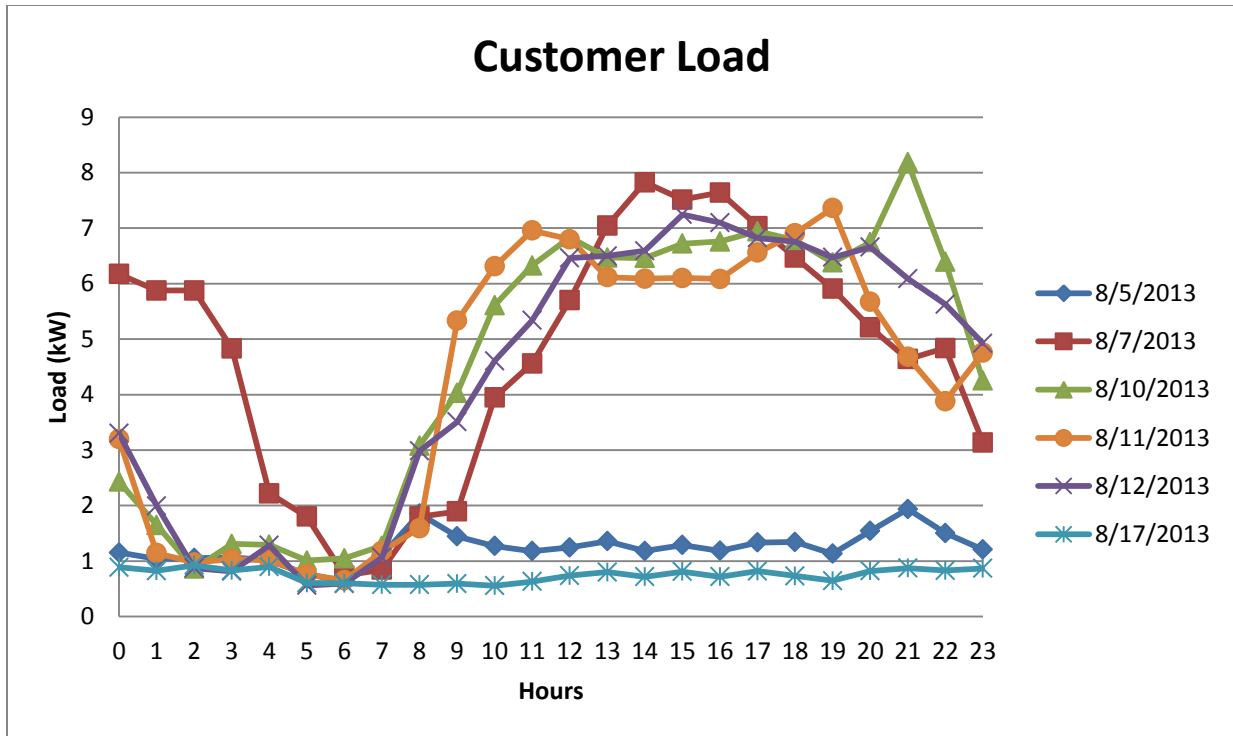


Figure 12: Transformer 2, Customer 1 Daily Load Profiles August 2013

From Figure 12, it can be seen that on 8/11/2013 at 8 a.m., there is an increase in usage of about 3.3 kW. A Nissan Leaf vehicle can be charged from 0% to 100% drawing 1.4 kW for 22 hours, 3.3 kW for 8 hours, or 6.6 kW for 4 hours based on the on-board charger rating.

3.1.2.1 Transformer 2 Peak analysis

Since Transformer 2 supplies eight customers who have smart meters installed, the peak electricity usage times can be easily determined by adding the load for all customers. Figure 13 below shows the daily load profile for transformer 2 on select days in August 2013 during which the outside temperature ranged between 52°F and 86°F. The peak usage of 46.82 kW is seen on 8/12/2013 around 4 p.m.

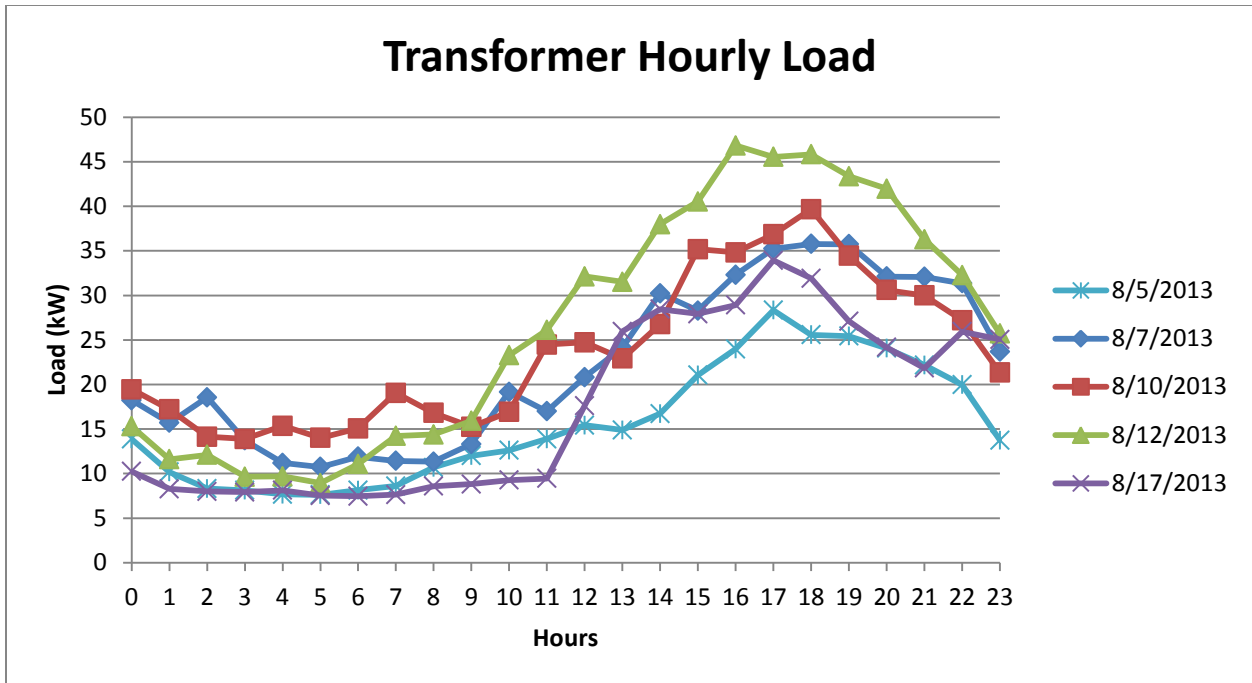


Figure 13: Transformer 2 Daily Load Profiles August 2013

To demonstrate the impact of temperature on electric power demand, below is a plot of the temperature, as well as the load on transformer 2, on 8/10/2013.

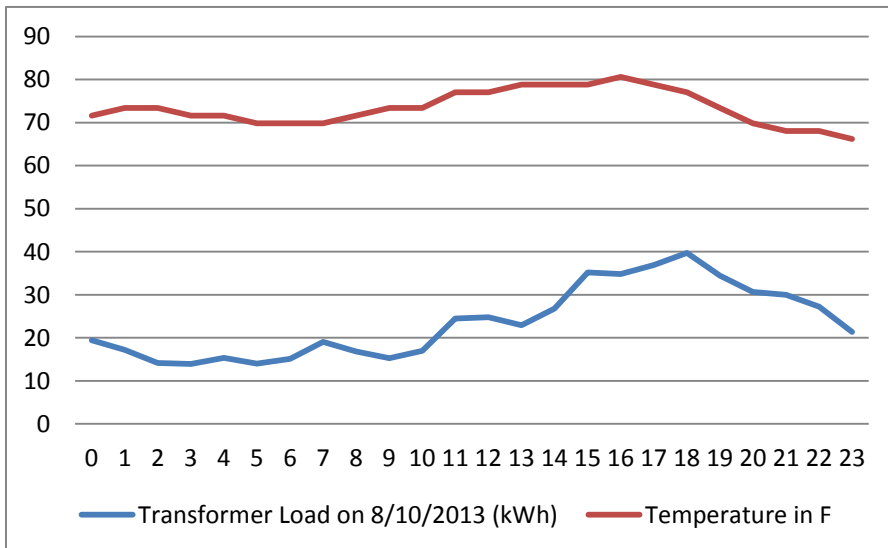


Figure 14: Effect of Temperature on Transformer 2 Load on 8/10/2013

It can be seen from Figure 14 that temperature has a direct effect on the power demand on transformer 2. Because it is summer, the higher the temperature, the higher the demand. This is because customers are putting on air conditioners and other cooling systems as temperature starts to rise.

3.1.3 Transformer 3

Transformer 3 is a single phase 50 kVA pad-mounted transformer that steps down 7620 V primary voltage to 120/240 V secondary service. This transformer serves five homes, one of which owns an electric vehicle. Home sizes range from 2,600 square feet to 3,200 square feet.

Table 12: Transformer 3 Customer Summary

Customers	EV?	Building Type	Base area of building (Square feet)	# Stories	Smart Meter?
C1	No	Residential	2,610	2.0	Yes
C2	No	Residential	3,064	2.0	Yes
C3	No	Residential	3,178	2.0	Yes
C4	No	Residential	2,654	2.0	Yes
C5	Yes	Residential	2,862	2.0	Yes

Customer 5, with an electric vehicle

This customer purchased a Toyota Prius plug-in hybrid early 2013. The figure below shows the summary of the daily load profile for this customer on sample days in August 2013.

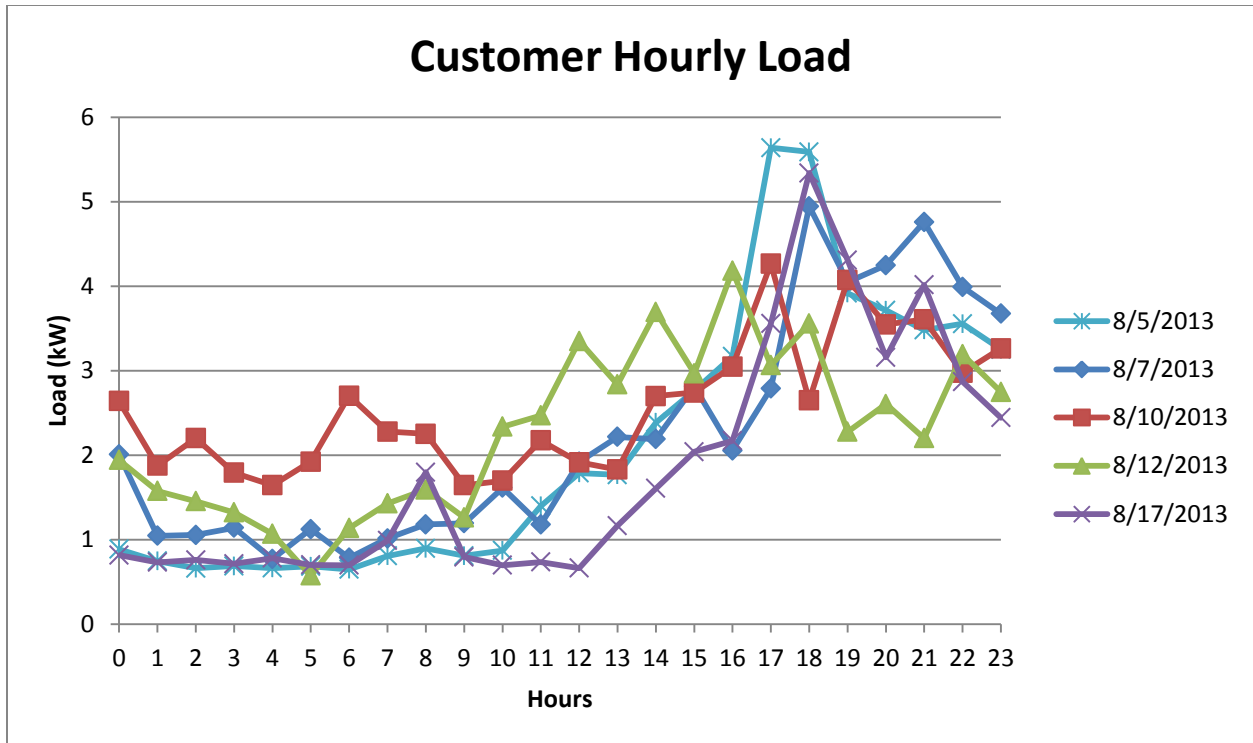


Figure 15: Transformer 3, Customer 5 Daily Load Profiles August 2013

From Figure 15, it can be seen that on some days, there is a sudden increase in electric usage of about 2 kW. Since a Toyota Prius plug-in vehicle can be charged on 1.8 kW or higher, it can be assumed that the customer was charging the vehicle during these times. For example, on 8/5/2013 at about 4 p.m., there is an increase of about 2 kW usage which lasts for about 3 hours.

3.1.3.1 Transformer 3 Peak analysis

Since Transformer 3 supplies five customers who have smart meters installed, the peak electricity usage times can be easily determined by adding the load for all customers. Figure 16 below shows the daily load profile for transformer 3 on select days in August 2013 during which the outside temperature ranged between 52°F and 86°F. The peak usage of about 23 kW is seen on 8/5/2013 at 6 p.m.

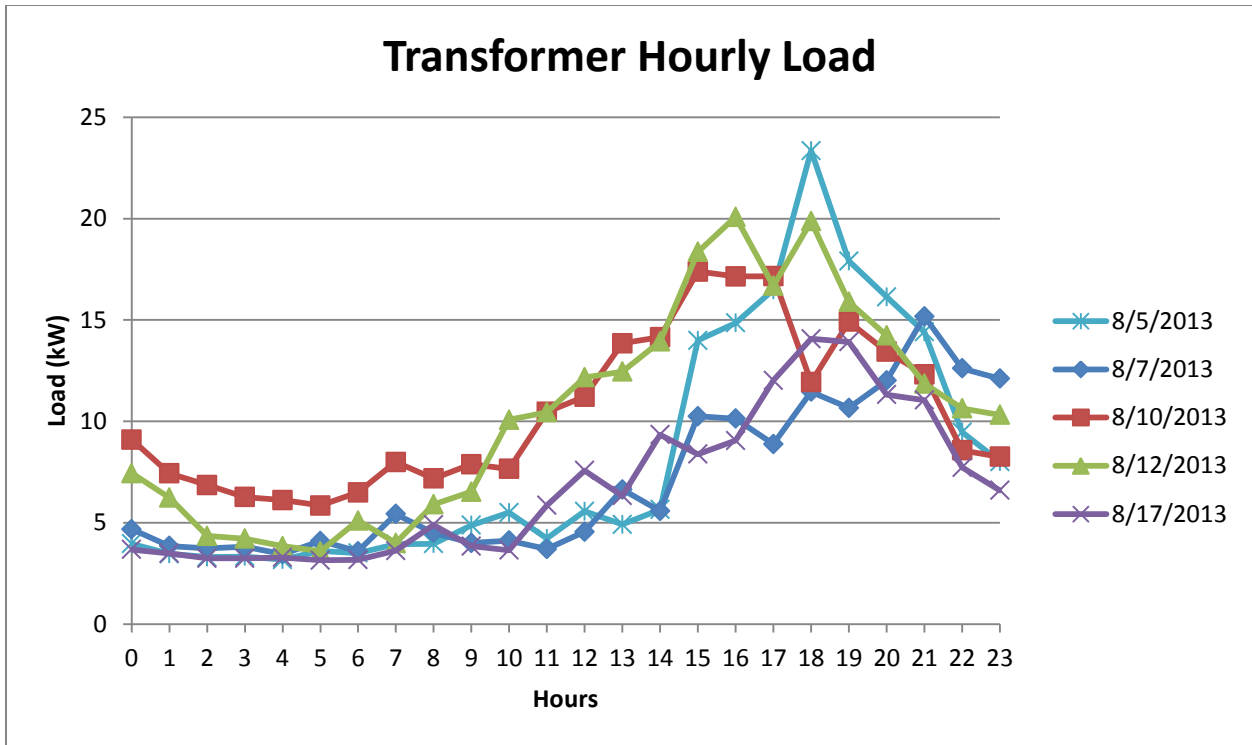


Figure 16: Transformer 3 Daily Load Profiles August 2013

To demonstrate the impact of temperature on electric power demand, below is a plot of the temperature, as well as the load on transformer 3, on 8/5/2013.

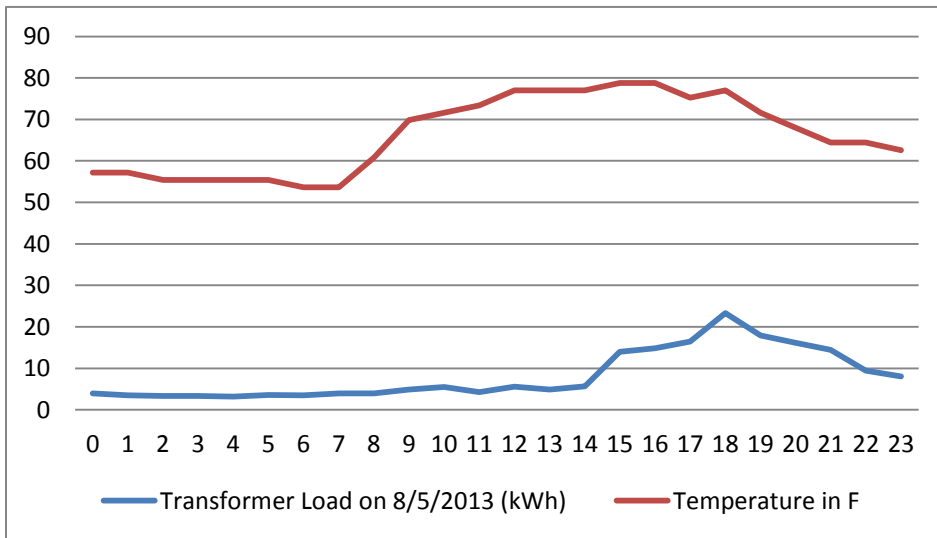


Figure 17: Effect of Temperature on Transformer 3 Load on 8/5/2013

It can be seen from Figure 17 that temperature has a direct effect on the power demand on transformer 3. Because it is summer, the higher the temperature, the higher the demand. This is because customers are putting on air conditioners and other cooling systems as temperature starts to rise.

3.2 Simulated EV Load

In order to evaluate the worst-case impact of a high penetration of electric vehicles on these distribution transformers, simulated electric vehicles are placed at each customer's home on each of these transformers during peak hours. Each home without an EV gets a simulated one, which reflects the behavior of other EVs in the neighborhood. Peak hours are taken to be the hours between 10 a.m. and 8 p.m.

3.2.1 Transformer 1

Simulated EVs were placed on this transformer during the traditional peak period as summarized in the table below.

Table 13: Transformer 1, Simulated EV Load

Customer#	EV Type	Simulated EV	Simulated EV Load Function (kW)	Charge Time (Hours)	Simulated Charge Period
C1	Toyota Prius	N/A	N/A	N/A	N/A
C2	N/A	Nissan LEAF	C2+6.6	4.0	4pm – 8pm
C3	N/A	Chevy Volt	C3+5.8	4.0	4pm – 8pm
C4	N/A	Toyota Prius	C4+5.8	2.0	6pm – 8pm
C5	N/A	Tesla Model S	C5+10	9.0	11am – 8pm

After placing a Nissan Leaf at the home of Customer 2, the peak load of transformer 1 increased from 19.88 kW to 25.86 kW as shown in Figure 18.

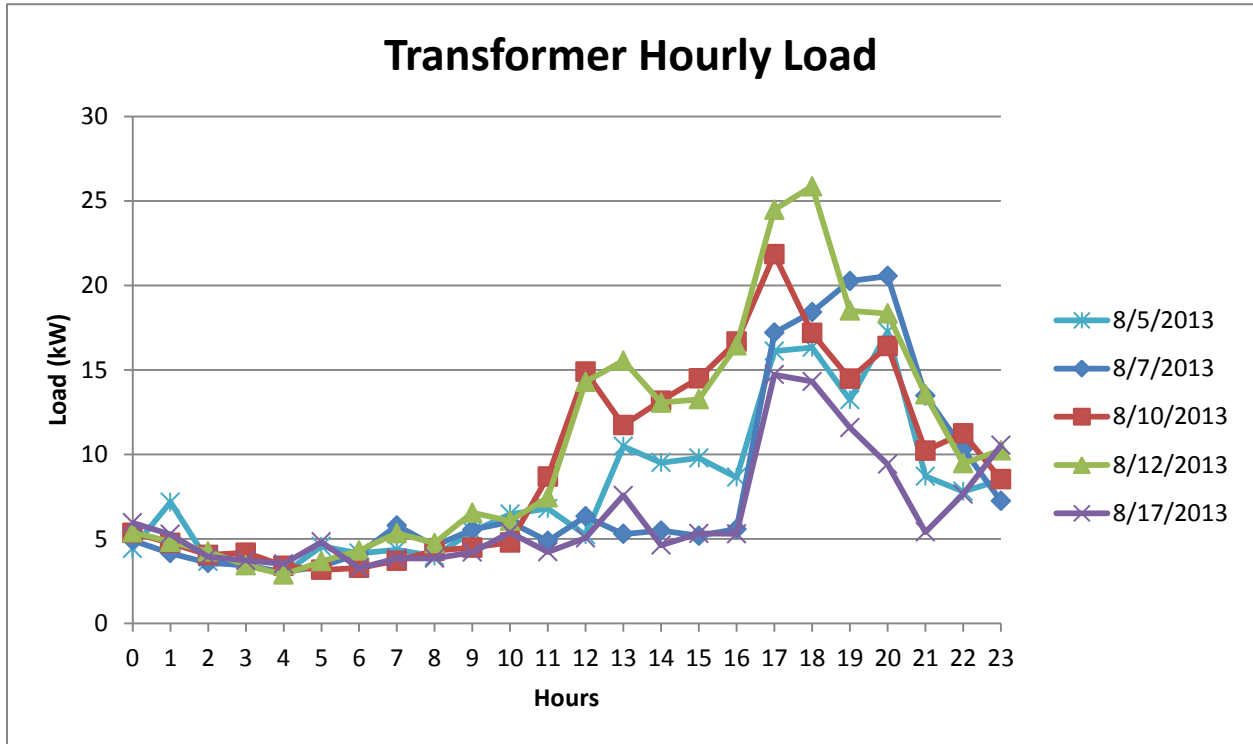


Figure 18: Transformer 1, Customer 2 Simulated LEAF Added

After placing a Chevy Volt at the home of Customer 3, the peak load is increased from 25.86 kW to 31.66 kW as shown in Figure 19.

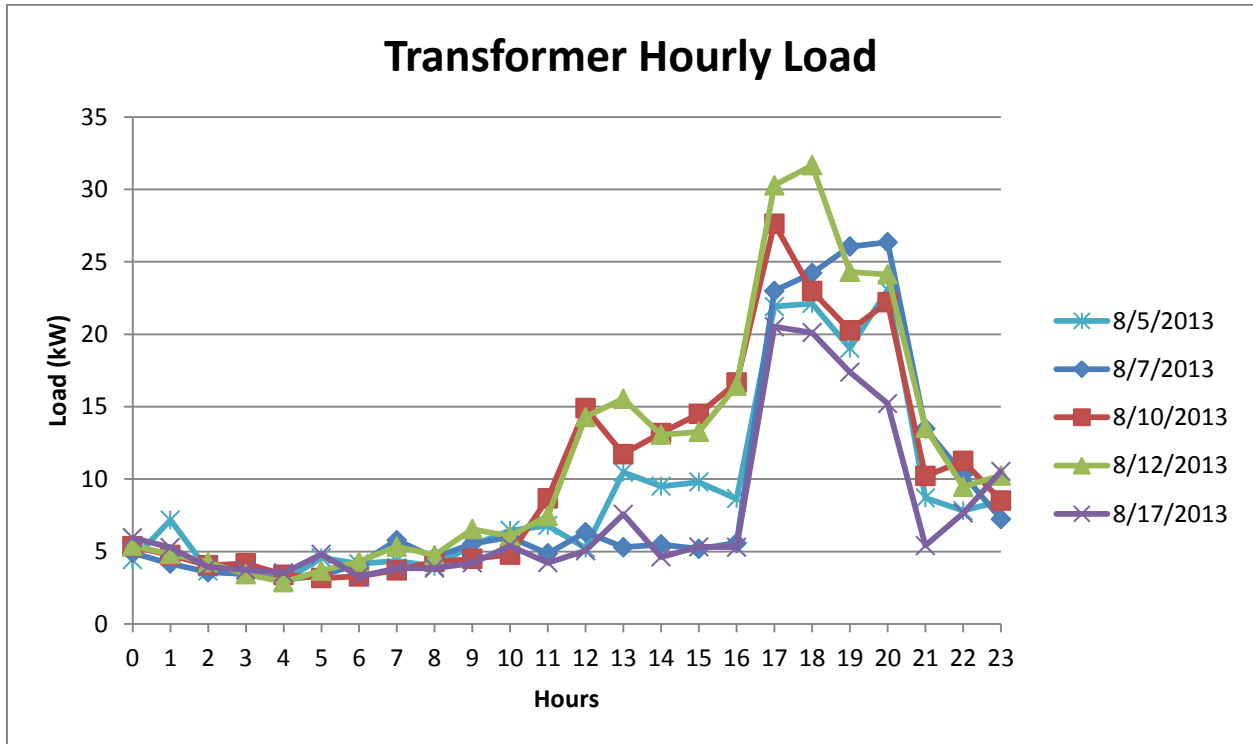


Figure 19: Transformer 1, Customer 3 Simulated Volt Added

After placing a Toyota Prius at the home of Customer 4, the peak load is increased from 31.66 kW to 35.88 kW as shown in Figure 20.

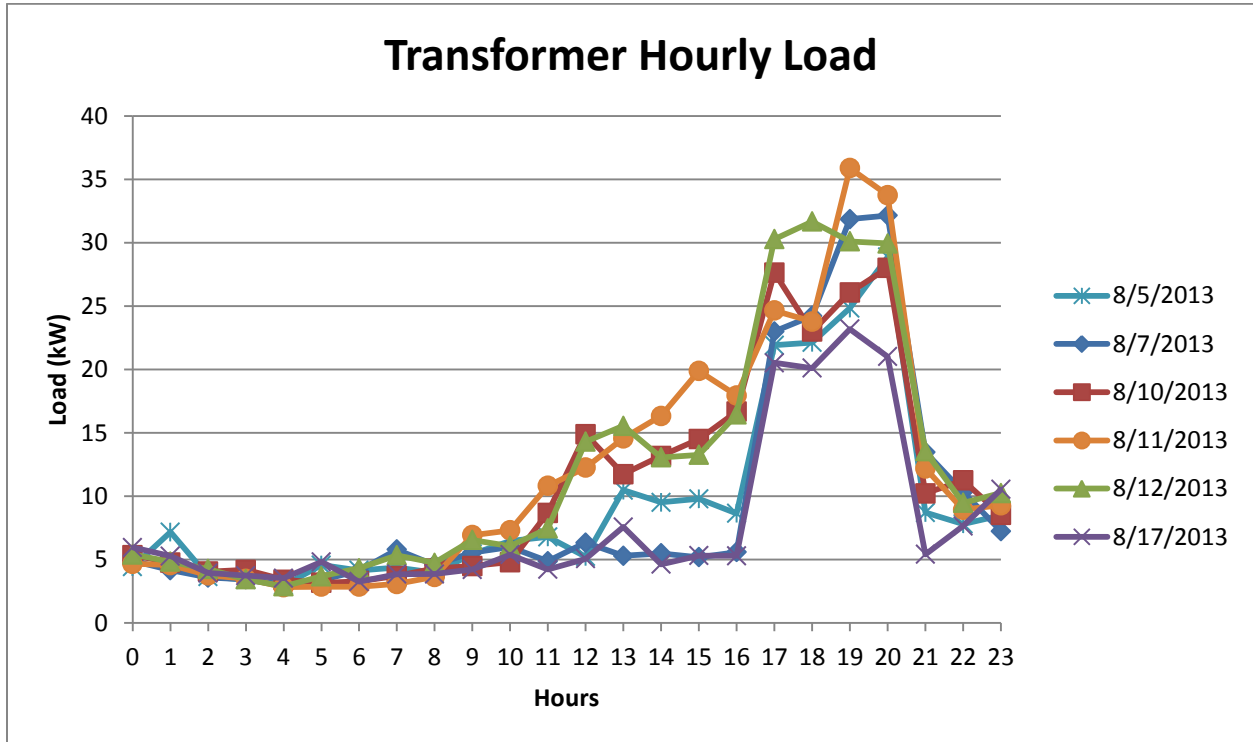


Figure 20: Transformer 1, Customer 4 Simulated Prius Added

After placing a Tesla at the home of Customer 5, the peak load is increased from 35.88 kW to 45.88 kW as shown in Figure 21. According to data in Table 8, the maximum allowable loading for this transformer is 173% of its name-plate rating of 25 kVA. Therefore, the maximum allowable loading is 43.25 kVA or 38.93 kW. With all four simulated EVs added to this transformer, this maximum allowable loading has been exceeded. In order to prolong the life of this transformer, TOU pricing incentives can be considered.

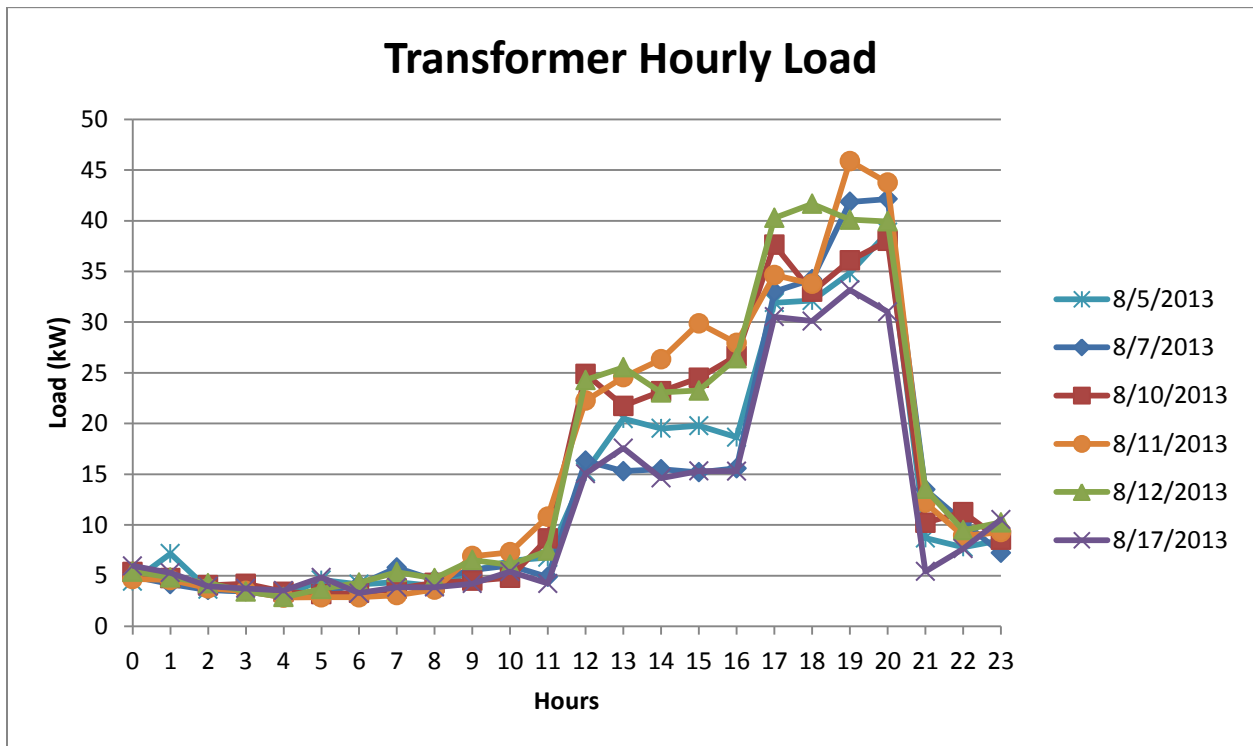


Figure 21: Transformer 1, Customer 5 Simulated Tesla Added

3.2.1.1 Effect of TOU Pricing Incentives

For transformer 1, if customer 5 can be persuaded to charge the Tesla during off-peak hours between 10 p.m. and 7 a.m., the peak load of the transformer will be reduced from 45.88 kW to

35.88 kW as shown in Figure 22 which is below the loading limit of the transformer. Note that off-peak hours are typically taken to be between 11 p.m. and 7a.m. as seen in section 2.5.2.

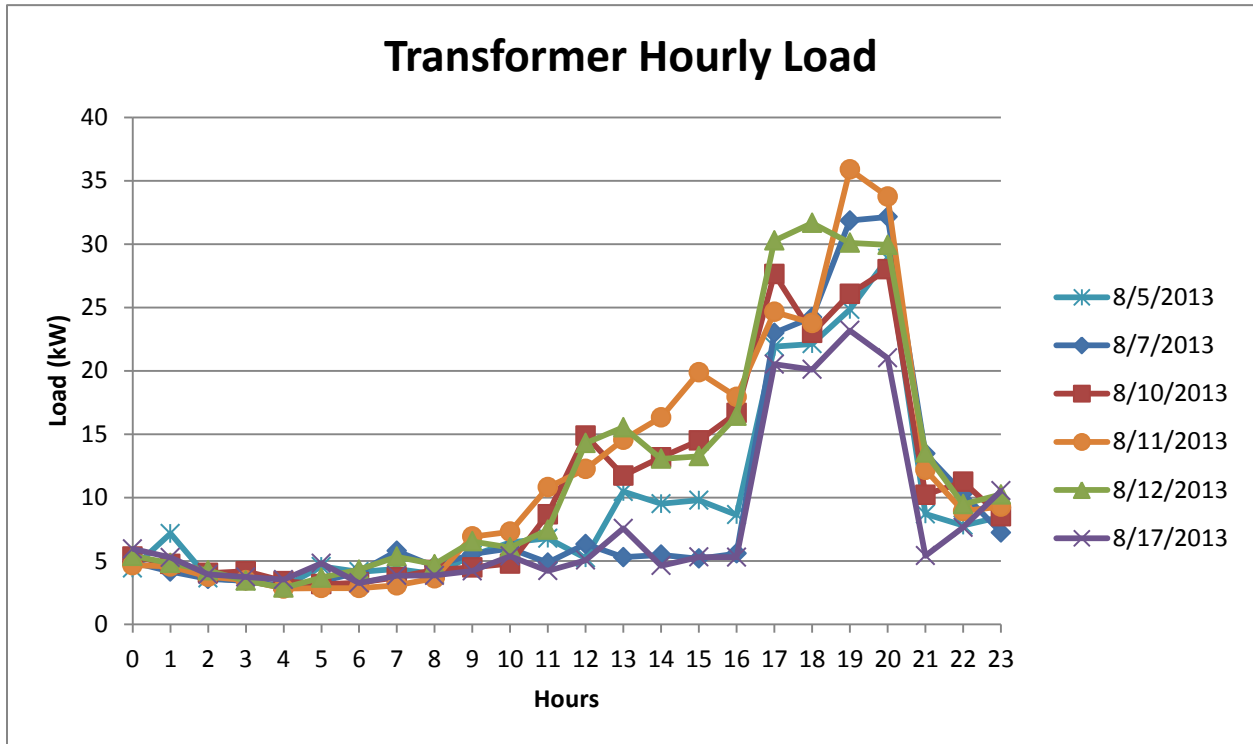


Figure 22: Transformer 1, Effect of Customer 5 Simulated Tesla charging off-peak

3.2.1.2 Transformer 1 Secondary Cable Loading Analysis

The overhead secondary service cable that serves each of the customers on Transformer 1 is a 4/0 Aluminum (Al) cable rated for 401A. For customers 1 through 4, this service cable is

supplied by a 350 Al cable main rated for 534A. See Figure 23.

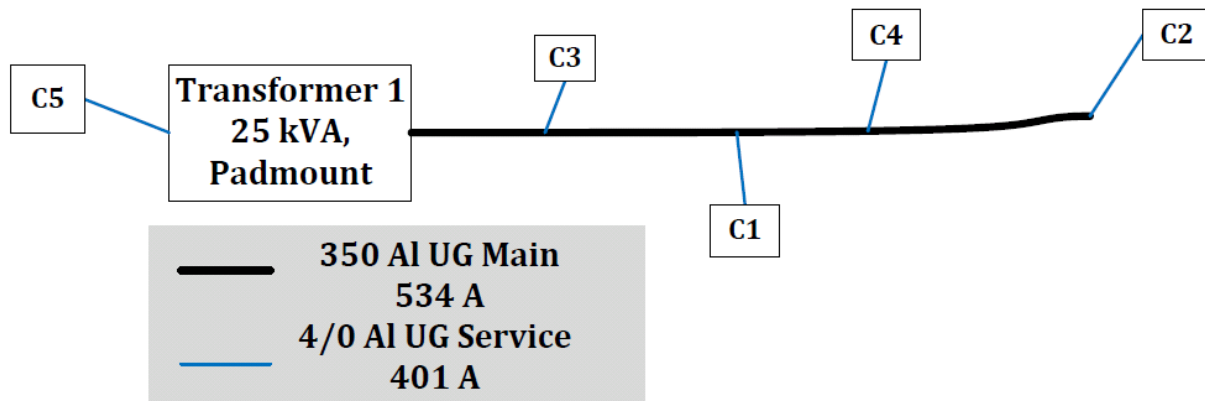


Figure 23: Transformer 1 Secondary Model, C1 through C5 represent the 5 homes served by the transformer

Assuming DSM, the peak load for this transformer is 35.88kW (or 39.87 kVA) seen at 7 p.m. on 8/11/2013. At the peak load hour, the total load for customers 1 through 4 is 37.43kVA. See Table 14. Therefore, the maximum current through the 350 Al cable is 155.96A. See Equation 10. The loading of the 350 Al cable is within the design limit. The loading of the 4/0 Al cables, rated for 401A, is also within design limit.

Table 14: Transformer 2, Customer load at peak load hour assuming DSM

Customers	Load at Peak Load Hour, 7:00 P.M., 8/11/2013	
	Load in kW	Load in kVA
C1	2.78	3.09
C2	16.12	17.91
C3	8.47	9.41
C4	6.32	7.02
C5	2.20	2.44
Total	35.88	39.87

Equation 10

$$I = \frac{S}{V}$$

$$I = \frac{37.43 \text{ kVA}}{240 \text{ V}} = 155.96 \text{ A}$$

Where:

I = Current in Amperes (A)

V = Voltage in Volts (V)

S = Apparent Power in Kilovolt-amperes (kVA)

Since the secondary cable loading is within design limits, it can be assumed that the primary cable loading is also within design limits.

3.2.2 Transformer 2

Simulated EVs were placed on this transformer during the traditional peak period as summarized in the table below.

Table 15: Transformer 2, Simulated EV Load

Customer#	EV Type	Simulated EV	Simulated EV Load Function (kW)	Charge Time (Hours)	Simulated Charge Period
C1	Nissan Leaf	N/A	N/A	N/A	N/A
C2	N/A	Nissan LEAF	C2+6.6	4.0	4pm – 8pm
C3	N/A	Chevy Volt	C3+5.8	4.0	4pm – 8pm
C4	N/A	Toyota Prius	C4+5.8	2.0	6pm – 8pm
C5	N/A	Nissan LEAF	C5+6.6	4.0	4pm – 8pm
C6	N/A	Chevy Volt	C6+5.8	4.0	4pm – 8pm
C7	N/A	Toyota Prius	C7+5.8	2.0	6pm – 8pm
C8	N/A	Tesla Model S	C8+10	9.0	11am – 8pm

After placing a Nissan Leaf at the home of Customer 2, the peak load of transformer 2 increased from 46.82 kW to 52.42 kW as shown in Figure 24.

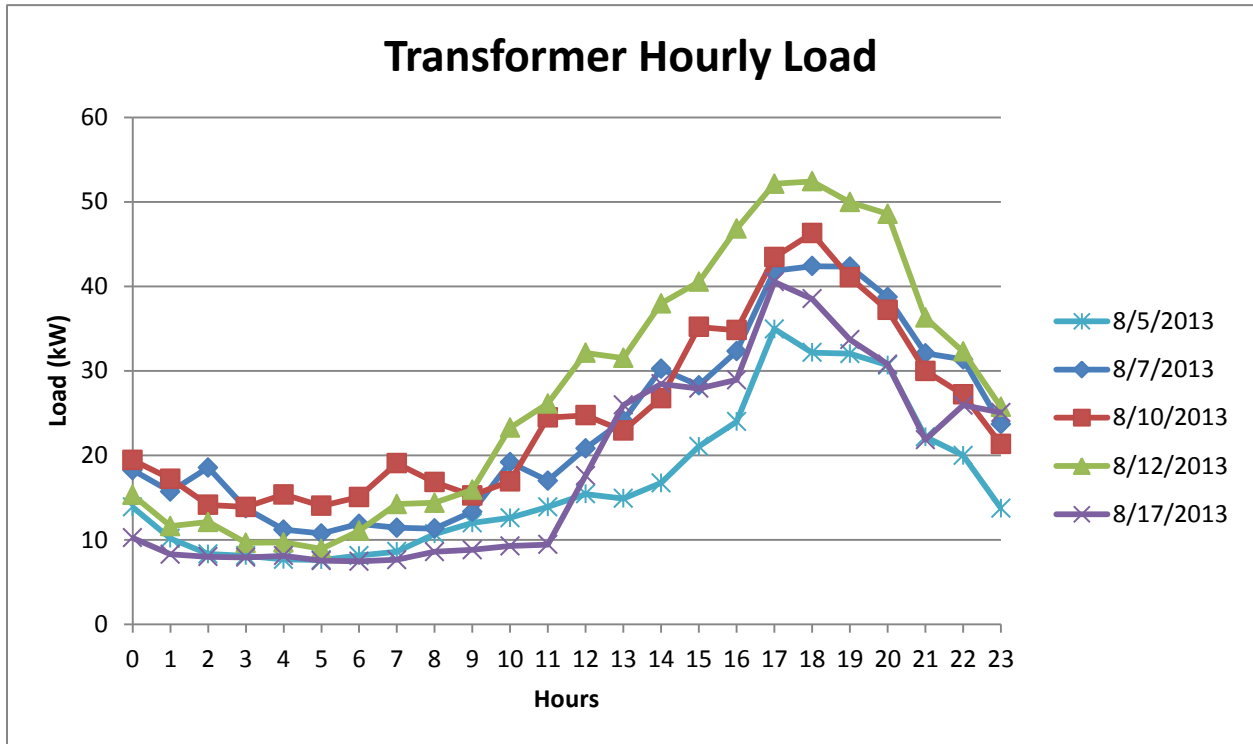


Figure 24: Transformer 2, Customer 2 Simulated LEAF Added

After placing a Chevy Volt at the home of Customer 3, the peak load of transformer 2 increased from 52.42 kW to 58.22 kW as shown in Figure 25.

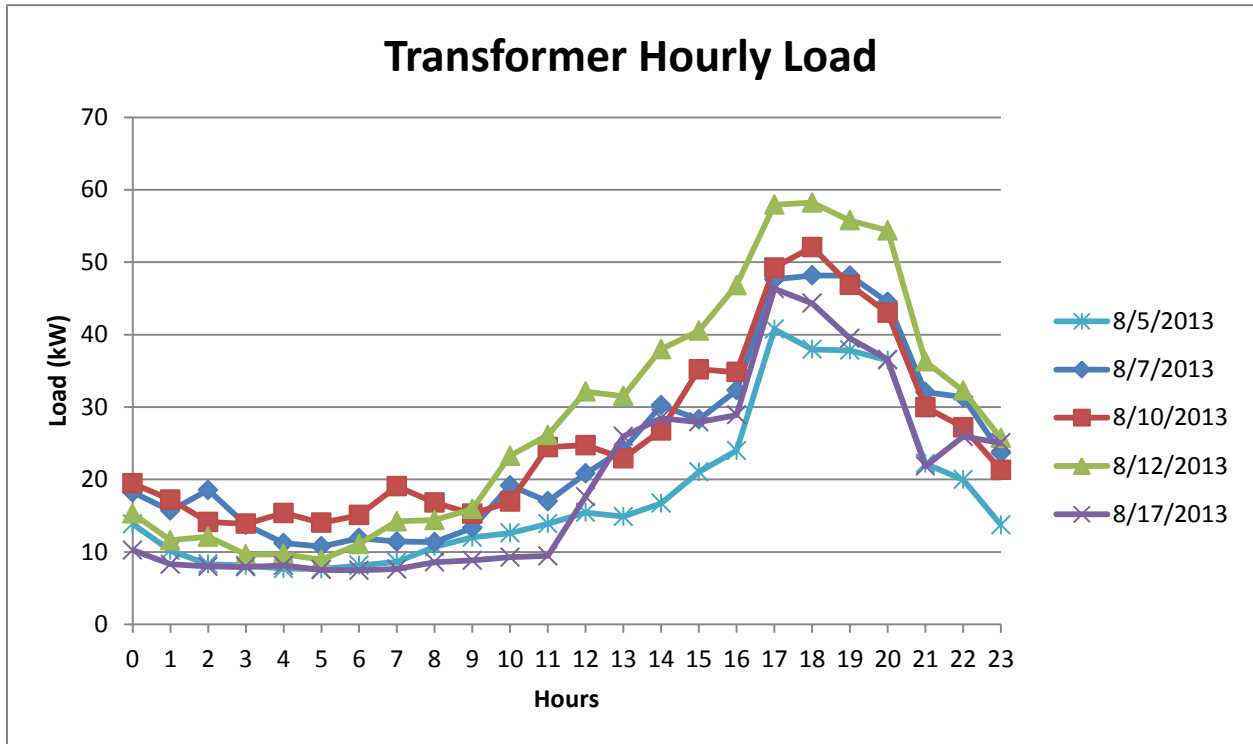


Figure 25: Transformer 2, Customer 3 Simulated Volt Added

After placing a Toyota Prius plug-in at the home of Customer 4, the peak load of transformer 2 increased from 58.22 kW to 61.56 kW as shown in Figure 26.

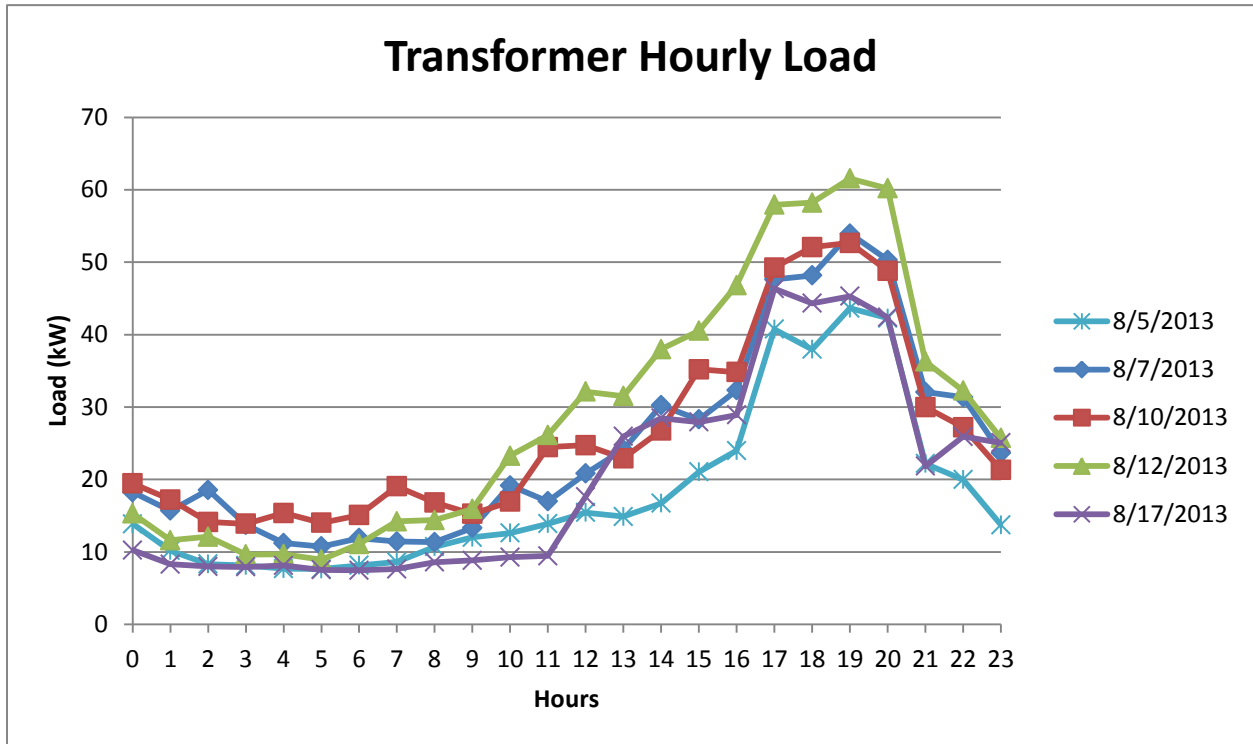


Figure 26: Transformer 2, Customer 4 Simulated Prius Added

After placing a Nissan Leaf at the home of Customer 5, the peak load of transformer 2 increased from 61.56 kW to 68.16kW as shown in Figure 27.

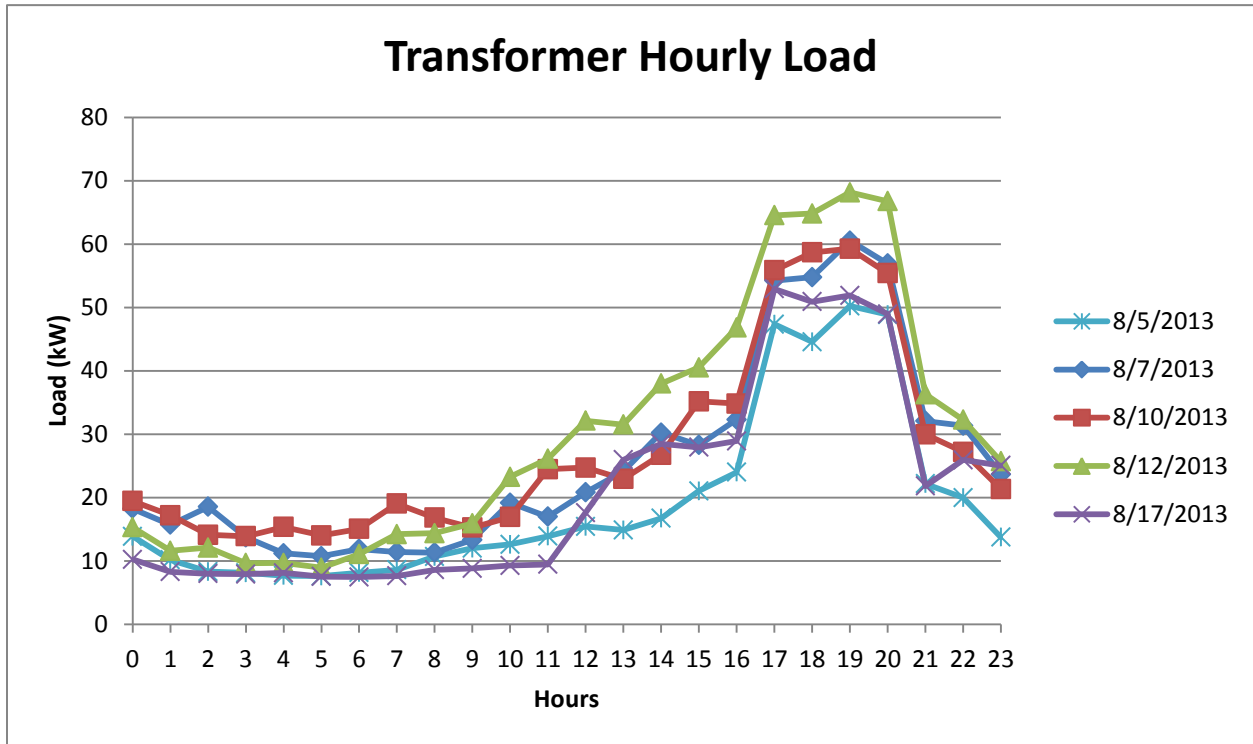


Figure 27: Transformer 2, Customer 5 Simulated LEAF Added

After placing a Chevy Volt at the home of Customer 6, the peak load of transformer 2 increased from 68.16 kW to 73.96kW as shown in Figure 28.

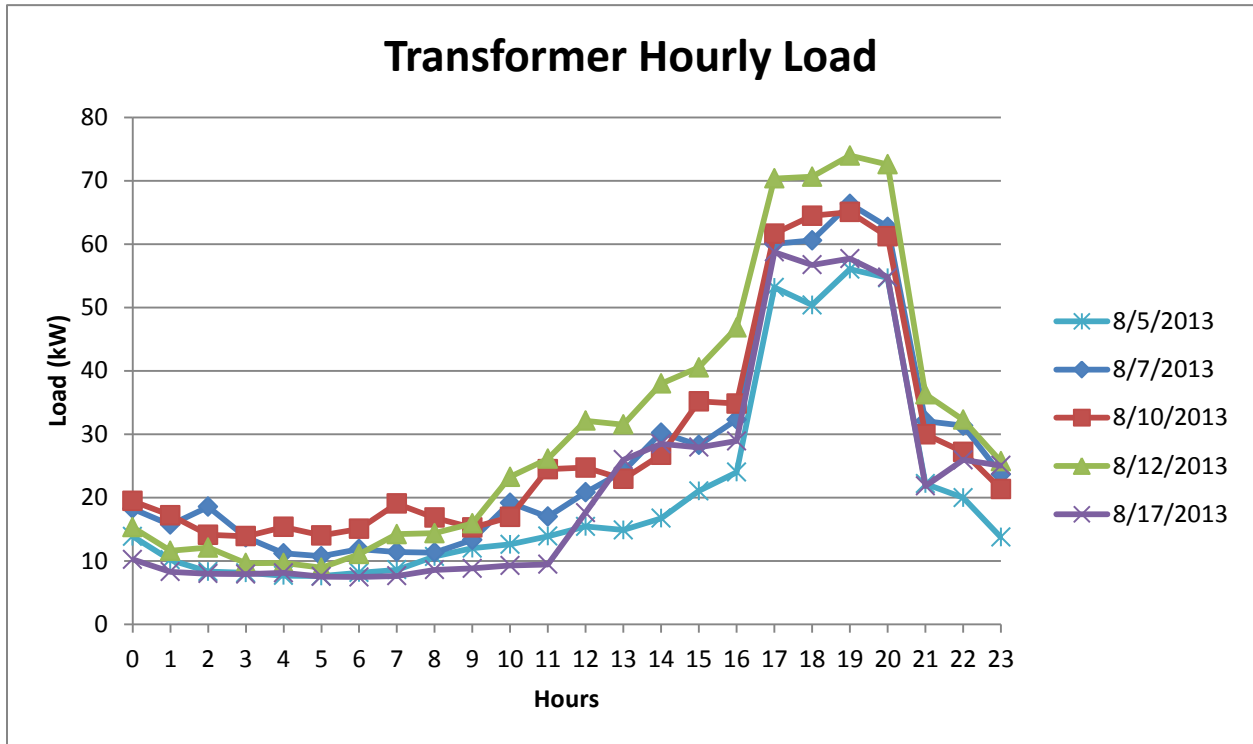


Figure 28: Transformer 2, Customer 6 Simulated Volt Added

After placing a Toyota Prius plug-in at the home of Customer 7, the peak load of transformer 2 increased from 73.96 kW to 79.76kW as shown in Figure 29.

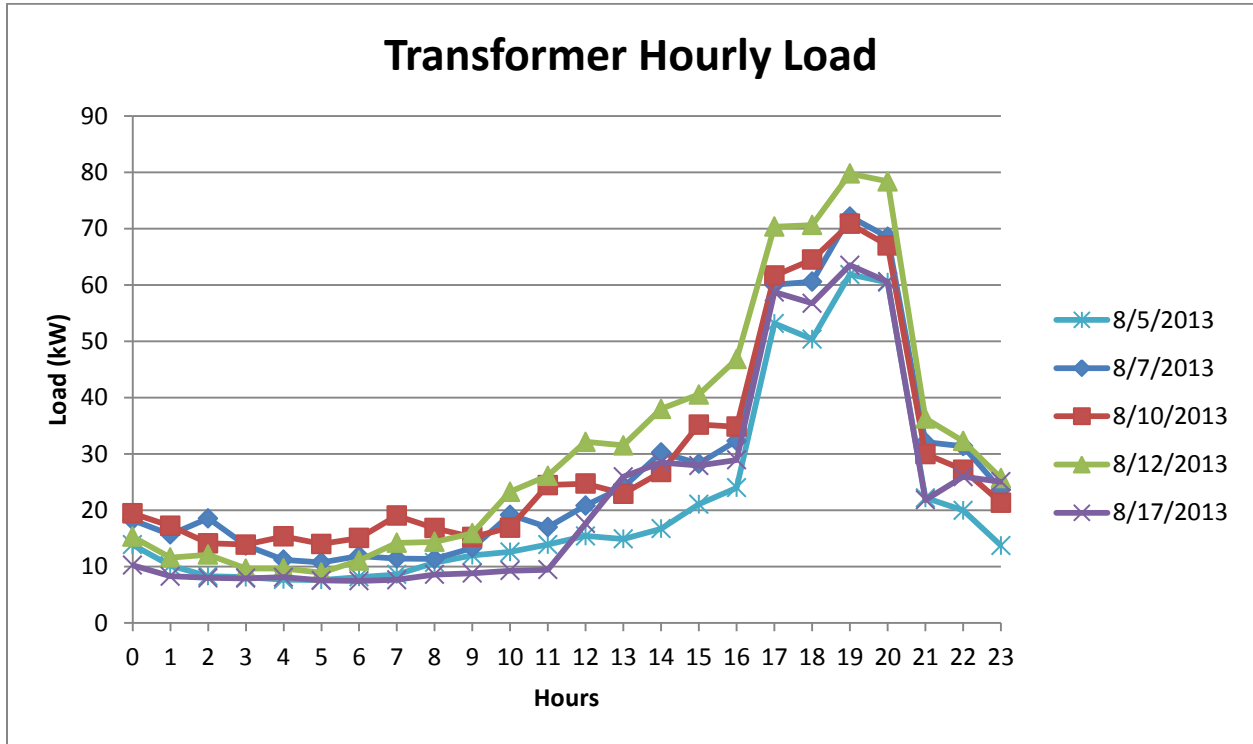


Figure 29: Transformer 2, Customer 7 Simulated Prius Added

After placing a Tesla at the home of Customer 8, the peak load of transformer 2 increased from 79.76 kW to 89.76kW as shown in Figure 30.

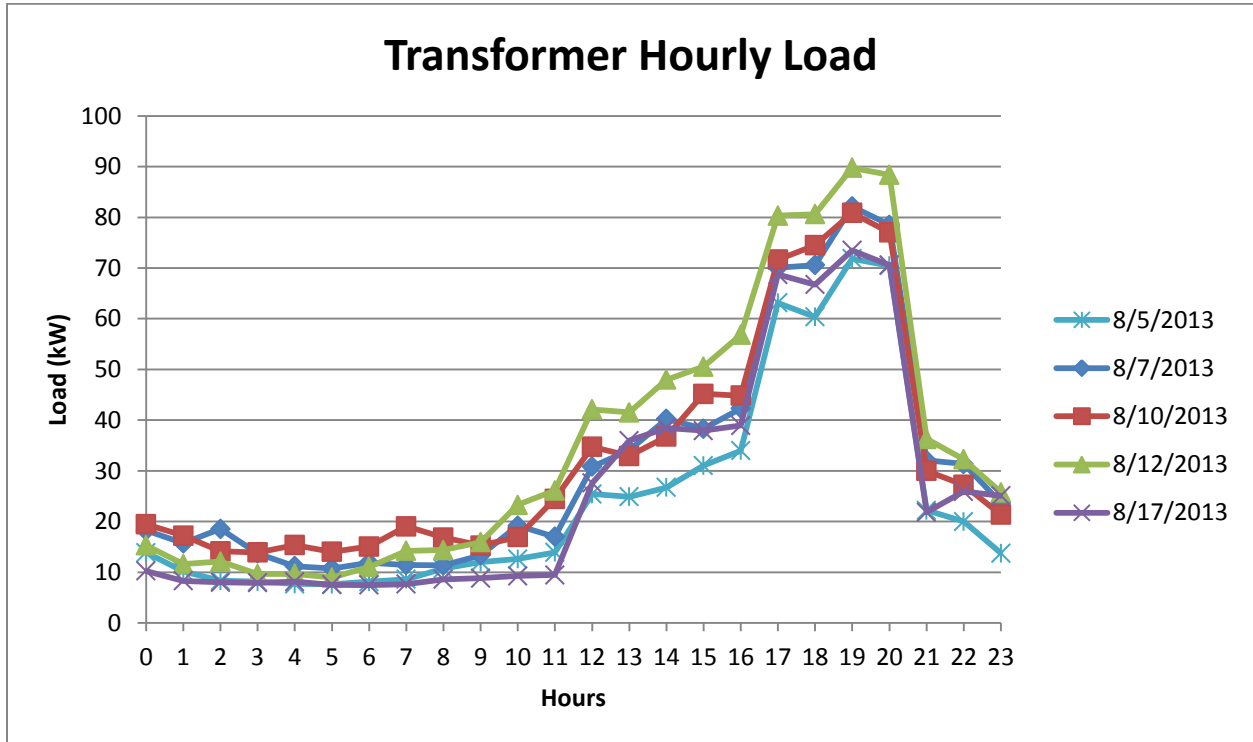


Figure 30: Transformer 2, Customer 8 Simulated Tesla Added

According to data in Table 8, the maximum allowable loading for this transformer is 173% of its name-plate rating of 25 kVA. Therefore, the maximum allowable loading is 43.25 kVA or 38.93 kW. With all seven simulated EVs added to this transformer, this maximum allowable loading has been greatly exceeded. In order to prolong the life of this transformer, TOU pricing incentives are considered.

3.2.2.1 Effect of TOU Pricing Incentives

For transformer 2, if customer 8 can be persuaded to charge the Tesla during off-peak hours between 10 p.m. and 7a.m., the peak load of the transformer will be reduced from 89.76 kW to 79.76 kW as shown in Figure 31.

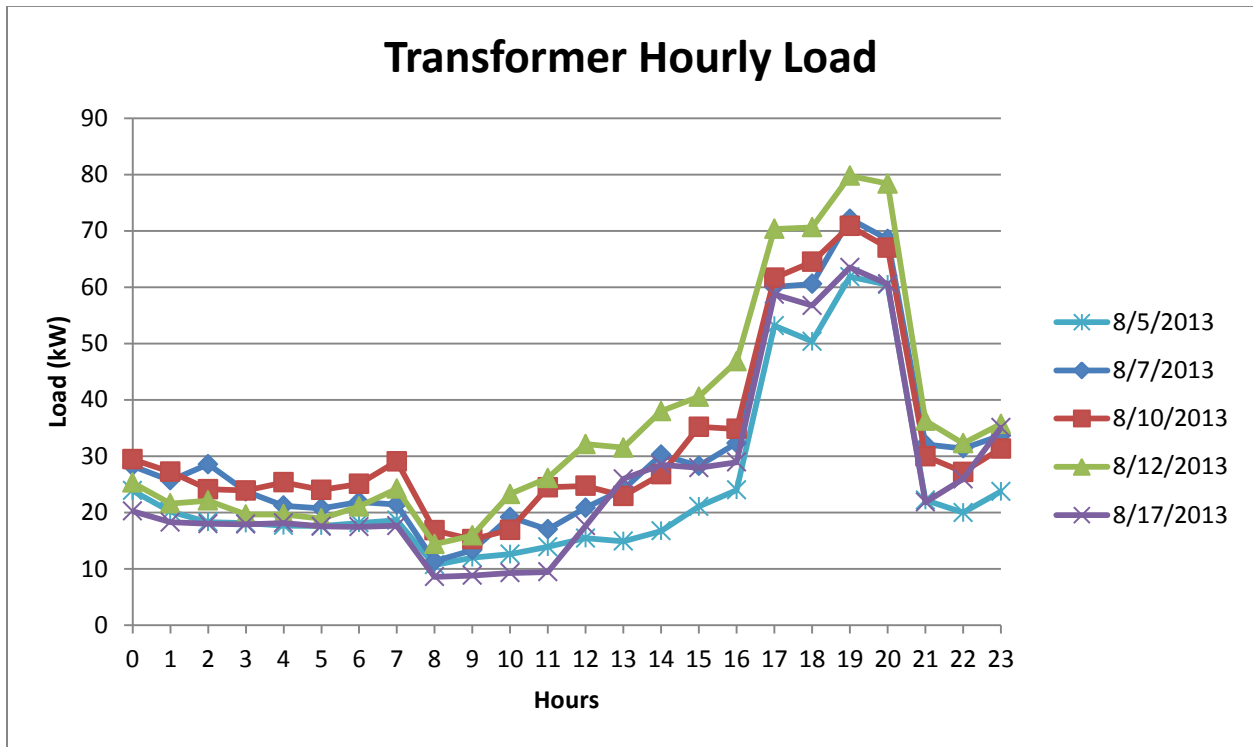


Figure 31: Transformer 2, Effect of Customer 8 Simulated Tesla charging off-peak

If customer 5 can be persuaded to charge the Nissan Leaf during off-peak hours between 11 p.m. and 3 a.m., the peak load of the transformer will be reduced from 79.76 kW to 73.16 kW as shown in Figure 32.

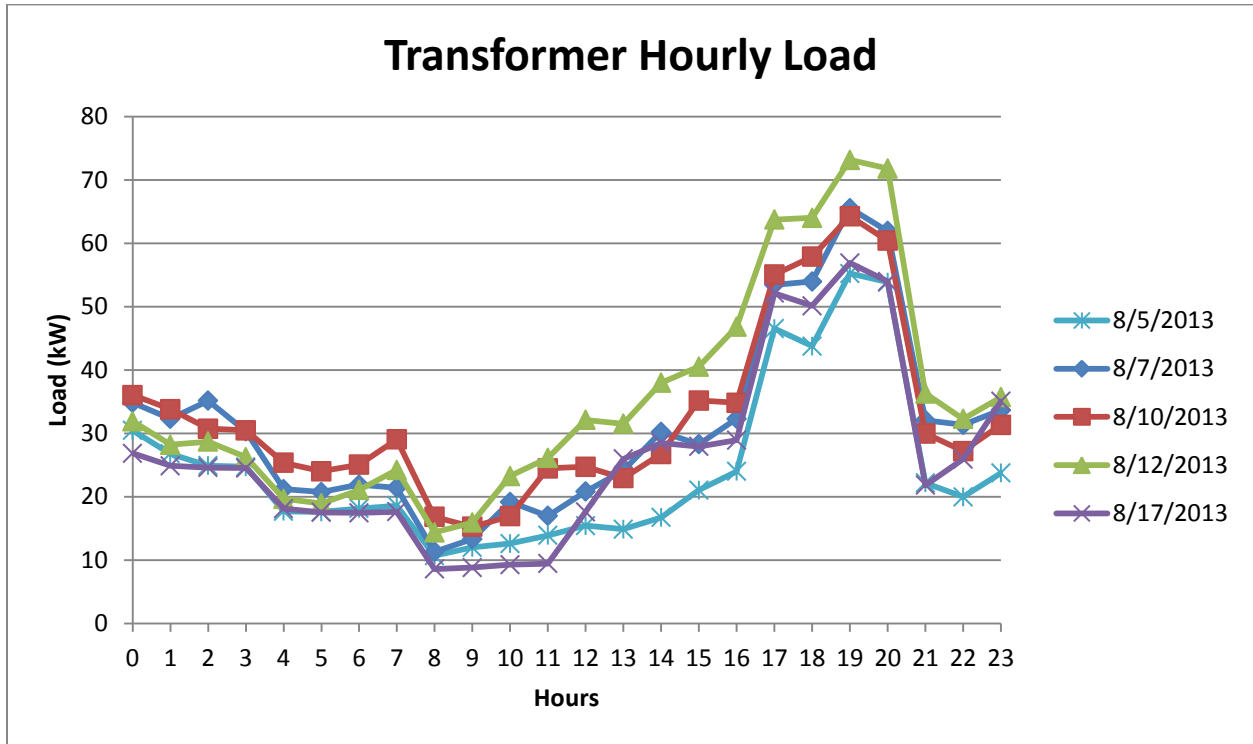


Figure 32: Transformer 2, Effect of Customer 5 Simulated Leaf charging off-peak

If customer 2 can be persuaded to charge the Nissan Leaf during off-peak hours between 11 p.m. and 3 a.m., the peak load of the transformer will be reduced from 73.16 kW to 66.56 kW as shown in Figure 33.

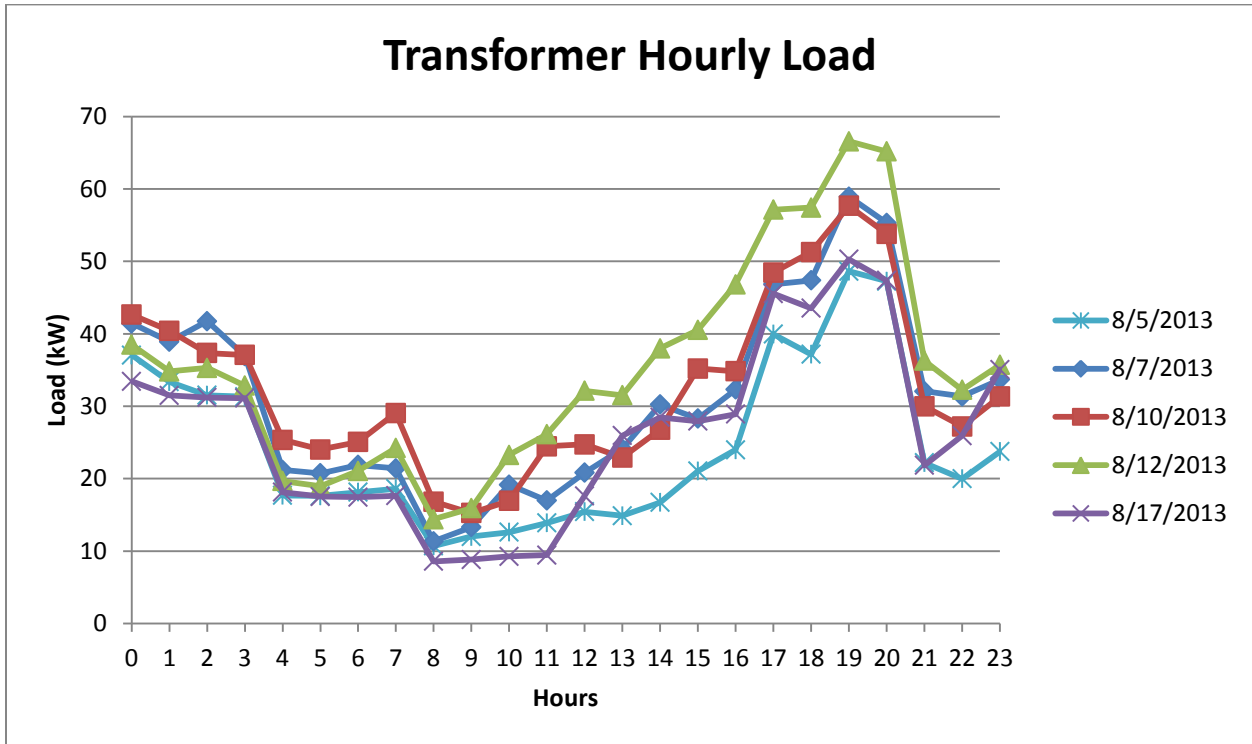


Figure 33: Transformer 2, Effect of Customer 2 Simulated Leaf charging off-peak

If customer 6 can be persuaded to charge the Chevy Volt during off-peak hours between 11 p.m. and 3 a.m., the peak load of the transformer will be reduced from 66.56 kW to 60.76 kW as shown in Figure 34.

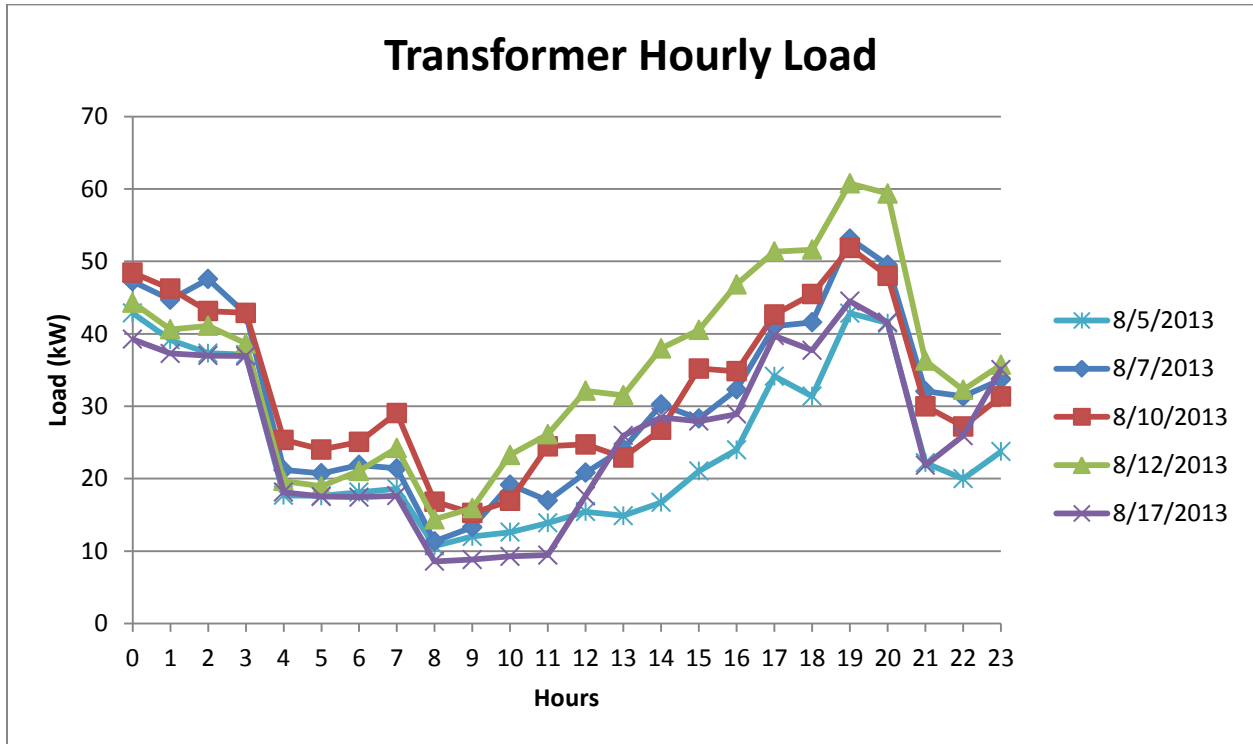


Figure 34: Transformer 2, Effect of Customer 6 Simulated Volt charging off-peak

If customer 3 can be persuaded to charge the Chevy Volt during off-peak hours between 11 p.m. and 3 a.m., the peak load of the transformer will be reduced from 60.76 kW to 56.71 kW as shown in Figure 35.

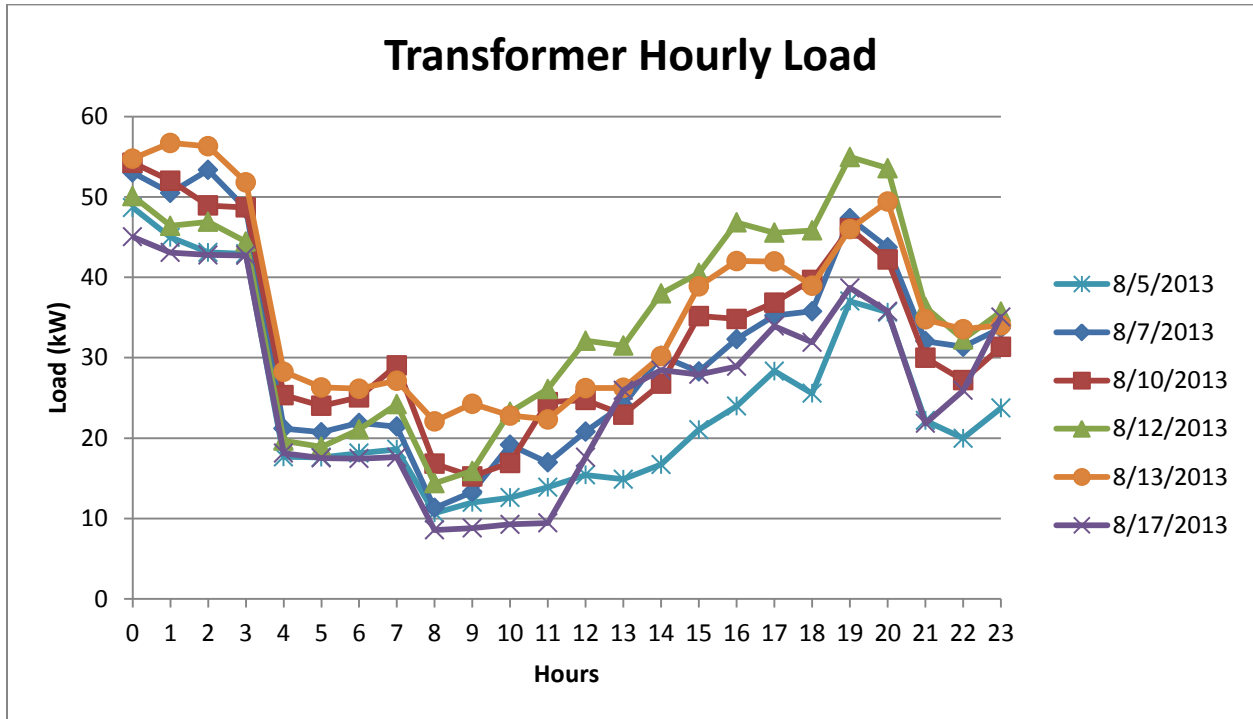


Figure 35: Transformer 2, Effect of Customer 3 Simulated Volt charging off-peak

From Figure 35, it can be seen that there are now two peaks forming on the load profile. Although the overall load peak has been reduced significantly from 89.76 kW to 56.71 kW using TOU pricing incentives, the load peak still exceeds the maximum allowable loading of the transformer. Also, the new load peak of 56.71 kW occurs during off-peak hours at 1 a.m. on 8/13/2013. At this point, device cycling is considered.

If customer 7 can be persuaded to charge the Toyota Prius plug-in during off-peak hours between 11 p.m. and 1 a.m., the peak load of the transformer will be increased from 56.71 kW to 62.51 kW as shown in Figure 36.

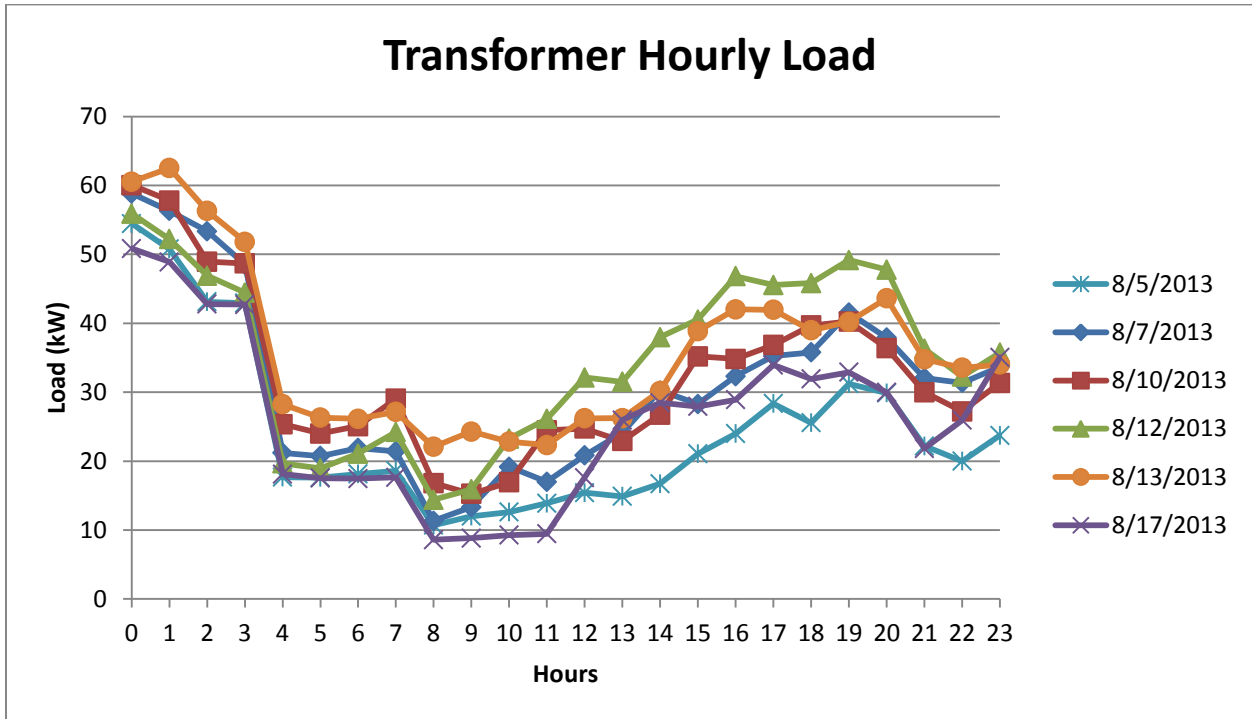


Figure 36: Transformer 2, Effect of Customer 7 Simulated Prius charging off-peak

If customer 4 can be persuaded to charge the Toyota Prius plug-in during off-peak hours between 11 p.m. and 1 a.m., the peak load of the transformer will be increased from 62.51 kW to 68.31 kW as shown in Figure 37.

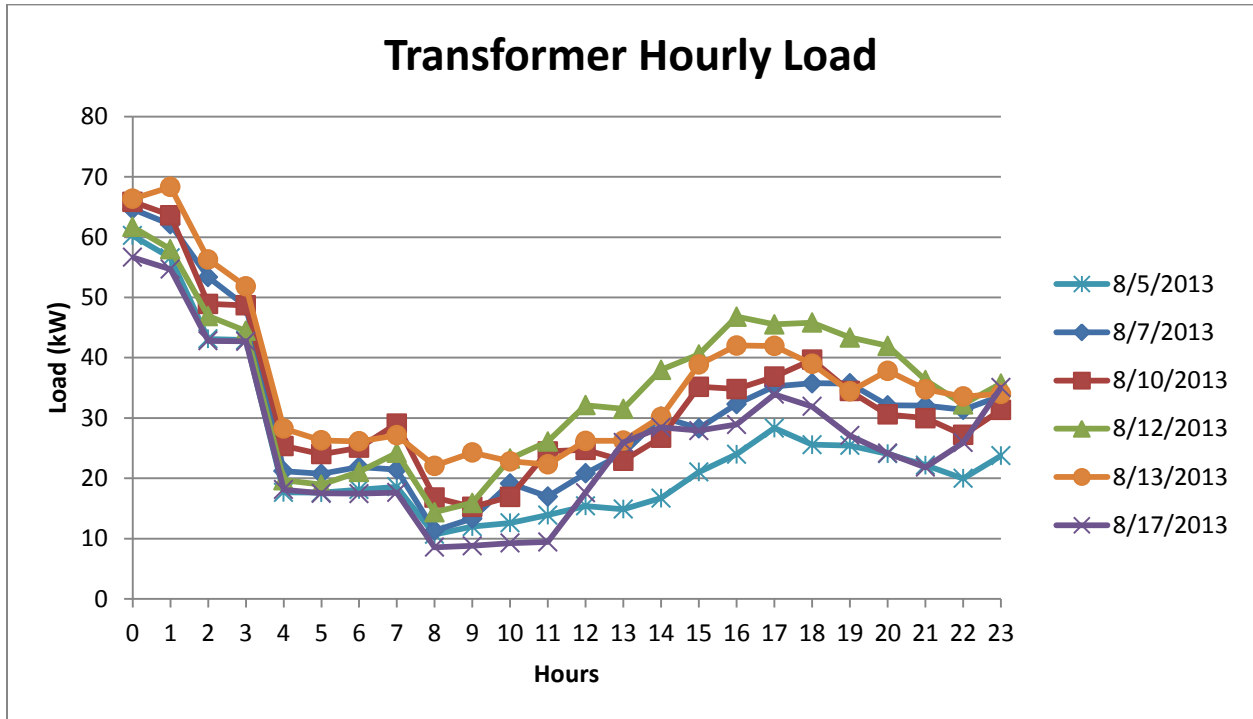


Figure 37: Transformer 2, Effect of Customer 4 Simulated Prius charging off-peak

3.2.2.2 Effect of Device Cycling

In order to reduce the peak load of customer 2 even further, some devices could be turned off during the period the EVs are charging including air conditioners, fans, lights, and humidifiers. Note that the focus now is to reduce the peak load that is occurring between 12 a.m. and 3 a.m. in the morning. Since study data was collected during the summer, this study will assess the impact of cycling air conditions (AC) and all non-essential loads during EV charging periods between 12 a.m. and 3 a.m. Prior to the addition of simulated EVs, the base load between 12 a.m. and 3 a.m. on sample days in August 2013 is shown in the chart below.

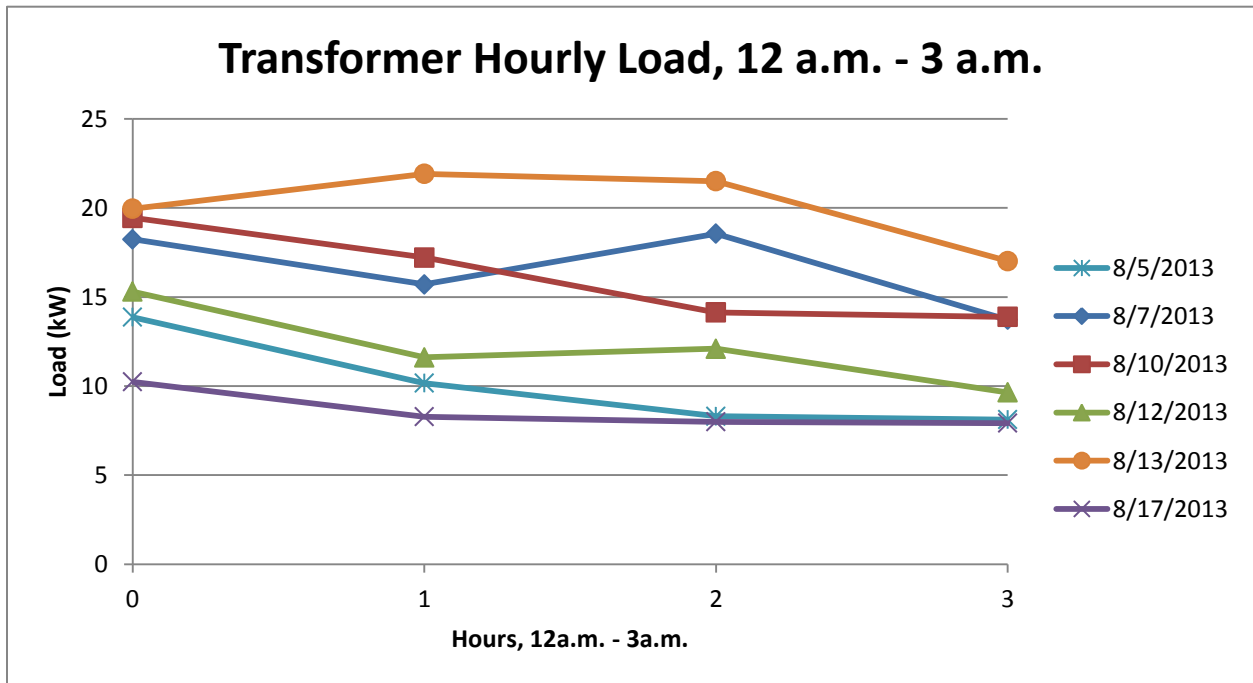


Figure 38: Transformer 2 Daily Load Profiles August 2013, 12 a.m. – 3 a.m.

As seen in Figure 38, the load between 12 a.m. and 3 a.m. on these sample days varies from about 8 kW to about 22 kW. Taking 8/13/2013 as a sample day, the load profiles for all 8 customers are shown in the chart below.

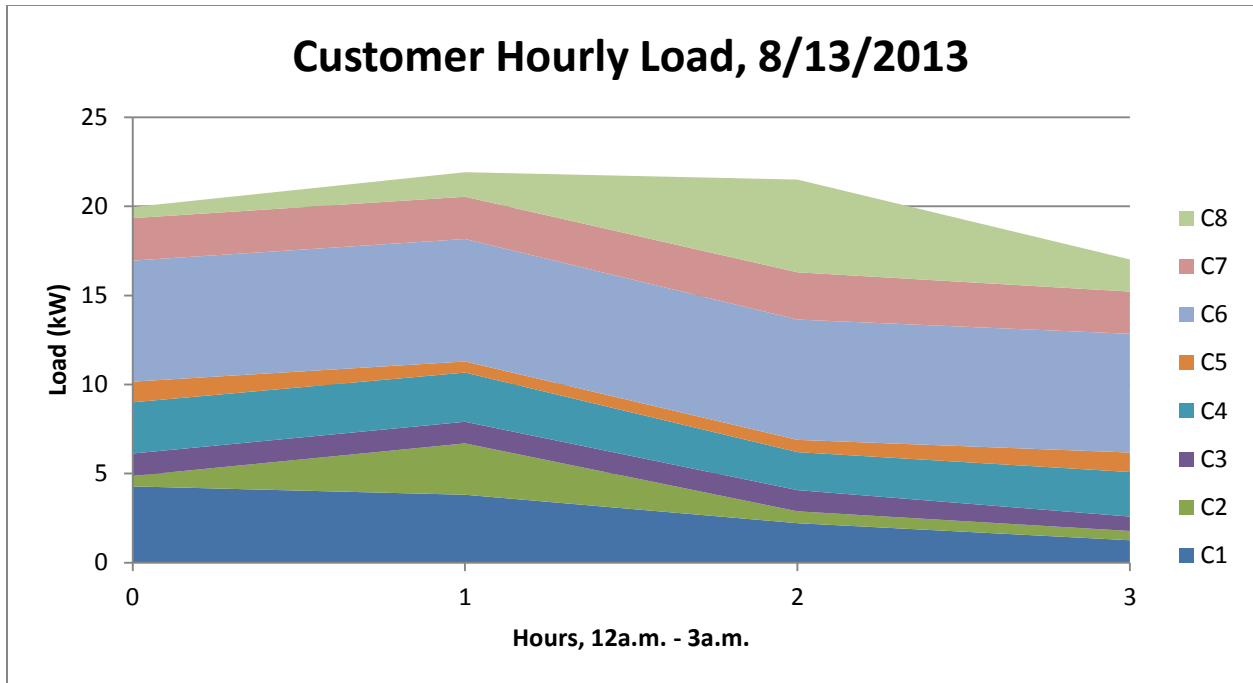


Figure 39: Transformer 2, Customer Hourly Load 8/13/2013, 12a.m. - 3a.m.

It can be seen from Figure 39 that the total electric load for these customers varied from about 17 kW to about 22 kW during the period between 12 a.m. and 3 a.m. on 8/13/2013.

Customer 6 had the highest usage. On this day, the temperature between 12 a.m. and 3 a.m. was 72°F and the humidity ranged between 88% and 94%.

To simulate a situation with all the air conditioners and non-essential loads for these customers turned off during these 3 hours, the load for each customer is set to equal the lowest usage recorded during the two week period of this study. It was seen that by turning off all air conditioners and non-essential loads, the peak base load between 12 a.m. and 3 a.m. on 8/13/2013 can be reduced by a maximum of 16.04kW.

Now, if the peak load of 68.31 kW in Figure 37 is reduced by 16.04 kW, the new peak load is 52.27 kW which still exceeds the maximum allowable loading of this transformer of 38.93 kW.

3.2.2.3 Transformer 2 Secondary Cable Loading Analysis

The eight homes served by Transformer 2 are supplied by 350 Aluminum (Al) main and 4/0 Al service underground cables. See Figure 40.

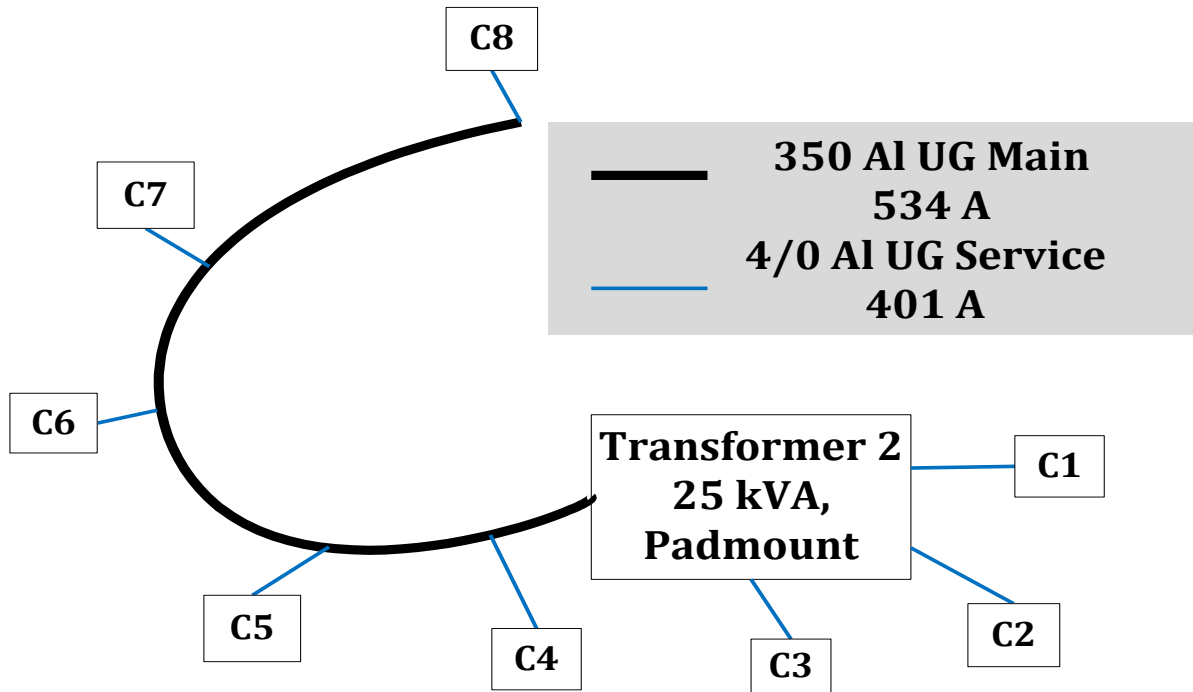


Figure 40: Transformer 2 Secondary Model, C1 through C8 represent the 8 homes served by the transformer

Assuming a combination of TOU pricing and appliance cycling through DSM, the peak load of Transformer 2 is 52.27kW and occurs at 1a.m. on 8/13/2013. The total load for customers 4 through 8 is 38.53kW at that time. The current flowing through the 350 Al cable, rated for 534A, to supply customers 4 through 8 is a maximum of 178.38A. See Equation 11 and Equation 12. The 350 Al cable loading is within the design limit.

Equation 11

$$S = \frac{P}{P.F.}$$

$$S = \frac{38.53kW}{0.9} = 42.81kVA$$

Where

P = Real Power in Kilowatts (kW)

S = Apparent Power in Kilovolt-amps (kVA)

P.F. = Power Factor

Equation 12

$$I = \frac{S}{V}$$

$$I = \frac{42.81kVA}{240V} = 178.38A$$

Where

I = Current in Amperes (A)

V = Voltage in Volts (V)

S = Apparent Power in Kilovolt-amps (kVA)

The 4/0 Al service cables are rated for 401A. Table 16 outlines the individual customer power usage at the transformer peak load hour. Based on the power usage at the customer level, the loading of the 4/0 Al cables is within the design limit. Since the secondary cable loading is within design limit, it can be assumed that the primary cable loading is also within design limit.

Table 16: Transformer 2, Customer load at peak load hour assuming DSM

Customers	Load at Peak Load Hour, 1:00 A.M., 8/13/2013	
	Load in kW	Load in kVA
C1	0.51	0.57
C2	7.03	7.81
C3	6.21	6.90
C4	7.01	7.79
C5	7.04	7.82
C6	7.32	8.13
C7	6.89	7.65
C8	10.27	11.42
Total	52.27	58.08

3.2.2.4 Transformer 2, Voltage Drop Calculations

i. Transformer percent voltage drop

With a transformer load of 58.1kVA assuming DSM, the transformer percent voltage drop (V.D.) is 3.14%. See Equation 13.

Equation 13

$$\% \text{ V. D.} = \frac{\text{Transformer Load (kVA)}}{\text{Nameplate Capacity (kVA)}} \times \% \text{ Voltage Regulation}$$

$$\% \text{ V. D.} = \frac{58.1\text{kVA}}{25\text{kVA}} \times 1.35\% = 3.14\%$$

ii. Secondary cable percent voltage drop

Table 17 summarizes the voltage drop calculations. Assuming DSM, the worst case voltage drop of 4.04% is seen by customer 8. The voltage drop results obtained are within the PSC's established voltage drop standard.

Table 17: Transformer 2, Secondary voltage drop calculations assuming DSM

Cust.	Peak load with DSM (kVA)	Transf. V.D. (%)	Distance of cable main from source (ft.)	Cable main V.D. (%)	Distance of service cable from source (ft.)	Service cable V.D. (%)	Total V.D. at the customer's meter (%)
C1	0.57	3.14	N/A	N/A	170	0.04	3.18
C2	7.81	3.14	N/A	N/A	60	0.17	3.31
C3	6.90	3.14	N/A	N/A	40	0.10	3.24
C4	7.79	3.14	80	0.15	60	0.17	3.46
C5	7.82	3.14	120	0.23	80	0.23	3.60
C6	8.13	3.14	160	0.31	90	0.27	3.72
C7	7.66	3.14	200	0.37	40	0.11	3.62
C8	11.41	3.14	250	0.68	50	0.21	4.04

3.2.3 Transformer 3

Simulated EVs were placed on this transformer during the traditional peak period as summarized in the table below.

Table 18: Transformer 3, Simulated EV Load

Customer #	EV Type	Simulated EV	Simulated EV Function Load (kW)	Charge Time (Hours)	Simulated Charge Period
C1	N/A	Nissan LEAF	C1+6.6	4.0	4pm – 8pm
C2	N/A	Toyota Prius	C2+5.8	2.0	6pm – 8pm
C3	N/A	Chevy Volt	C3+5.8	4.0	4pm – 8pm
C4	N/A	Tesla Model S	C4+10	9.0	11am – 8pm
C5	Toyota Prius	N/A	N/A	N/A	N/A

After placing a Nissan Leaf at the home of Customer 1, the peak load of transformer 3 increased from 23.35 kW to 29.95 kW as shown in Figure 41.

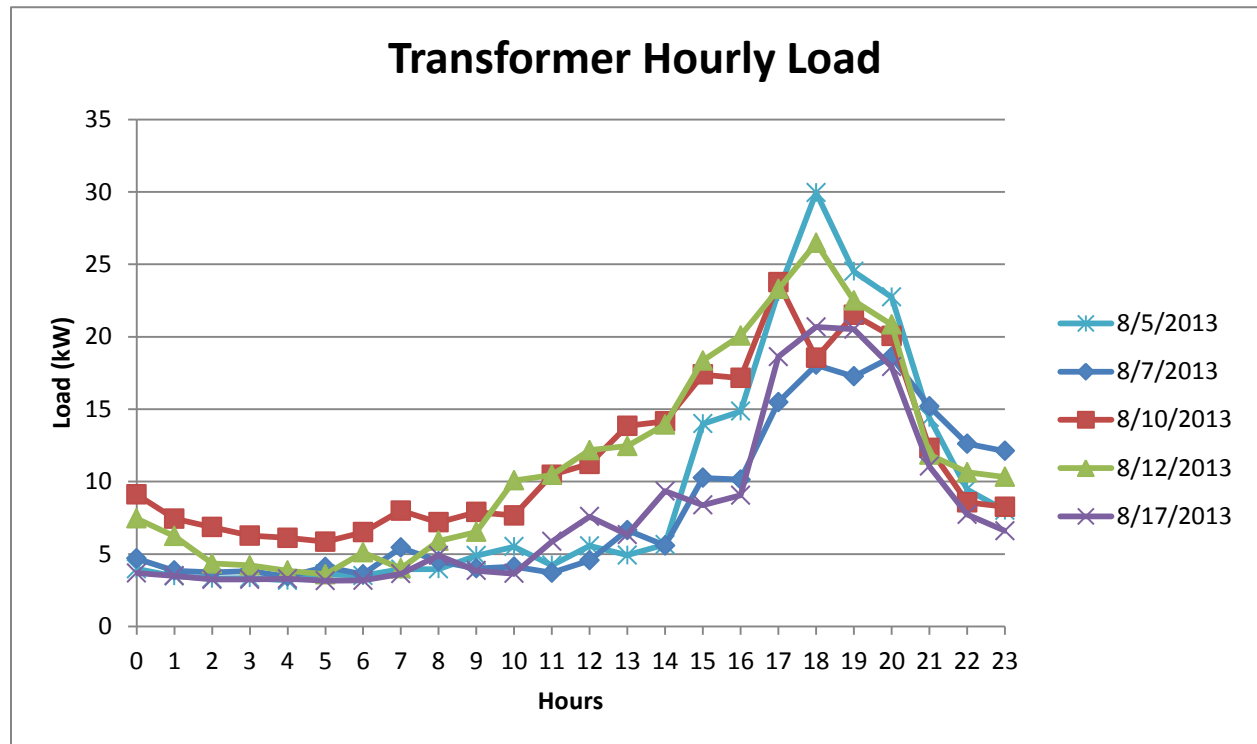


Figure 41: Transformer 3, Customer 1 Simulated LEAF Added

After placing a Toyota Prius plug-in at the home of Customer 2, the peak load of transformer 3 increased from 29.95 kW to 30.34 kW as shown in Figure 42.

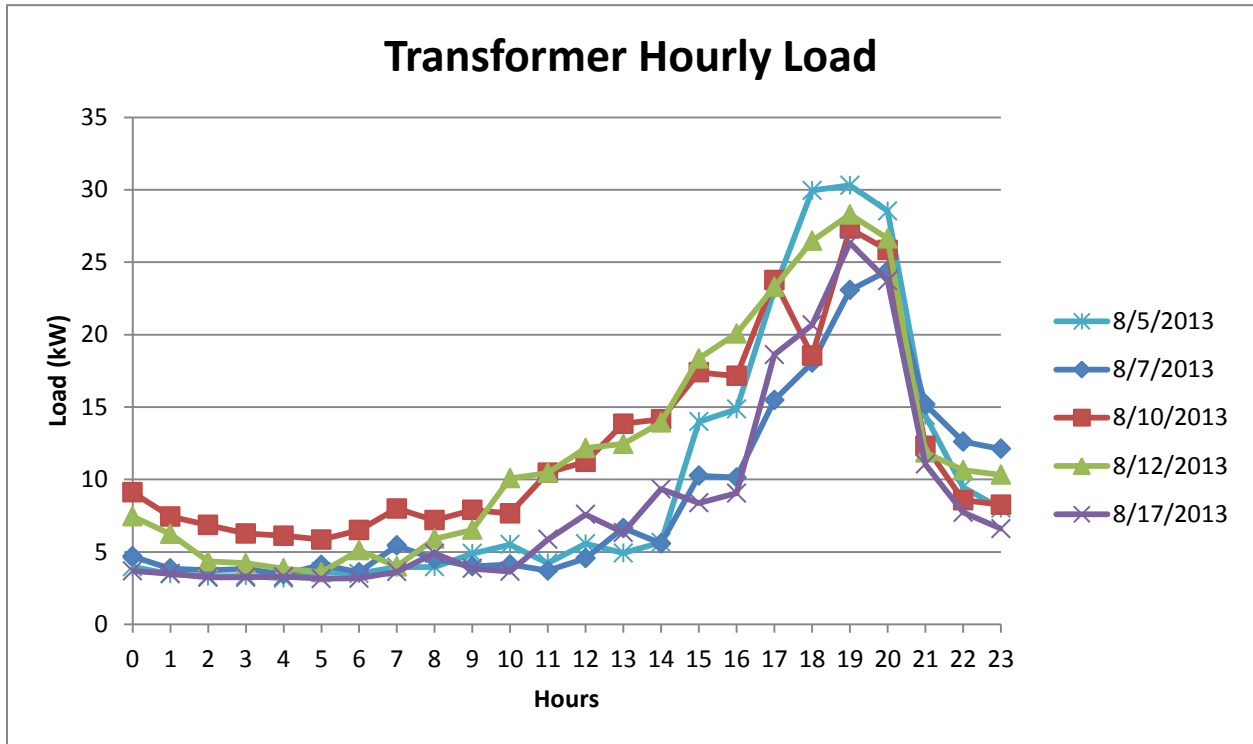


Figure 42: Transformer 3, Customer 2 Simulated Prius Added

After placing a Chevy Volt at the home of Customer 3, the peak load of transformer 3 increased from 30.34 kW to 36.14 kW as shown in Figure 43.

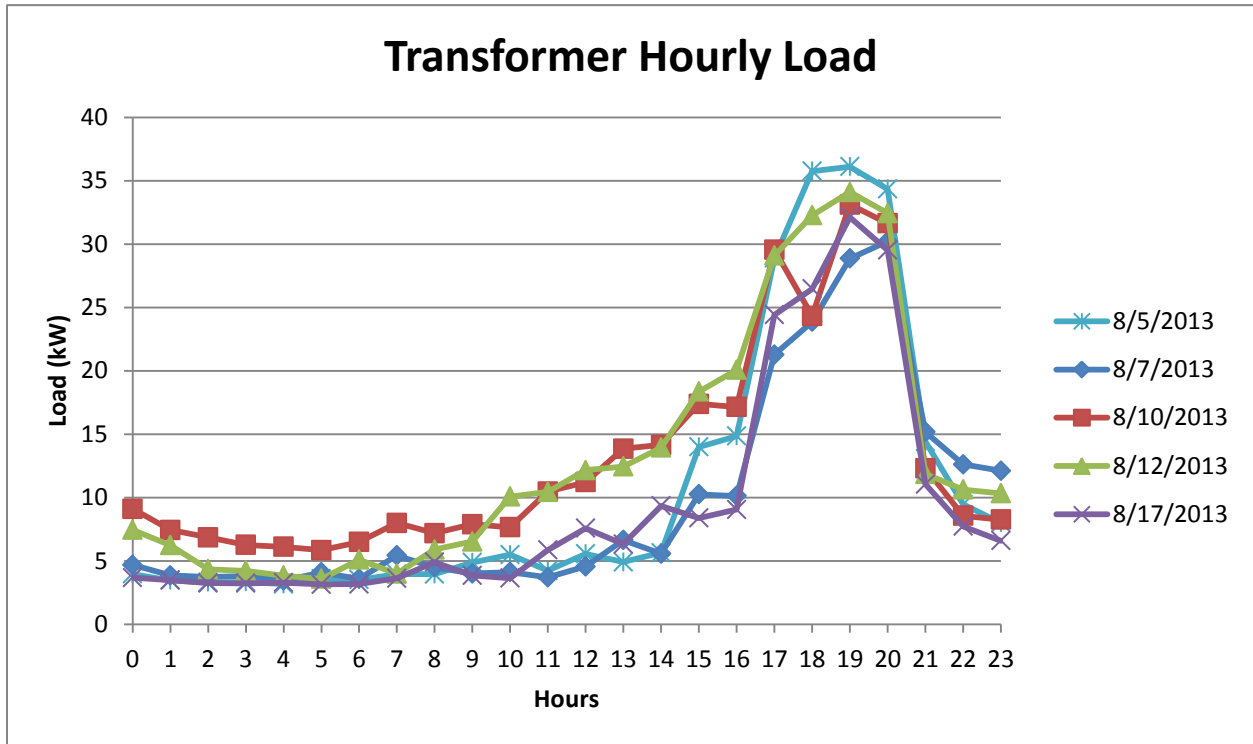


Figure 43: Transformer 3, Customer 3 Simulated Volt Added

After placing a Tesla Model S at the home of Customer 4, the peak load of transformer 3 increased from 36.14 kW to 46.14 kW as shown in Figure 44.

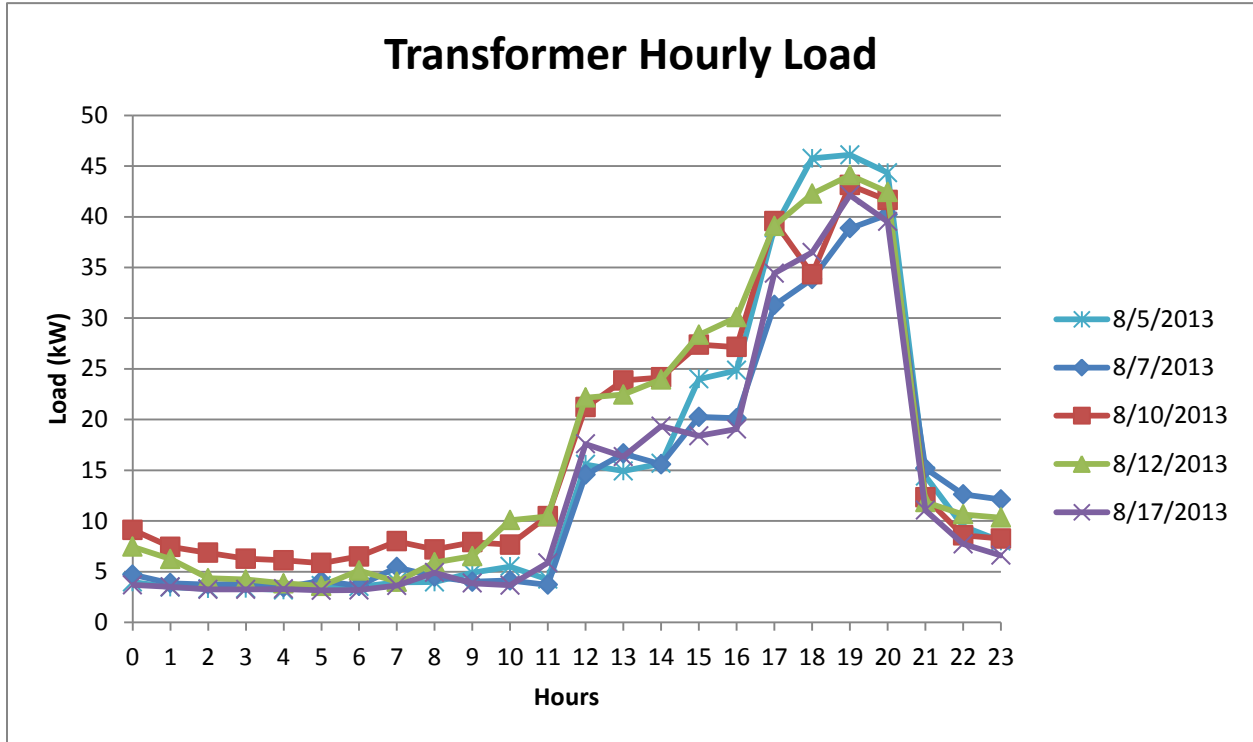


Figure 44: Transformer 3, Customer 4 Simulated Tesla Added

According to data in Table 8, the maximum allowable loading for this transformer during the summer is 175% of its name-plate rating of 50 kVA. Therefore, the maximum allowable loading is 87.5 kVA or 78.75 kW. With all four simulated EVs added to this transformer, this maximum allowable loading was not exceeded.

3.2.3.1 Transformer 3 Secondary Cable Loading Analysis

The overhead secondary service cable that serves each of the customers on Transformer 3 is a 4/0 Aluminum (Al) cable rated for 401A. For customers 4 and 5, this service cable is

supplied by a 350 Al cable main rated for 534A. See Figure 45.

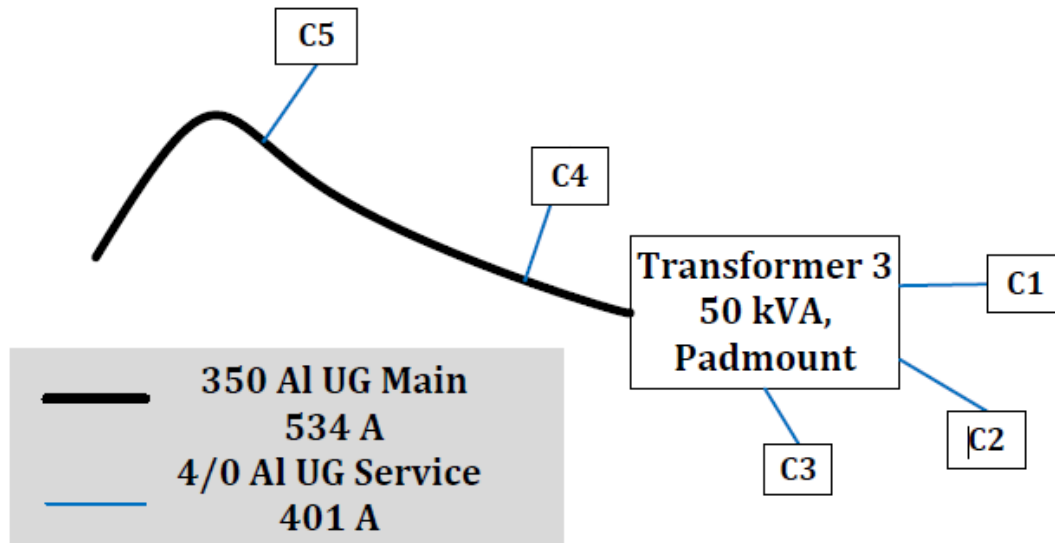


Figure 45: Transformer 3 Secondary Model, C1 through C5 represent the 5 homes served by the transformer

The peak load for this transformer is 46.14kW (or 51.27 kVA) seen at 7 p.m. on 8/13/2013. At the peak load hour, the total load for customers 4 and 5 is 18.84kVA. See Table 14. Therefore, the maximum current through the 350 Al cable is 78.5A. See Equation 10. The loading of the 350 Al cable is within the design limit. The loading of the 4/0 Al cables, rated for 401A, is also within design limit.

Table 19: Transformer 2, Customer load at peak load hour assuming DSM

Customers	Load at Peak Load Hour, 7:00 P.M., 8/13/2013	
	Load in kW	Load in kVA
C1	9.97	11.08
C2	7.44	8.27
C3	11.77	13.08
C4	11.64	12.93
C5	5.32	5.91
Total	46.14	51.27

Equation 14

$$I = \frac{S}{V}$$

$$I = \frac{18.84 \text{ kVA}}{240 \text{ V}} = 78.5 \text{ A}$$

Where:

I = Current in Amperes (A)

V = Voltage in Volts (V)

S = Apparent Power in Kilovolt-amps (kVA)

Since the secondary cable loading is within design limits, it can be assumed that the primary cable loading is also within design limits.

4 Discussion

Based on the peak load during the analysis period, it was found that Transformers 1, 2, and 3 have a medium, high, and low risk of experiencing overloads respectively due to a higher EV penetration. A large scale penetration of electric vehicles will have an impact on low voltage distribution transformer loading. Table 20 below summarizes the sample transformer specifications, peak load during the analysis period, and the level of risk of failure based on loading.

Table 20: Study Results showing Risks of Transformer Overload

Transformer #	# of meters served	% EV Penetration¹	Transformer Capacity (kVA)	Peak load in study (kW)	Peak load assuming DSM	Summer load limit (kW)	Risk of Overload
1	5	20%	25	45.88	35.88	38.93	Medium
2	8	12.5%	25	89.76	52.27	38.93	High
3	5	20%	50	46.14	N/A	78.75	Low

The risk of overload shown in Table 20 above is based on a potential increase in electric vehicle concentration on each of the transformers shown. To reduce the impact of EV loading, EV-TOU pricing and other DSM techniques like appliance cycling during peak usage periods were employed. However, as in the case of transformer 2, even these measures may not be sufficient to adequately manage the impact of a large scale penetration of EVs. By including EV penetration analysis in periodic load forecast analysis, electric utility planners can forecast the maximum loading on low voltage distribution transformers as a result of EV penetration. TOU pricing incentives may or may not cause EV customers to adopt new electricity usage patterns.

¹ Data in the percent EV penetration column of this table is based on the assumption that each customer will eventually buy one EV. However, it is possible that customers may decide to purchase more than one EV.

Also, financial incentives may not be adequate to convince customers to sign up for appliance cycling programs.

5 Conclusion

When multiple customers served by the same distribution transformer charge their EVs at home at the same time, especially during periods of high power demand, the transformer is subjected to overloads. This study analyzed the loading on three distribution transformers, as well as their distribution cables in Maryland.

Out of the three transformers analyzed in this study, Transformer 2, which is a 25 kVA transformer and serves eight residential homes, has the highest risk of experiencing an overload if all customers served by the transformer purchase EVs. Transformer 2 has a nameplate rating of 25kVA (22.5kW assuming a 0.9 power factor). With one EV owner, Transformer 2 has a peak load of 46.82kW during the study period between August 4 and August 17, 2013. When seven additional EVs of different types were added in a simulated scenario during peak usage hours between 10 a.m. and 8p.m., the peak load for Transformer 2 increased from 46.82kW to 89.76kW, which is outside the transformer thermal limit.

The impact of TOU pricing was analyzed as follows. Charging for EVs could be delayed until after 11 p.m. during the summer, based on off-peak EV-TOU pricing rates previously discussed. The expectation is that every vehicle must be completely charged by 7 a.m. the next morning. So while the additional electricity demand is roughly the same, it now occurs at a time of much lower total electricity demand. In this scenario, risks of overloading low voltage distribution transformers are reduced but not totally avoided.

In this research, when five out of seven simulated EVs on Transformer 2 are moved to off-peak hours between 11 p.m. and 7 a.m., the peak usage, which was 89.76kW and occurred at 7 p.m. on 8/12/2013 reduced to 56.71kW and occurred at 1 a.m. on 8/13/2013. Also, two main load peaks were formed, one of which was during the traditional “off-peak” period between 12

a.m. and 3 a.m. Although this transformer now has a reduced risk of experiencing an overload, the loading limit of 38.93kW is still exceeded. When all simulated EVs are moved to off-peak hours, the peak load increased from 56.71kW to 68.31kW, and there is just one load peak period between 12 a.m. and 3 a.m.

By implementing appliance cycling, which is basically turning off air conditioners, lighting, and other non-essential electric loads during the hours between 12 a.m. and 3 a.m., this 68.31kW peak load can further be reduced to 52.27kW. Even then, the loading limit of 38.93kW is still exceeded by 8% - 34% during a 3 hour window. However, the loading on both the primary and secondary cables is within thermal limits. Also, the voltage drop at the customers' meters is within the established PSC standard.

It should be noted that for this 25kVA transformer supplying eight customers, the available capacity per customer is low, compared to Transformer 1 which is a 25kVA transformer and serves five customers or Transformer 3 which is a 50kVA transformer and also serves five customers. Based on this study, EV impacts for most utility distribution systems are likely going to be localized to smaller transformers and other devices where the available capacity per customer is already low. It will be helpful to have a proactive utility approach of identifying where EVs are appearing on their system and address near-term localized impacts on low voltage distribution transformers and cables. Developing customer demand management programs and technologies for managing long-term charging loads, like EV TOU rates and appliance cycling DSM programs, and gaining customer utilization of such programs will enable large-scale EV adoption.

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