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Parameter Identification for Optimal Electric Vehicle Rate Structures

Final Report

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Parameter Identification for Optimal Electric Vehicle Rate Structures

Final Report

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Executive Summary

This is the final report of NYSERDA Project 39151: Parameter Identification for Optimal Electric Vehicle Rate Structures. This project was conducted by Clarkson University investigators Thomas Ortmeyer, Lei Wu, and Dylan Dean. Greg Pedrick was the project manager for this research.

This project focused on the longer term impacts of electric vehicle (EV) charging on the electric power system. In particular, the study considers a 10 percent or greater EV penetration rate. This penetration level is sufficient to support a robust network of EV chargers. Optimistically, we could reach the 10 percent penetration level in as quickly as five years.

Electric vehicles present unique challenges to the power system utilities when it comes to charging these vehicles. Each year EVs become more affordable and as battery technology improves, EVs can go further. This research develops an EV transportation model based on data from the National Household Travel Survey, which models the impacts on the distribution system. The impacts of EV charging on daily peak load, voltage imbalance, transformer overloads, and line overloads are analyzed. This report gives special emphasis to the effects of DC Fast Charging, both alone and in combination with expected levels of Level 2 charging. This report defines DC Fast Charging as the charging technology where rectified ac power is supplied to the vehicle through a DC connector, and has the capability to charge the vehicle in one hour or less. This definition is intentionally broad and covers several subcategories that are either in place or under development.

Key findings include:

- Advanced EV penetration levels above 10 percent in urban/suburban areas should provide sufficient market for a robust network of commercial DC Fast Charge charging stations.
- The bulk of personal vehicle EV charging will take place at home with Level 2 charging.
- The combination of commercial DC Fast Charging and home charging will contribute to the distribution system peak load and reduce voltage levels on the feeders.

1 Introduction

There is growing interest in electric vehicle (EV) and plug in hybrid electric vehicle (PHEV) technologies because of their reduced fuel usage and greenhouse gas emissions. The NYSERDA Project 39151: Parameter Identification for Optimal Electric Vehicle Rate Structures, performed research into the impact of pure EV charging on the power grid in New York State. This study assumes that PHEV's will not use DC Fast Charging. Each year the popularity and number of EVs on the road increases. With a growing presence in America's transportation system, an increased impact on the power grid from the charging of EVs is expected. There are three categories of EV charging: Level 1, Level 2, and DC Fast (Level 3). Perhaps most concerning amongst the charging methods is the DC Fast chargers that are gaining popularity as an "away from home" charging option. It is anticipated that charging stations analogous to gas stations with around 10 of these DC Fast charging units will constitute a majority of the public charging market. Currently, Tesla "Super Charger" stations employ as many as 12 DC Fast charging units at a single station. The DC Fast charging unit's anticipated popularity over Level 1 and Level 2 public charging options stems from the speed and convenience of the units. EV owners will most likely opt for the fastest, most convenient and cost effective charging option for public charging. Still, it is anticipated that most EV owners will continue to charge at home overnight.[1]

To best investigate the effect of a large number of EV charging units in NYS, a simulation of a typical State utility's power system is the basis for this investigation. This study uses a Power system simulation software called Distribution Engineering Workstation (DEW). To simulate the load from EV charging on the system, a model using MatLab based on numerous statistical figures and stochastic methods are covered later in this document. A base case analysis of the system's power flow from the system serves as a basis of comparison. Adding charging stations to loaded feeders in the system tests the effect of various penetration levels of EVs and charging stations on the system. The analysis monitors the effect of adding chargers to the system on transformer overloads, voltage flicker, and voltage sensitive components in an effort to expose any reliability issues that may arise as a result of the additional load from EV charging.

2 Background and Literature Review

The focus of this chapter provides an overview of the information associated with this study as well as reviews on studies and sources. The analyses and methods discussed in other papers were excellent in some areas, but weak in others. This section covers these areas in more detail.

2.1 Distribution System Impacts Resulting from Electric Vehicle Charging

Much work has gone into determining the best method by which to model the future tendencies of EVs in the transportation system and how they will impact the distribution system. The best way to identify the impact of EVs on the distribution system is to utilize an accurate transportation model to determine the methods of charging and the most likely charging times. While this strategy is the basis of numerous papers, most analyze the impacts of EV charging on a distribution system and primarily focus on Level 1 and 2 charging.[1, 2, 3,4] Others briefly cover impacts of DC Fast, but not in any particular depth.[1]

Some research papers model the activity of EVs unrealistically, randomly distributing the charging behavior of a population of EVs throughout the course of the day without taking into account documented travel tendencies. The resulting model would prove unreliable if used for power system planning activities. A common practice to develop a transportation model is to use data from the National Household Travel Survey (NHTS) in conjunction with probability functions to determine likely charging times for EVs.[5,6,3] Some studies utilize empirical localized travel data to serve as a basis for their transportation model.[3 7, 8,9,10] This method for creating a transportation model is logical and may be the best method for accurately predicting the most likely arrival and departure times for vehicles as well as daily travel distances. The travel distances are useful for developing an accurate representation of state of charge (SOC) upon arrival to a charging unit. An accurate depiction of SOC for a population of vehicles is pivotal for accurately modeling the load from a charging event. Some models take into account the likelihood of EVs departing more than once per day and potentially charging more than once per day using various charging methods, be it Level 1, 2, or 3.[7,5,1] Some models only focus on the impacts from Level 1 and Level 2 charging.[2]

Models must also be developed for the vehicles and their charging systems. Some papers choose arbitrary values for battery capacity and vehicle range in their analyses.[6, 3, 8] A more accurate model can be developed by using readily available data on current EVs like the Nissan Leaf or Chevy Volt.[7, 1, 2, 10] The chargers and their associated specifications are a critical aspect of developing an accurate load model. There are numerous charging specifications used by the EV charging industry including the EPRI-NEC and SAEJ1772 standards that can accurately represent the charging load for Level 1 and 2 [1, 2, 3] as shown in Table 2.1. The EV and transportation models are described by a combination of factors including vehicle type, charging power level, start time, and the miles driven and associated SOC.

Table 2-1. Charging Standards for EV Chargers

Standard	Charging Level		
	1	2	3
EPRI-NEC	120VAC, 15A (12A), 1.44kW	240VAC, 40A, 1-Phase	480VAC, 3-Ph, 60-150kW
SAEJ1772	120VAC, 12A, 1-Phase 1.44kW	208-240VAC 32A, 1-Ph, 6.66-7.68kW	208-600VAC, 400A, 3-Ph, >7.68kW

Most papers analyze the effects of charging on a distribution system use models developed either independently or by EPRI or IEEE.[2] Although this is an accurate way to find the impact on a distribution system as it considers the spatial characteristics of the distribution feeder, using a geographically specific distribution system can give more pointed and relevant results, which is crucial in the scope of this study. In most documents, this study included, the EVs are placed arbitrarily around the spatial geography of a distribution feeders. Most papers utilize different methods to analyze the system to determine the impact of the EVs charging on the distribution system. Most papers utilize different methods to determine the impact of EV charging on a distribution system including Monte Carlo analysis and daily load flows resulting from increased EVs penetration. Many papers conclude that distribution system impacts including transformer thermal overloading, phase imbalance, voltage regulation, power losses, transformer degradation, and harmonic distortion are the primary impacts of EV charging.[1, 2, 4] With respect to DC Fast charging, due to the higher peak load from the charger, the effect on three-phase distribution lines and three-phase transformers is exacerbated and becomes a greater focus of concern when compared to lower level charging. The addition of these chargers to the system pose less risk for system imbalance and single phase distribution transformer overloads. Additionally, the peak load of DC Fast chargers temporally coincides with the distribution system peak load, which gives further emphasis to distribution equipment concerns.[1, 2] When conducting a study on the impact of EV charging on the distribution system, it is important to consider a multitude of factors when developing a model to most accurately emulate the potential impact of EVs. It should also be noted that the potential impacts of EVs are increasing as the battery capacity of EVs is increasing and chargers are becoming faster and more powerful.

The impact of EV charging on the distribution system is generally well studied, although sometimes with less accurate transportation models and often without significant attention to potential impacts of DC Fast charging. It is important to understand the future impact of EV charging on power system planning and the potential need to increase the robustness of distribution transformers and feeders.

3 Model Description

This chapter describes the processes used for studies in this document. It is crucial to replicate a realistic scenario for EV charging. A realistic EV charging scenario ensures the most accurate representation of the effect of charging on the system. This chapter also describes the NYS distribution system and the software used to model it. Additionally, the charging model used in the analysis and the techniques used to develop it are explained. Perhaps the most important aspect is a transportation model that accurately represents when EVs will arrive to charge at the stations.

3.1 Distribution System Model

The State power distribution grid base case used in this study was obtained from the partnering NYS utility as well as the DEW database so the base case system could run. Once the system was analyzed, the software generated a file that outlines the loads at each feeder in the system on a monthly basis. The base system on which the analyses are conducted is a multiple feeder system located in southern NYS. There are 22 customer load types included in the base case system. Figure 3.1 shows a schematic of the base case distribution system. The system simulation is an accurate representation, both geographically and in content, of the existing system in NYS. The connected loads in the simulation represent individual customers and vary from residential loads to commercial class loads. The customers are connected to the lines with either single phase or three-phase overhead, underground, or pad-mount transformers. The system simulation encompasses a fairly large area with multiple feeders. For the purpose of analysis, the most heavily loaded feeder is selected to test the effect of EV charging on the system.

In the system base case, one substation stood out as the most loaded. In the modeled case there are overloads on the substation transformer during high load hours in the summer time. These high load hours, when the overloads occur, will be the time interval of interest for the purposes of testing. Testing the effects of EV charging at high load hours should represent the potential worst case scenario.

Figure 3-1. Base case system schematic

3.2 DC Fast Charging Station Load Model

In this study, MatLab created a model of a DC Fast charging station. To model the load of a DC Fast charging station in the system several variables are considered. This section outlines the strategies that have led to the development of the DC Fast charging station load profiles used in this study. The models and assumptions used in this study intends to project EV usage five or more years in the future.

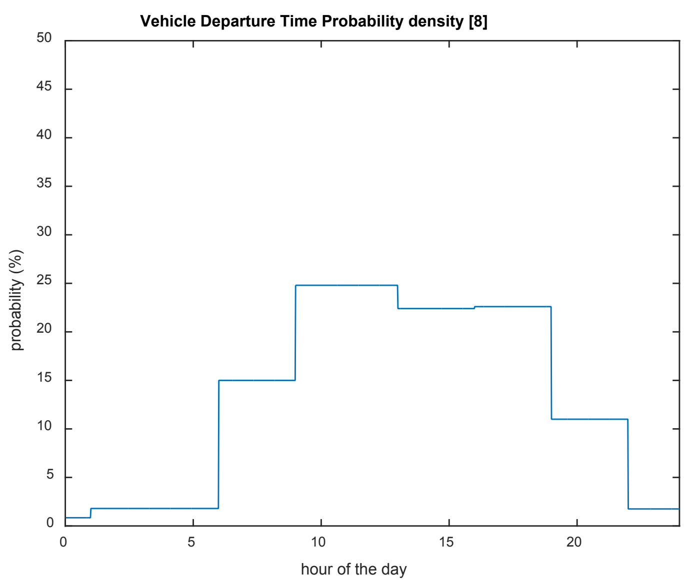
3.2.1 Variables and Assumptions

The first step in the development of the DC Fast charging station load profile model is identifying the variables. The first variable in the model is the total population of vehicles in the system under study. The population of vehicles in the system is approximately 140,000 vehicles, using data from the U.S. census estimate. [711,12] The second variable in the model is the penetration rate of EVs in the system. For the purpose of the model this variable changes for different scenarios. The first scenario assumes the value of the penetration rate to be 10 percent. This level is considered to be the penetration level of EVs in five years under an aggressive EV adoption scenario. The penetration rate of EVs in the total population of vehicles determines the number of chargers in the system based on the economic feasibility of the charging stations, assuming a payback period of about 10 years. Some variables are assigned to reflect electrical ratings and efficiency ratings of both DC Fast charging units and the EV used in the analyses. Other variables will be elaborated upon throughout the model description, in context, as they become relevant.

The load profile for DC Fast charging stations used statistical data for human behavior with random elements integrated to best display the stochastic nature of various variables in the model. Based on current gas station usage tendencies, this study assumes that individuals will just drive into a charging station and connect to a free charger without having to pre-schedule, with the market adding additional chargers as the need arises.

The temporal distribution for departure times in the U.S. is used to develop the load profile for DC Fast charging stations. The distribution remained largely unchanged since the 80s. The U.S. temporal departure distribution reflects the probability of an individual to depart on a trip throughout the course of a day. These trips could include from home to work, work to the grocery store, or from home to a sporting event, etc. The temporal departure distribution was obtained from NHTS 2009 Table 29.[13] Figure 3.2 shows a graphical representation of the distribution. The assumption is that the public DC Fast charging stations will be used when it is most convenient to the individual driver. Under such an assumption, it is likely that individuals will tend to charge their vehicles using public charging stations when they are en route to a destination. The temporal departure probability distribution is a key component in modeling the DC Fast charging station load profile.

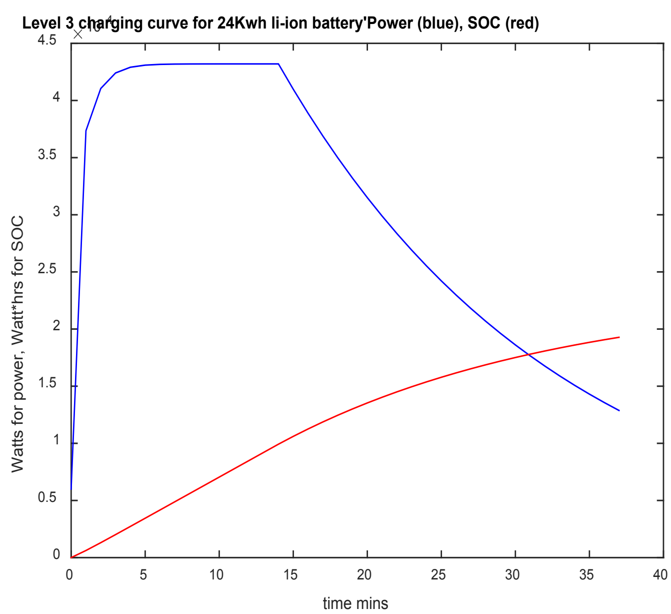
Figure 3-2. Temporal Departure Probability Distribution



The load profile of a single charging vehicle is equally important to the development of the DC Fast charging station load profile model. DC Fast chargers charge lithium ion batteries in a manner that does not damage the battery and typically will not charge a connected battery to a full SOC in order to protect the battery. To avoid damage, the battery must charge slowly for the final increment of capacity.[14] This final period of slow charging at a commercial station will not be attractive for either the driver or station owner. In this study, the maximum charge rate for vehicles using DC Fast Charging is 80 percent of full SOC.

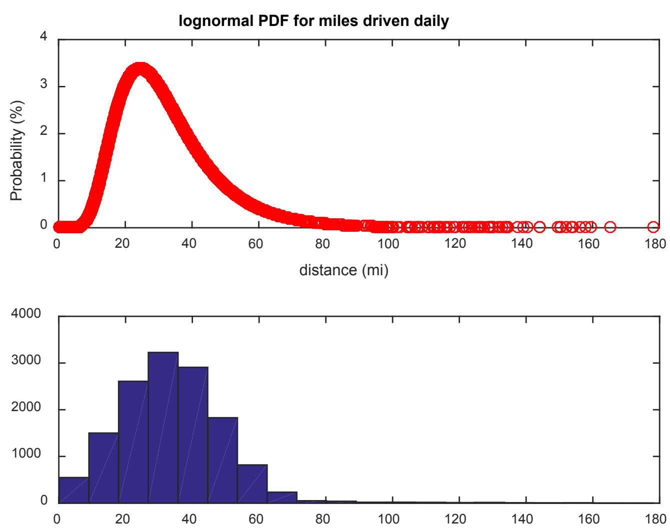
The DC Fast charging cycle charges at constant current for the first portion of the charge, increasing the voltage until the rated output of the charger reaches the battery's voltage rating. The charging then goes into a tapered region, where the charge maintains constant voltage and the charging current slowly decays as the SOC increases.[15] Figure 3.3 shows DC Fast charging characteristics. The charger load profile in Figure 3.3 represents a vehicle with an initial SOC of zero percent. The blue line in the figure represents DC power to the battery. The red line represents SOC of the battery in watt-hours (Wh) throughout the charge cycle for a 24kWh battery. Note that the red line does not reach 24 kWh when the charge cycle ends because the battery is only charged to 80 percent capacity.

Figure 3-3. DC Fast charging profile (single vehicle)



In addition to the temporal probability distribution for departure, the daily distance driven and associated SOC for a given sample must be taken into account. A data point is created for each vehicle in the population of EVs considered in this study. For each data point, the assigned value for daily miles driven is based on a lognormal distribution of daily miles driven by drivers in NYS. The distribution used in the analysis, shown in Figure 3.4, is a combination of two distributions. The first distribution of daily miles traveled is based on the lognormal distribution with the mean of 32.5 miles and a standard deviation of 12 miles. The mean value for daily distance traveled by drivers in NYS is 32.5 miles according to the National Highway Travel Survey.[13] This gives the distribution of average miles driven per day for the population. The second distribution accounts for the drivers who do not fit the standard curve on a given day as drivers will travel farther on some days by a fair amount. To account for these drivers, a portion of the driven days are assumed to be high mileage days. The assumed mean for this distribution is 90 miles with a standard deviation of approximately 30 miles. The combination of these two distributions yields the distribution shown in Figure 3.4.

Figure 3-4. Distribution of Daily Miles Driven



Equation 1. PDF for daily distance driven $$g(d;\mu,\sigma) = \frac{1}{d\sqrt{2\pi\sigma^2}} e^{\frac{-(\ln(d)-\mu)^2}{2\sigma^2}}$$

$$d > 0$$

$g(d;\mu,\sigma)$: PDF for vehicle travel
μ: Logarithmic mean
σ: Logarithmic Standard deviation
d: Distance traveled (miles)

After obtaining the probability distribution of daily miles driven for the population of EVs in the study, the data for SOC of the samples is developed using Eq.2 and Eq.3. SOC of EV batteries is an index of the energy status of a battery. A SOC of 100 percent represents a full charge. An SOC of zero percent represents a fully depleted state. The SOC distribution was created with the assumption that the Nissan Leaf is representative the EVs in the study. Anticipated battery and charger technology improvements will likely lead to larger EV battery capacity and charging rates. These have the potential to affect EV adoption rate, EV owner choice between Level 2 and DC Fast charging. These changes could also affect the EV penetration level where commercial Fast DC Charging becomes commercially viable. However, the expectation is for the commercial DC Fast Charging to stay with multi-charge station businesses with a load factor similar to that predicted in this study.

The Nissan Leaf has a 24kWh battery with efficiency of about 0.28 kWh/mile. [16, 17] It is assumed that each EV will start the day with a full charge attained by charging at home with a Level 1 or Level 2 charger. The decision of individual drivers to use commercial DC Fast chargers throughout the day is based on the idea of "range anxiety."[18] Range anxiety is a term created to refer to the fear of running out of charge, which poses more difficulty than running out of fuel in an internal combustion engine vehicle. When one runs out of gas, refueling is as simple as refilling the tank. The prospect of recharging an EV on the roadside is a bit more daunting. Therefore, the function of a vehicle's SOC will determine the assumed probability and frequency of an individual utilizing a public charging station. The lower the SOC, the more likely the individual will utilize a DC Fast public charging station.

At the time of this study, there were no official figures on the impact of SOC on an individual's probability of charging. For the purpose of this study, the effect of SOC on the probability of using public charging has been assumed, quantified, and accounted for. Table 3.1 provides a summary table of the probability of using public charging with relation to EV SOC. Assuming the SOC of a vehicle is greater than 80 percent, there will be zero probability that the individual will utilize public DC Fast charging. This is due to the fact that DC Fast chargers will only charge the vehicle's battery to 80 percent to avoid the risk of damaging the battery.[14] There is a high probability of an individual to use public charging with an SOC below 20. Depleting lithium ion EV batteries below 20 percent can damage the battery and effect longevity. The upper bound and lower bound for charge level for an EV battery are about 95 percent and 20 percent respectively for many manufacturers.[15]

Equation 2. Initial SOC of an EV arriving to the station $\boldsymbol{E_i = \left(1 - \frac{\alpha d}{d_R}\right) * 100\%}$

E_i: Initial SOC of an EV battery
d: Daily distance traveled by an EV
α: Number of days since last charge (1~2 avg)
d_R: Max range of the EV (Nissan leaf ≅ 80mi)

Table 3-1. Probability of utilizing public charging as a function of State of charge

Probability of utilizing LV3 Charging as a Function of State of Charge										
SOC	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	90-100%
Prob of Charge	0.95	0.8	0.7	0.4	0.2	0.1	0.1	0.05	0	0

Equation 3. PDF for initial battery SOC. $$\boldsymbol{h(E;\mu,\sigma) = \frac{1}{\frac{d_R}{\alpha}(1-E)\sqrt{2\pi\sigma^2}} e^{\frac{-\left[\ln(1-E)-\left(\mu-\ln\left(\frac{d_R}{\alpha}\right)\right)\right]^2}{2\sigma^2}}}$$

$$0 < E < 1$$

h: PDF for initial battery SOC. (derived from Eq1. and Eq2.)
E: Initial SOC of an individual EV
σ: Logarithmic standard deviation for SOC.
μ: Logarithmic mean for SOC

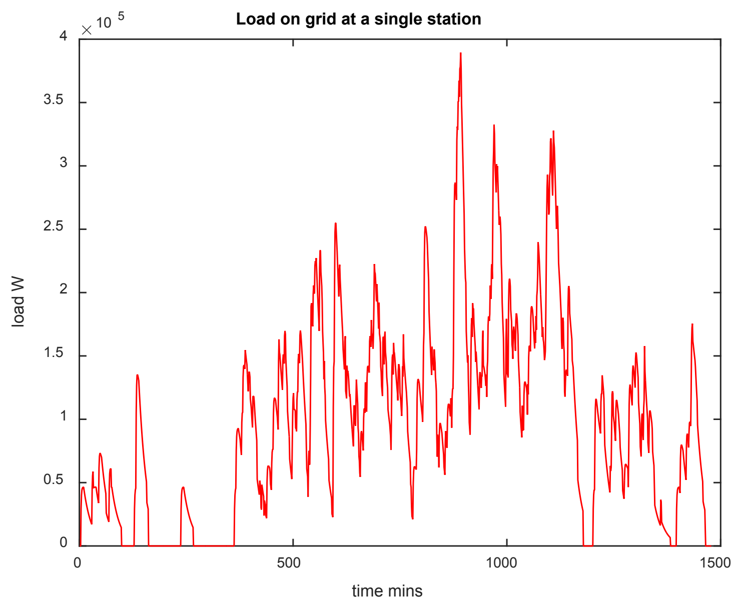
The probability of using public charging varies with the vehicle SOC at any point in time. Table 3-1 shows the likelihood of using public DC Fast charging with relation to SOC used in this study. The number of vehicles using DC Fast public charging in that time interval is then determined from the SOC of all vehicles traveling at that point in time.

The load profile of each charge event varies depending on the initial SOC of the battery upon arrival. The number of DC Fast charge events for each SOC block is calculated based on the number of EVs in the population. Next, the charge events for each block are quantified and modeled with an associated SOC. This initial SOC for each time block creates a generalized minute-by-minute load profile for all of the samples in the block. These load profiles for each block build the load profile of a given public DC Fast charging station.

The temporal departure distribution defines eight time blocks. The number of charges per time interval is determined by multiplying the probability from each time interval by the total number of public charge events for the day. Once the total number of charge events for a time interval is known, charge events are randomly assigned start times with the assumption that the probability within the time interval is uniformly distributed.

Each charger has a one-minute resolution daily load profile associated with it. The assumed number of chargers per station is 10 units chosen at random from the population of chargers to populate a station. The station load profile consists of the sum of the load profiles of the chargers chosen for the station, as referenced in Figure 3.5 below. The status of the charge events in the system for a given time block is stored in a matrix.

Figure 3-5. Representative Daily load profile of a single LV3 charging station



Multiple DC Fast charging station load profiles are created using this model unless the number of chargers in the system is equal to the number of chargers per station. Each load profile differs a bit. For the purpose of testing, five of these DC Fast charging station load profiles were added to the DEW database to test the effect.

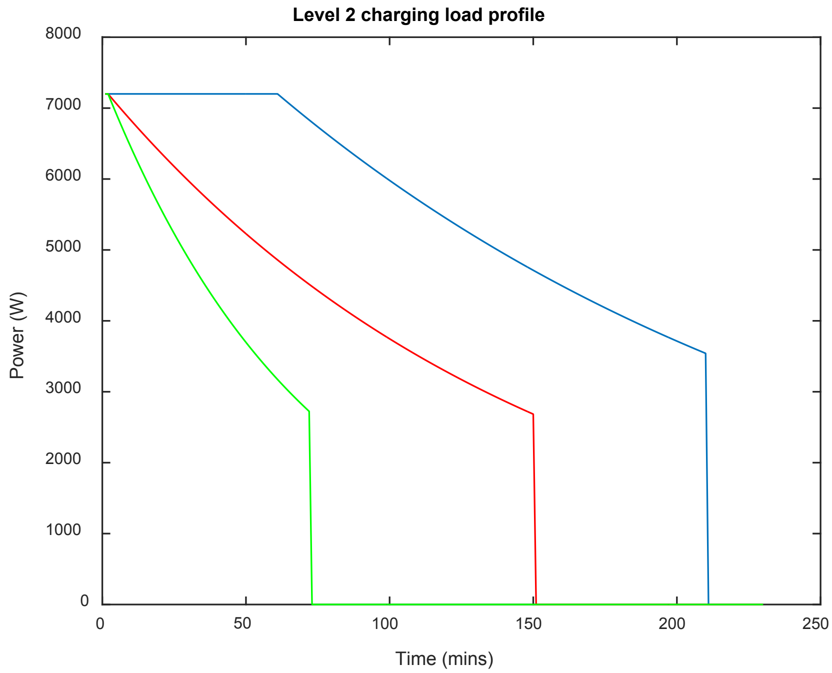
3.3 Level 2 charging model

The Level 2 charging model is created in conjunction with the DC Fast model and includes an assumed scenario of uncontrolled domestic charging for the population of EVs. The study assumes that each EV plugs in at home to recharge their EV until reaching full SOC, which stems from the assumption that each EV starts the day with a 100 percent SOC by charging overnight with Level 2 chargers. Level 2 chargers are faster than Level 1 EV service equipment (EVSE) and as EVs grow in popularity, Level 2 chargers will most likely become the preferred charging method. The Level 2 charger used in the analysis is a 240V 30A unit, capable of 7.2kW. The “arrive and plug” model determined the charging start times for home charging in the analysis. A uniform probability distribution assumes the start times of Level 2 charging are between the hours of 4 p.m. and 6 p.m. However, the initial SOC of the vehicles at the time of plug in are not uniformly distributed, but rather based on the distribution of SOC for the population developed earlier.

The impact study of Level 2 home charging analyzes two scenarios. First, a robust DC Fast charging infrastructure in the system provides ample public charging options in addition to Level 2 home charging. Second, there is no DC Fast charging infrastructure and assumes all charge events are home charge events. In the first scenario, the presence of DC Fast charging infrastructure in the system increases the SOC for a great number of EVs utilizing home charging. This is due to the fact that when an individual utilizes DC Fast charging during the day, their initial SOC when plugging in at home will usually exceed 60 percent. This, in turn, reduces the load on the residential distribution transformers.

To efficiently model the Level 2 charging loads in DEW, nine new load classes were added to the database. The distribution of Level 2 charge events breaks down into three categories by initial SOC. The distribution of home charge events is broken into low initial SOC (five to 25 percent), medium SOC (35 to 55 percent), and high SOC (>65 percent). Figure 3-6 references the load profiles of each home charge event level. The green represents high SOC, red represents medium SOC, and blue represents low initial SOC. To create the nine load classes each of the three load profiles has three different start times in the DEW database, each modeled with a start time of 4 p.m., 5 p.m., and 6 p.m.. Based on the transportation model developed, these hours represent the most likely start times for charging.

Figure 3-6. Level 2 Charging Load Profiles



Once the Level 2 load classes are added to the DEW database, they are placed around the spatial geometry of the feeder. To add the loads to the distribution system simulation, the load classes are added to load buses on the feeder. The number of Level 2 charger loads added to each load bus is determined based on the number of pre-existing residential loads on a given bus. For the geographic region used in this analysis, there are an average of 2.2 vehicles per residence. Based on is figure, the number of Level 2 charger loads that are added to each load bus are less than or equal to half the number of pre-existing residential loads on the bus. The overall number of Level 2 loads from the nine load classes added to the system is set based on a 10 percent penetration of EVs in the system (283 on the feeder). However, the loads added to each load bus from the nine load classes are selected at random.

To simulate a 20 percent penetration of EVs, the load profiles of the nine classes in the database double in magnitude. This effectively simulates two EVs with similar initial SOCs plugging in the same hour for each Level 2 load added to the distribution system created in the 10 percent scenario. Using this method to simulate an elevated penetration of EVs maintains the distribution of home charge events in the system. Table 3-2 shows a tabular summary of the distribution of Level 2 charging loads added in each scenario

Table 3-2. Summary of distribution of vehicles doing Level 2 charging on the feeder

Scenario 1 distribution of home charge events. (Combined Level 2 & DC Fast)						
Start Time	4PM		5PM		6PM	
EV Penetration Level	10%	20%	10%	20%	10%	20%
Low Vehicle SOC	3	6	3	6	3	6
Med Vehicle SOC	40	80	40	80	40	80
High Vehicle SOC	53	106	53	106	53	106
Scenario 2 distribution of home charge events. (Level 2 Only)						
Start Time	4PM		5PM		6PM	
EV Penetration Level	10%	20%	10%	20%	10%	20%
Low Vehicle SOC	20	40	20	40	20	40
Med Vehicle SOC	45	90	45	90	45	90
High Vehicle SOC	26	52	26	52	26	52

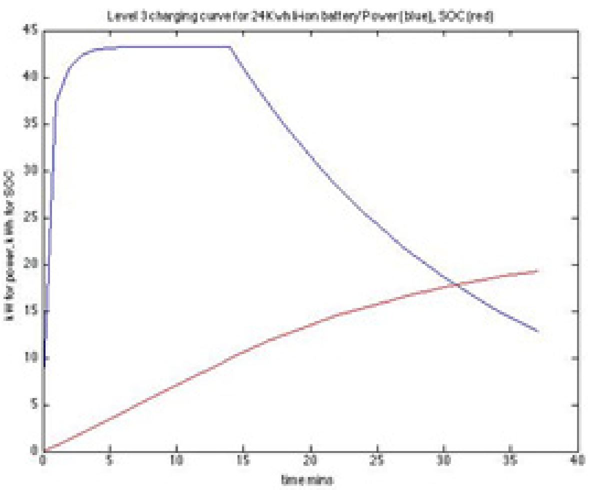
3.4 Cost model

The cost to use public DC Fast charging stations is a significant aspect of their implementation. The cost of a charge must benefit the customer and provide a reasonable payback period for the business owners. This study assumes that the payback period is approximately 10 years.

3.4.1 DC Fast Charging Station cost of electricity

A DC Fast charging station consumes three-phase power at 480 V. Each station will have 10 individual 50kW charging units at a single location and will use a monthly flat rate for electricity rates instead of time-of-use rates. A flat rate is preferable for a charging station because many charge events take place during peak load hours. However, time-of-use rates are preferable in the event that charging stations employ utility sized batteries to shift the load of DC Fast charging to off peak hours. The rate changes with the amount of power and energy consumed as well as time of year, incurring an $18 monthly "customer charge." The applicable delivery charges include a demand charge and a usage charge. The demand charge for the first 5kW or less is 1.26$/kW in the summer months (June through September), or 0.74$/kW for all other months (October through May). The DC Fast charging stations will likely spend most of the in use time above 5kW. The demand charges for power consumption over 5kW are $12.89/kW in the summer months and $7.49/kW all other months. The usage charges applied are as follows. For usage under 1,250 kWh the rate is $0.06489/kWh in the summer months and $0.05009/kWh for all other months. For usage up to 30,000kWh or 300 hours (whichever is greater), the usage charges are 0.02977$/kWh in the summer months and 0.02868$/kWh for all other months. For usage in excess of 30,000kWh or 300 hours (whichever is greater) the usage charges are 0.01499$/kWh for the summer months and 0.01389$/kWh for all other months. There are also metering charges, processing charges, and various surcharges that may apply to DC Fast charging stations as well.

Figure 3-7. DC Fast charging vehicle load profile



3.4.2 Customer Cost to Charge

An analysis was conducted to apply the cost function to a single charging EV, as shown in Figures 3-7 and 3-8. Figure 3-7 represents the load profile of a charging battery as well as the SOC of the battery throughout the charge cycle. Figure 3-8 represents the cost of energy charging a single vehicle. This plot does not represent the additional demand charge incurred monthly by the station. The amount of demand charge incurred depends on the number of chargers at a given station. For a station with a single charger the demand charge equates to about $350 monthly. For a station with six charging units that at some point operate simultaneously at peak for 15 minutes, the demand charge would be over $3,570 monthly for summer months and over $2,200 for non-summer months. At this rate, assuming 255 charge events per charging unit per month, an additional $1.40 would need to be added to the cost of each charge to account for the demand charge. Assuming the cost to charge is about $2.30 for a customer plugged in for 30 minutes to cover the energy cost. To recover the initial investment for the charging infrastructure an additional fee would need to be added to the cost of charging. In the case of a charging station with 10 charging units costing $15,500 per unit and an assumed installation cost of $7,000 per unit with an anticipated payback period of 10 years, the station must recover at least $1,875 in profits per month. Assuming 2,500 charges at the station occur per month, an additional fee of $0.75 would have to be included in each charge to recover investment. This brings the approximate cost to charge for the customer to about $3.05 for 30 minutes. This price is just an anticipated starting point for the cost of a DC Fast charge to the customer. This analysis doesn't account for the price of the facilities, maintenance, or costs other than electricity and the charging units.

Figure 3-8. Cost of single vehicle charging

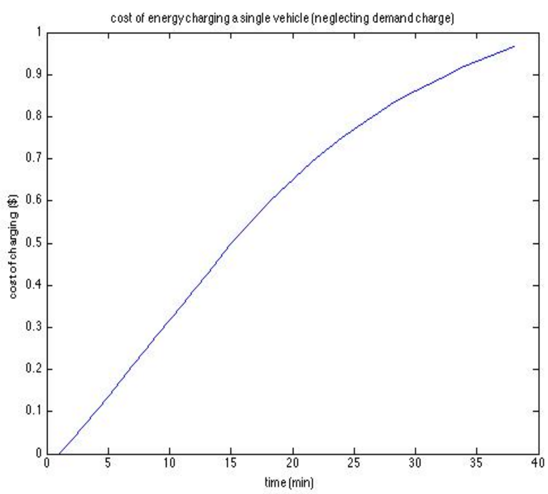


Table 3-3 outlines the costs to charge an EV battery from 20 to 80 percent based on the various electric tariff structures from the partnering utility. Scenarios include summer and winter prices for a charge event starting at 5 p.m., for all four tariff structures analyzed in the study for Level 1, 2, and 3. For a Level 1 charge event using a Panasonic Level 1 charging cable with a normal operating output of 1.2kW, the duration of the charge is 12hrs. For Level 2 charge events, if using the EATON 240V/30A Level 2 charger, the duration of the charge is 3hr 10min. The duration of the charge is about 30 minutes for the DC Fast charging scenarios if using the AeroVironment 44kW charger.[19]

Table 3-3. Cost to charge rate structure comparison

EV Charging Cost Comparison	Summer (Weekday)			Winter (Weekday)		
Charge Level	1	2	3	1	2	3
Start Time	5 p.m.	5 p.m.	5 p.m.	5 p.m.	5 p.m.	5 p.m.
End Time	5 a.m.	8:10 p.m.	5:30 p.m.	5 a.m.	8:10 p.m.	5:30 p.m.
Residential Service Rate	$1.10	$1.10	N/A	$0.92	$0.92	N/A
General Service Rate	$0.98	$1.88	$4.08	$0.76	$1.27	$2.70
Residential Time of Use Rate	$1.02	$3.55	N/A	$0.61	$1.35	N/A
General Time of Use Rate	$2.21	$8.05	$8.44	$0.47	$2.39	$1.11

4 Testing Strategies and Analysis of Results

This chapter explains the methods used to test the effect of EV charging on the simulated distribution system as well as the results obtained from these tests. There are also discussions on several charging scenarios throughout the analysis. The base case, in which nothing is done to the distribution system, provides a basis of comparison for all of the scenarios used in this analysis. The combined Level 2 domestic and DC Fast public charging scenario is a likely future in which a robust DC Fast charging infrastructure exists and residents utilize home charging to start each day with a fully charged EV. The individual DC Fast scenario gives perspective on the effect of DC Fast charging stations on the load profile, feeder, and distribution equipment in the analysis to help determine which charging methods will have the greatest impact. The individual Level 2 analysis looks at the system with varying penetrations of EVs where only home charging is available. The Level 2 model assumes that there are no DC Fast charging stations available and that all domestic charging is carried out by Level 2 EVSE. For each of the charging scenarios, the daily energy consumption from the feeder is calculated based on the power flows discussed in this chapter. Table 4-1 shows the daily energy consumed in each scenario and the percent increase from the base case.

Table 4-1. Summary of Scenarios Daily Energy Consumption

Feeder Daily Energy Consumption Comparison		
	1 Day Energy kWh	% increase
Base Case	119,600	0.00%
10% DC Fast	121,800	1.81%
20% DC Fast	124,100	3.70%
40% DC Fast	136,300	13.91%
10% Combined LV2 & LV3	124,500	4.07%
20% Combined LV2 & LV3	127,000	6.13%
10% Level 2	122,700	2.54%
20% Level 2	124,600	4.17%

Tests are conducted using tools in DEW that include Power Flow, Voltage Distance analysis, and Violations Checker. The power flow tool in DEW defines a time interval and analyzes a portion of the circuit. In these tests, the feeder conducts the power flow. The analyses are conducted assuming constant P/Q. The software conducts the power flow for each time step in the defined time interval and outputs a graphic and tabular representation of the per-phase real power, reactive power, and bus voltage for the feeder.

To obtain the voltage distance relationships referenced in this chapter the voltage distance tool in DEW was used. To use this tool, a single time point is defined to conduct the analysis using the peak load time. To explore the effect of EV charging on the system thoroughly, five segments of the distribution line were analyzed. The furthest point of the distribution lines for each segment was chosen as the endpoint of the analysis. The DEW voltage distance tool records the voltage at each component along the path from the substation to the defined endpoint and creates a tabular summary of the results in addition to a graphic representation of the voltage distance relationship.

The DEW Violations checker was used to study the effects of the distribution equipment violations in the system. The violations checker functions by measuring the current and voltage at each component in the specified circuit. In the case of the analyses in this chapter the substation components and all components on the feeder of interest are analyzed at peak load for violations. Equipment ratings for all simulated equipment in the circuit are stored in the database. The violations checker compares the measurements at each component at each defined time point in the analysis to the devices ratings to determine if a component is overloaded and the extent of the overload.

It should be noted for these tests, the EV penetration rates assumed in these tests represent likelihood of these penetrations presenting themselves at least five years in the future. The current penetration of EVs in the NYS transportation system stands at about 0.2 percent and 0.4 percent in the U.S., respectively.

4.1 Base Case

To gain a basis of comparison for all tests and results in this experiment, a clear and comprehensive analysis of the base case must be conducted. For this study, the most heavily loaded feeder is used to conduct tests. In the base case there are 22 load classes in the system that are distributed to represent various load types, from residential to commercial and even PV generation. The DEW software conducted analyses of the power flow and equipment violations to serve as a basis of comparison for testing the effect of adding EV charging loads to the system.

4.1.1 Power Flow

For the base case system, the power flow is conducted on the substation and feeder on the specified time interval from August 6, 2015 at 12:01 a.m. to August 8, 2015 at 11:58. In this case no EV charging stations added to the system. The power flow results are recorded and variations in power flow on the phases occur hourly. This corresponds with the built in loads on the system being time varying with a one-hour resolution. Figure 4-1 references a graphical representation of the power flow for the substation. The maximum and minimum power flow values for each phase were found for the time range of the analysis, as shown in Table 4-2. The substation peak load is as high as 20,342 kW on phase C at 7 p.m. on August 6, 2015.

The power flow was also conducted on the most heavily loaded feeder for the base case. Figure 4-2 displays a graphical representation of the power flow for the two-day time interval. The base case peak load and bus voltage results from the power flow are summarized in Table 4-3. The daily peak load for the feeder in the base case is found to be 3,616.35 kW on phase A at 7 p.m. These peak load values for the feeder and substation serve as a basis of comparison to effectively analyze the effect of EV charging on the daily load profile and daily peak load for this feeder. Table 4-4 shows a plot Legend for the figures.

The voltage distance relationship for the three-phase distribution lines from the feeder provides a basis of comparison for analysis of the effect of EV charging on the line voltage downstream from the feeder. The results of the voltage distance analysis for the base case provide a direct comparison for scenarios discussed later in this chapter.

Table 4-2. Substation Base Case Power Flow Max and Min Power Flow Results

	Max Real Power Flow (Phase A)	Max Real Power Flow (Phase B)	Max Real Power Flow (Phase C)
Power (MW)	18.302	17.310	20.342
Time	8/6/15 19:00	8/6/15 19:00	8/6/15 19:00
	Min Real Power Flow (Phase A)	Min Real Power Flow (Phase B)	Min Real Power Flow (Phase C)
Power (MW)	13.146	12.395	14.266
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

Table 4-3. Feeder Base Case Power Flow Results

Feeder Base Case Power Flow Results (Bus Voltage)			
	Phase A	Phase B	Phase C
Max Bus Voltage (120V Base)			
Bus Voltage (V)	126.2	126.8	127.0
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00
Min Bus Voltage (120V Base)			
Bus Voltage (V)	125.0	126.0	126.4
Time	8/6/15 19:00	8/6/15 19:00	8/6/15 19:00
% Difference	0.94	0.60	0.49
Feeder Base Case Power Flow Results (Real Power Per Phase)			
	Phase A	Phase B	Phase C
Max Real Power Flow (Kw)			
Power (KW)	3616	3159	3279
Time	8/6/15 19:00	8/6/15 19:00	8/6/15 19:00
Min Real Power Flow (KW)			
Power (KW)	2537	2215	2298
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

Figure 4-1. Substation Base Case Power flow, in kilowatts

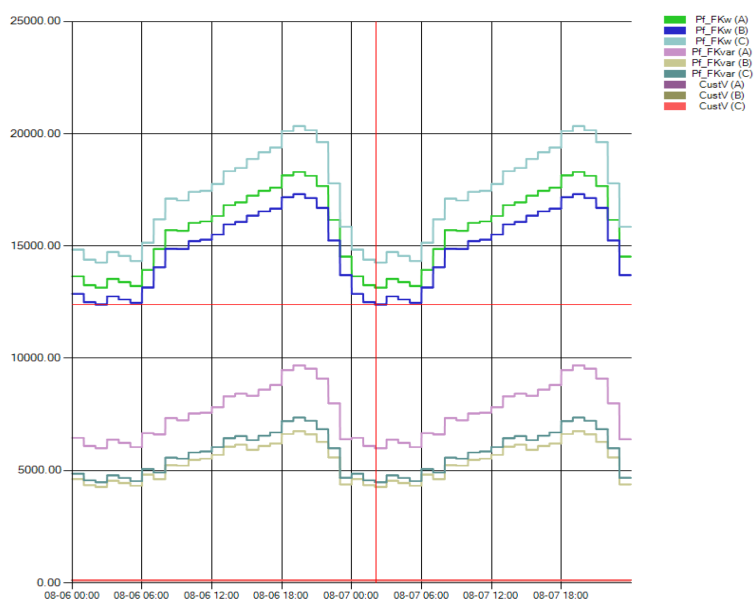


Figure 4-2. Feeder Base Case Power Flow

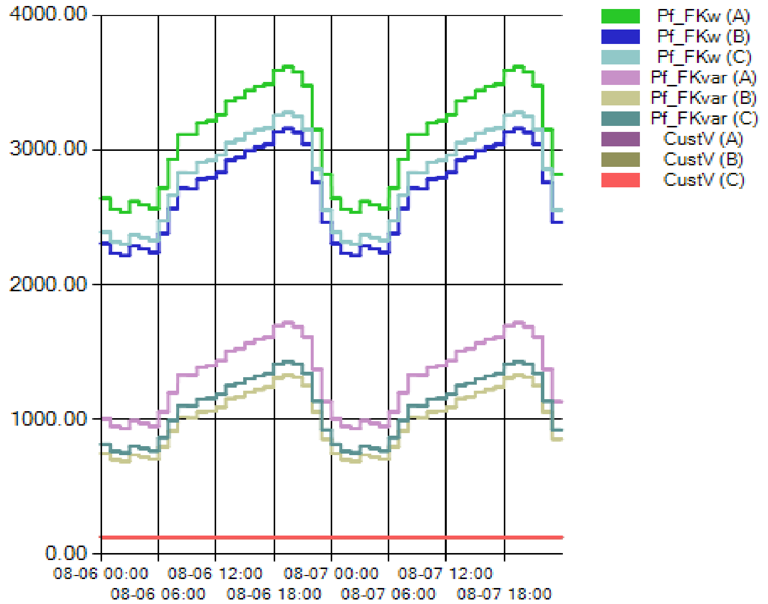


Table 4-4. DEW Power Flow Plot Legend Guide

Power Flow Plot Legend		
	Pf_FKw(A)	Real Power Flow in Phase A in kW
	Pf_FKw(B)	Real Power Flow in Phase B in kW
	Pf_FKw(C)	Real Power Flow in Phase C in kW
	Pf_FKvar(A)	Reactive Power Flow in Phase A in kVARs
	Pf_FKvar(B)	Reactive Power Flow in Phase B in kVARs
	Pf_Fkvar(C)	Reactive Power Flow in Phase C in kVARs
	CustV (A)	A Phase Bus Voltage on 120V Base
	CustV (B)	B Phase Bus Voltage on 120V Base
	CustV (C)	C Phase Bus Voltage on 120V Base

4.1.2 Base Case Equipment Violations

The violations viewer in DEW generates a summary of component violations that occur without the addition of new EVs or charging stations to the system. The results of the DER and power flow violations checker tools are noted and saved to serve as a basis of comparison for further tests. The distribution violations checker is also run to serve as a basis of comparison to analyze transformer overloads that occur as a result of adding new charging stations to the system.

This base case analysis identified violations. The station transformers are rated 35MVA (in the emergency state), 138:13.2kV at 5.1 percent impedance. The transformers are equipped with a 16 step load tap changer with five percent regulation. The station transformers are rated 21MVA in normal state with no fans, and rated 31.5MVA in normal state with 100 percent fans. Upon running the DEW violations checker on the substation, it is evident that during peak load, station transformers SubTr1 and SubTr2 at the substation experience overloads by margins of 76 percent and 21.6 percent respectively while in normal state with no fans. It is assumed that these transformers would operate with cooling fans fully active at this load level. With both transformers operating normally with 100 percent fans, only transformer SubTr1 is overloaded by about 22 percent over the 132 A rating. The total three phase power flow for SubTr1 is measures 35,398.6 kVA and total current at about 148A at peak load. Transformer SubTr2 is not overloaded while the fans are running at 100 percent at peak load.

Violations of distribution equipment on the feeder are analyzed as well. At peak load there are 70 instances of single phase distribution transformer overloads. Some of the distribution transformers are overloaded by margins as high as 135 percent. There is one instance of three-phase overhead distribution transformer overload on the feeder. The three-phase transformer is rated 30kVA at 2.4kV: 120V, grounded wye connected. The overload rating of this transformer is 4.17A. The transformer is overloaded by 144 percent over rated current; this violation could be partially attributed to the low voltage on the connected line. There are only two instances of three-phase distribution line overloads in the base case at peak load. The most significant of the overloaded three-phase lines is located close to the substation and overloaded by about 72 percent over the 303A rating. The overloaded section of three-phase line is only 15 feet long. There is only one instance of single phase line overload at peak load by a margin of over 25 percent. The single phase line in question feeds numerous residential loads. There are numerous low voltage violations at load points on the feeder at peak load with voltages under 105V on a 120V base. There are two step transformers on the feeder overloaded by as much as 167 percent and 127.4 percent respectively on the A and C phases.

4.2 DC Fast Charging Only on the Feeder

In this section analyzes the effects of DC Fast EV charging stations on the substation and feeder for various penetrations of EVs. The charging station models used reflect various penetrations of EVs in the population. The total population of vehicles in the study system is 140,000 vehicles. The number of individual chargers in the system is set for each penetration level based on the economic feasibility of the charging stations. To ensure the model reflects economic feasibility, the individual charger monthly usage rate is set between 200 and 300 charge events per charger per month, with an average of 255 charge events per charger per month. This usage rate ensures a payback period of approximately 10 years. Without adding any additional home charging loads to the system, the DC Fast charging stations with 10 individual charging units per station are added around the spatial geography of the f eeder to analyze the effect on the system. The charging stations are only added on the feeder in this study and not elsewhere in the distribution system. The DEW power flow tools and violations checker tools determine the severity of the impact of the DC Fast charging stations on the feeder and distribution equipment. The DC Fast charging station loads connect to the system via 500kVA, three-phase, 13.2kV: 480V (Line-to-Line) transformers. The transformers allow for a worst case scenario of all 10 charging units operating at peak simultaneously. The size of the transformer also allows for future expansion without transformer replacement in the event that additional charging units are necessary.

4.2.1 DC Fast Charging with 10 Percent EV Penetration

This section analyzes the impact of a 10 percent penetration of EVs on the system with DC Fast charging stations, neglecting the impact of home charging. To determine the number of DC Fast charging stations on the feeder that represents a 10 percent penetration of EVs, an economic feasibility analysis determined the number of stations that could exist in the system with a 10-year payback period. It is determined that for a single distribution feeder in the system, a single DC Fast charging station represents about a 3.4 percent penetration of EVs in the system. Therefore, a 10 percent penetration of EVs in the system would allow about three economically feasible DC Fast charging stations on a single feeder, assuming that DC Fast charging will constitute about 20 percent of daily charging events.[3]

4.2.1.1 Power Flow

The power flow is conducted on the feeder using a one-minute resolution due to the nature of the DC Fast charging station load profile which can vary significantly in one minute. The loads from the DC Fast charging stations create sharp peaks in the load profile and increase the peak load for the day from 3616kW to 3673kW at about 6 p.m. Figure 4-3 references a graphical representation of the power flow. In this scenario, the peak load shifts to 5:48 p.m. from 7:00 p.m. in the base case. The addition of the charging stations creates some variation in the bus voltage. Table 4-5 shows the results of the power flow for this scenario compared with the base case.

A study of the voltage distance relationship on the feeder three-phase distribution lines focused on five line segments. The voltages at the end of each line segment at peak load were recorded for this scenario and compared with the results of the base case to determine the effect of the DC Fast charging stations on the distribution lines. Table 4-6 displays a summary of the results. The greatest difference from the base case at peak load occurs on line segment 1 on phase A with a 0.427 percent drop in line voltage. There is a graphical representation of the difference in the voltage distance relationship for phase A of line segment 1 shown in Figure 4-9 at the end of Section 4.2.3.

Figure 4-3. Feeder Power Flow with 3 Charging Stations (10 percent penetration)

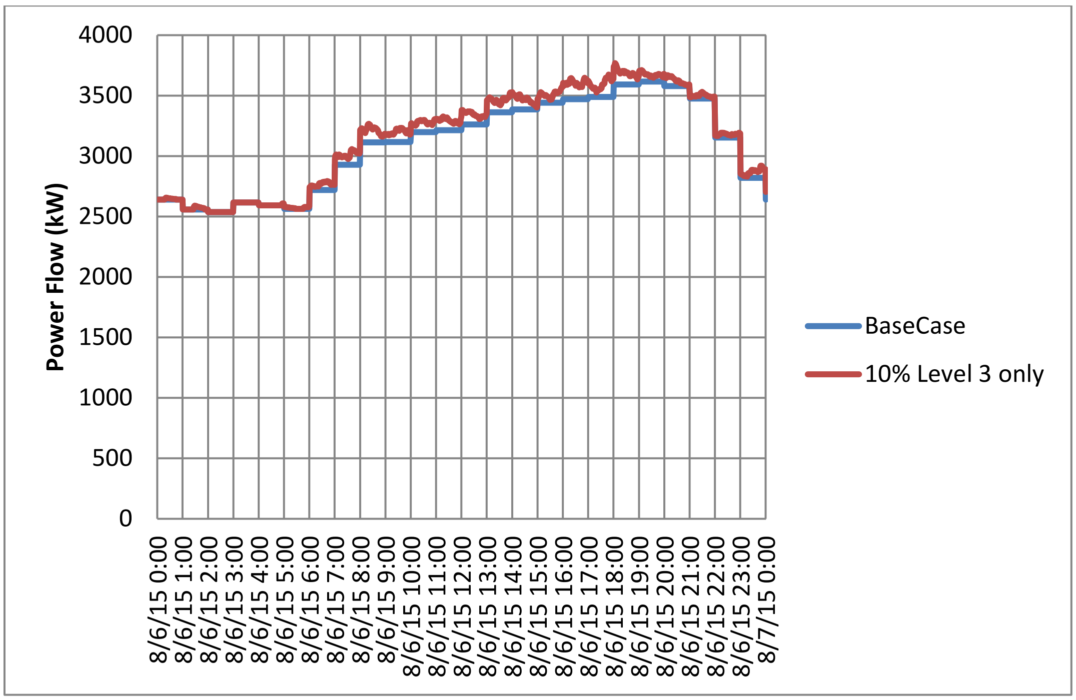


Table 4-5. Feeder Power Flow Results and Base Case Comparison

Real Power Flow Base Case Comparison		
Phase-A	**Phase-B**	**Phase-C**
Max % Difference in Real Power		
5.3	6.0	5.7
Time		
8/6/15 17:48	8/6/15 17:48	8/6/15 17:48
Base Value (kW)		
3,489	3,041	3,165
New Peak Value (kW) w/ Charging Station Added		
3,674	3,222	3,346
Reactive Power Flow Base Case Comparison		
Phase-A	**Phase-B**	**Phase-C**
Max % Difference in Reactive Power		
9.7	12.1	11.3
Time		
8/6/15 17:48	8/6/15 17:48	8/6/15 17:48
Base Value Reactive Power (kVAR)		
1,611	1,240	1,338
New Value w/ Charging Station Added (kVAR)		
1,767	1,390	1,490

Table 4-6. Voltage Distance results for the Feeder with 10 percent EV penetration and only level 3 charging

Min Voltage on line at peak load					
	Base case		10% Penetration LV3		%diff
Seg1	Voltage	Distance from Feeder (ft)	Voltage	Distance from Feeder (ft)	
A	115.2	8,915	114.7	8,915	0.43
B	122.6	7,715	122.2	7,715	0.33
C	114.9	8,915	114.5	8,915	0.37
Seg2					
A	109.4	6,833	109.0	6,834	0.39
B	121.4	4,926	121.0	4,926	0.27
C	119.2	6,834	118.8	6,834	0.28
Seg3					
A	119.9	10,687	119.4	10,687	0.40
B	122.1	11,240	121.7	11,240	0.37
C	122.0	11,420	121.6	11,420	0.33
Seg4					
A	120.2	11,593	119.7	11,593	0.39
B	122.9	11,593	122.5	11,593	0.33
C	122.7	11,593	122.3	11,593	0.32
Seg5					
A	119.9	9,387	119.5	9,387	0.39
B	122.5	8,397	122.0	8,397	0.33
C	122.6	8,546	122.2	8,546	0.32

4.2.1.2 Distribution Equipment Violations

The violations checker tool in DEW conducted an analysis of violations on equipment downstream from the feeder. With a 10 percent penetration of EVs in the system and three DC Fast charging stations on the feeder, there are relatively few new violations on the distribution equipment as a result of the new chargers. With only three DC Fast charging stations on the feeder, there are minimal necessary upgrades to the distribution system. The station transformer SubTr1 is overloaded by 22 percent at 6 p.m., which is about the same as the base case.

There is one instance of three-phase overhead transformer overload that occurs at peak with a margin of 146 percent compared with 144 percent in the base case. The increase in the severity of the overload is partially due to the drop in the voltage of the three-phase distribution lines resulting from the addition of the DC Fast charging stations. As in the base case, 70 instances of single phase distribution transformer overloads at peak load remain. With the exception of the change in line voltage due to the addition of the DC Fast charging stations to the system, the single phase transformers are otherwise not directly affected by the charging stations present in the system. As in the base case, only one instance of a single phase line which is overloaded about 29 percent over the 134A current rating remained; a four percent increase from the base case. There are three instances of three-phase line violations in this scenario as in the base case. The most severe section of three-phase line overload present on the 15ft section of line exceeds the rated current of 303A by 75 percent. This overload is three percent higher than that in the base case. There are 4 instances of step transformer overloads in this case which are found at the new peak load time of 6 p.m. These overloads represent two step transformers, each overloaded on their A and C phases. The step transformer overloads are less severe at the new peak load time than in the base case peak load time. This is due to the lower demand of the many connected residential loads downstream at 6 p.m. However, when compared with the base case peak load time of 7 p.m. it is found that the severity of the overloads is exacerbated by a fraction of a percent for each step transformer.

4.2.2 DC Fast Charging with 20 Percent EV Penetration

In this scenario the presence of home charging is ignored in the system to gain perspective of the individualized effect of DC Fast charging activity on the distribution system. This scenario analyzes a 20 percent penetration of EVs in the population. It is assumed that with an increase in the number of EVs in the system, the number of charging stations will increase to meet the demand as long as the stations themselves are economically feasible with a reasonable payback time. In this scenario six DC Fast charging stations are placed around the spatial geography of the feeder to represent a 20 percent penetration of EVs in the system.

4.2.2.1 Power Flow

The analysis of the power flow results determined that the increase the number of DC Fast from three to six charging stations on the feeder yields an increase in daily peak load. The daily peak load is increased to 3907 kW from 3673 kW in the 10 percent penetration case and 3616 kW in the base case. A plot of the power flow generated by the DEW software for this scenario can be referenced in Figure 4-4. A plot comparing the base case, 10 percent penetration, and 20 percent penetration power flows can be referenced in Figure 4-5. A summary of the results of the power flow for this scenario can be referenced in Table 4-7 with a comparison to the base case in Table 4-8. At the substation bus, the voltage level remains fairly constant, although downstream from the feeder the voltage level at the load points varies due to the demand of the DC Fast charging stations. The effect is particularly pronounced downstream from the DC Fast charging stations and becomes more evident upon conducting the voltage distance study.

A study conducted of the voltage distance relationship on the distribution lines for the feeder at peak load analyzed five line segments. The line voltages at the tail ends of the lines at peak load are recorded and compared with the base case results as summarized in Table 4-9. The most significant change occurs on line segment 1 with the percent change in voltage calculated at 0.488 percent. The percent change for each line segment is increased from 0.427 percent in the previous 10 percent penetration case results in Table 4-6. A voltage distance plot for line segment 1 provides a basis of reference for the most significantly changed line segment. The plot can be referenced in Figure 4-6. The voltage drop noticed on the A and C phases, occurs over a step transformer, which is overloaded by 123 percent on the C phase and 42 percent on the A phase. The voltage drop is present in the base case at peak load, although with about 0.5 percent decrease in voltage magnitude from the base case to this scenario. A diagram of the layout of the distribution lines in the system with reference to the breakdown of the five line segments (numbered in black 1-5), the placement of the charging stations (numbered in red 1,6-10), and the two step transformers of interest in this paper (denoted in green by S1, S2) are referenced in Figure 4-7.

Figure 4-4. Power Flow of Feeder with 20 percent Penetration of EVs and only DC Fast Charging

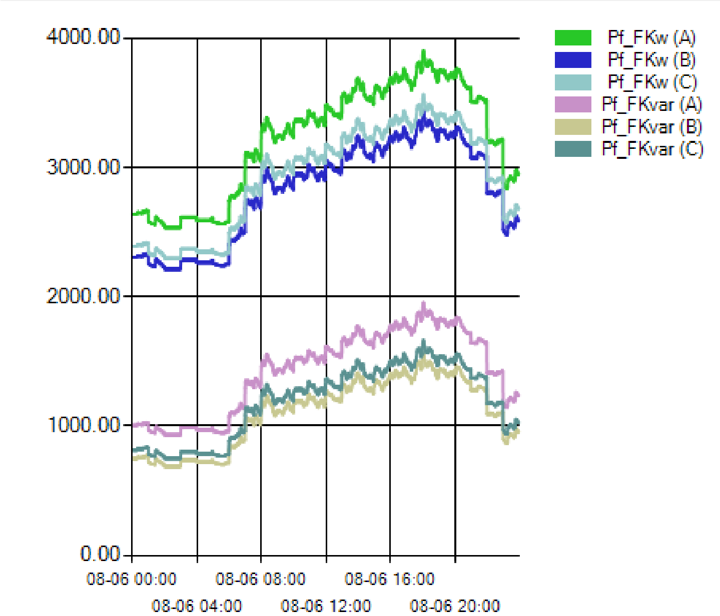


Figure 4-5. Comparison of A-Phase Power Flow with Base Case, 10 percent, and 20 percent Penetration (with DC Fast charging only)

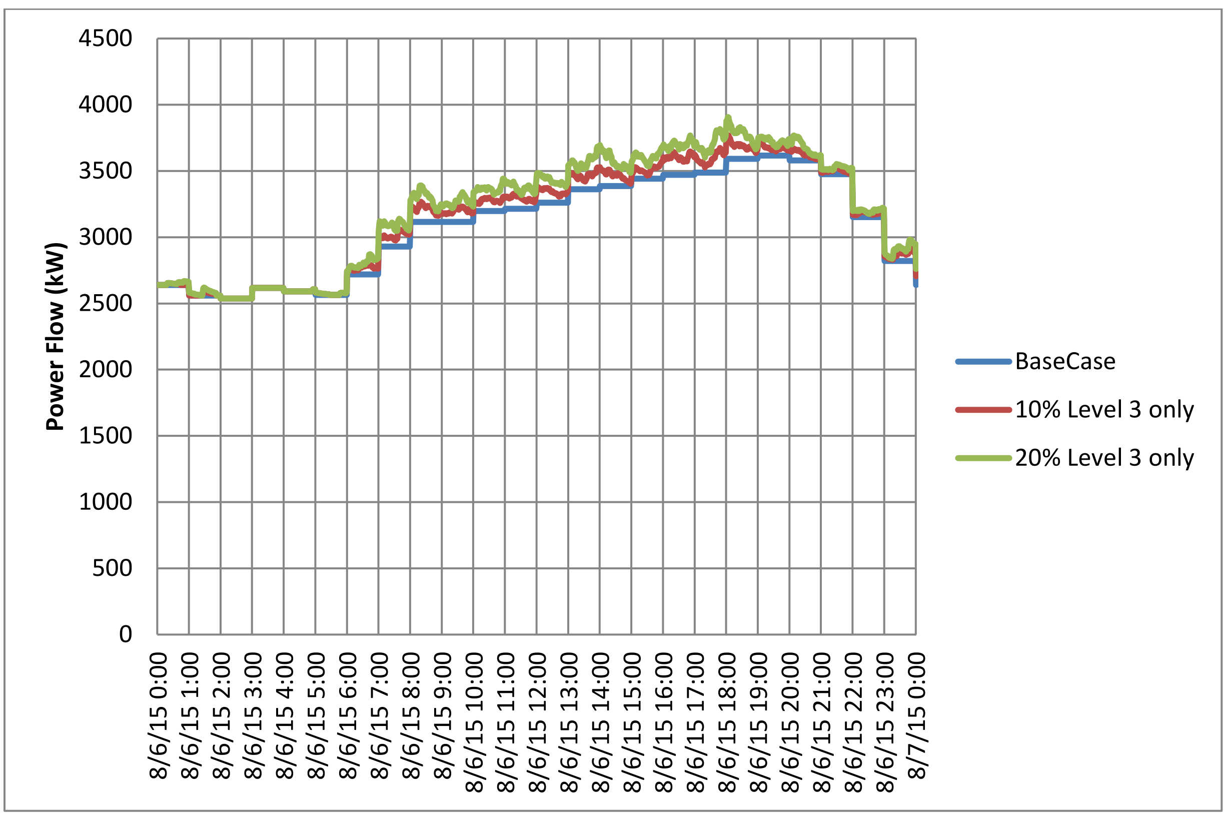


Figure 4-6. Voltage Distance Plot for the Feeder (line Segment 1) with 20 percent EV penetration with DC Fast charging only

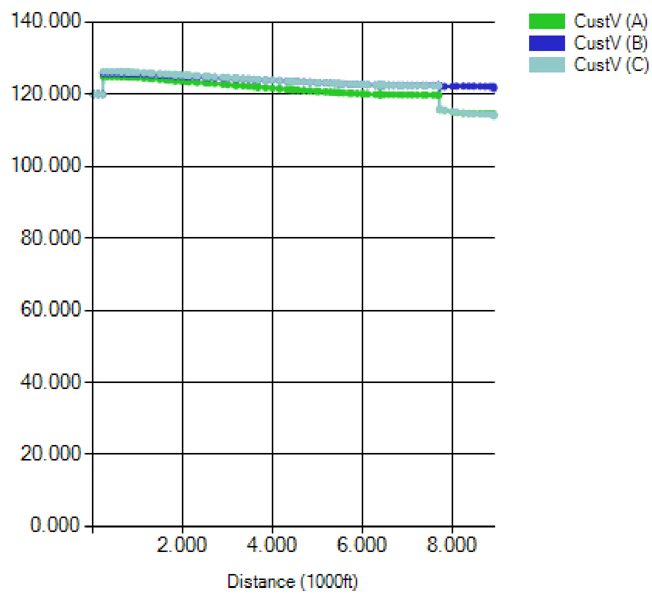


Table 4-7. Power flow min and max results for 20 percent penetration (DC Fast Charging only)

Feeder Power Flow Results (Bus Voltage) w/ 20% Penetration			
	Phase A	Phase B	Phase C
Max Bus Voltage (120V Base)			
Bus Voltage (V)	126.2	126.8	127.0
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00
Min Bus Voltage (120V Base)			
Bus Voltage (V)	124.9	125.8	126.2
Time	8/6/15 18:03	8/6/15 18:03	8/6/15 18:03
% Difference	1.06	0.76	0.62
Power Flow Results (Real Power Per Phase) w/ 20% Penetration			
	Phase A	Phase B	Phase C
Max Real Power Flow (Kw)			
Power (KW)	3,907	3,444	3,567
Time	8/6/15 18:03	8/6/15 18:03	8/6/15 18:03
Min Real Power Flow (KW)			
Power (KW)	2,538	2,214	2,298
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

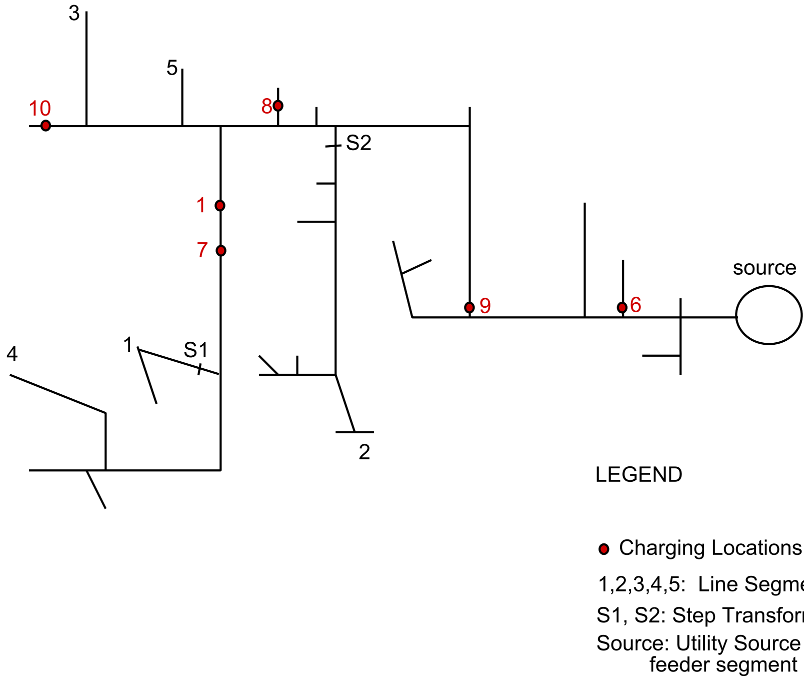
Table 4-8. Power Flow Base Case Comparison for 20 percent Penetration Case with DC Fast Charging Only

Real Power Flow Base Case Comparison		
Phase-A	Phase-B	Phase-C
Max % Difference in Real Power		
9.54	10.80	10.34
Time		
8/6/15 13:55	8/6/15 13:55	8/6/15 13:55
Base Value (kW)		
3,362	2,922	3,054
New Value (kW) w/ Charging Station Added		
3,683	3,238	3,370
Reactive Power Flow Base Case Comparison		
Phase-A	Phase-B	Phase-C
Max % Difference in Reactive Power		
17.5	22.2	20.6
Time		
8/6/15 13:55	8/6/15 13:55	8/6/15 13:55
Base Value Reactive Power (kVAR)		
1,508	1,152	1,251
New Value w/ Charging Station Added (kVAR)		
1,771	1,408	1,509

Table 4-9. Voltage distance values for the Feeder distribution lines with 20 percent EV penetration and DC Fast charging. (Base Case Comparison)

Min Voltage on line at peak load					
	Base case		20% Penetration LV3		%diff
Seg1	Voltage	Distance from Feeder (ft)	Voltage	Distance from Feeder (ft)	
A	115.18	8,915	114.62	8,915	0.49
B	122.57	7,715	122.10	7,715	0.38
C	114.91	8,915	114.42	8,915	0.43
Seg2					
A	109.39	6,834	108.87	6,834	0.48
B	121.36	4,926	120.96	4,926	0.33
C	119.17	6,834	118.76	6,834	0.34
Seg3					
A	119.90	10,687	119.37	10,687	0.44
B	122.08	11,240	121.62	11,240	0.38
C	121.96	11,420	121.51	11,420	0.37
Seg4					
A	120.22	11,593	119.68	11,593	0.44
B	122.87	11,593	122.41	11,593	0.38
C	122.72	11,593	122.27	11,593	0.370
Seg5					
A	119.93	9,387	119.40	9,387	0.44
B	122.46	8,397	122.00	8,397	0.38
C	122.64	8,546	122.20	8,546	0.36

Figure 4-7. Distribution line segment diagram showing location of 6 residential Level 2 EV chargers and the five line segments impacted



4.2.2.2 Distribution Equipment Violations

There are some equipment violations as a result of an increase in DC Fast charging station penetration. There exists an initial overvoltage violation on a fixed shunt capacitor near the substation. The device is rated for initial voltage up to 126V, the customer level voltage reaches a level of 126.9V at the day's lowest demand at 2 a.m., which violates the device's rating by 0.72 percent. The substation transformer SubTr1 is overloaded by 24.3 percent at peak load in this scenario from about 22 percent in the base case. There are still 70 instances, single phase distribution transformers overloaded at the peak load as in the base case. The four instances of step transformer overloads are exacerbated by only a fraction of a percent from the previous case. The 15ft overloaded section of three-phase line is overloaded by 80.4 percent at peak load. The increase in violation is due to the decrease in line voltage and increase in power flow on the section of line at peak load compared to the base case. Only a single instance of single phase line overload on the system remains with a peak load overload of 29.2 percent as well as only one instance of three-phase overhead distribution transformer overload. The transformer is overloaded by 146.4 percent compared to 146 percent in the previous 10 percent penetration scenario.

4.2.3 DC Fast Charging with 40 Percent EV Penetration

In this case the number of chargers per station is set to 20 units to simulate multiple stations on a single substation transformer to explore the effects. This simulates a case of multiple charging stations consolidated in a geographic location much like some gas stations are in business districts in NYS. This scenario represents a 40 percent penetration of EVs in the system. Based on the DC Fast charging station economic feasibility assumptions, the allowable number of stations is 12.

4.2.3.1 Power Flow

Upon running the power flow over the time interval on the feeder, the bus voltage is reduced when compared to the base case. The bus voltage level averages about 125.7V at the feeder at peak load with the stations added to the system. When compared with the base case values of around 126V the change is insignificant. There are no observable significant short time variations in bus voltage at the feeder, to constitute Voltage Flicker at the feeder. In this scenario the peak power flow is increased to 4,443kW from 3,907kW in the 20 percent penetration scenario. A graphical representation of the power flow for the feeder generated by the DEW software is referenced in Figure 4-8. A tabular summary of the power flow can be referenced in Table 4-10. A graphical comparison of the power flow for each of the penetration levels to the base case is discussed in this chapter as referenced in Figure 4-9.

The voltage distance study was conducted for this scenario. This scenario found the most significant drop in voltage was due to the addition of DC Fast charging stations occurs on the A phase of line segment 2 with a 3.4 percent drop from the base case. This change is due to the placement of a charging station of the line. The charging station's location is evident in the line segment 2 voltage distance plot as referenced in Figure 4-11. The second most significant change occurs on the A phase of line segment 1 with a 1.5 percent drop in line voltage. Figure 4-10 shows a graphical comparison of the A phase of line segment 1 voltage distance relationship for the high penetration DC Fast scenario to the base case as well as the 10 percent and 20 percent penetration scenarios. Table 4-11 references a tabular base case comparison of the voltage distance characteristics for the five line segments for this scenario.

Figure 4-8. Feeder Power Flow with 12 DC Fast Charging Stations (40 percent EV penetration)

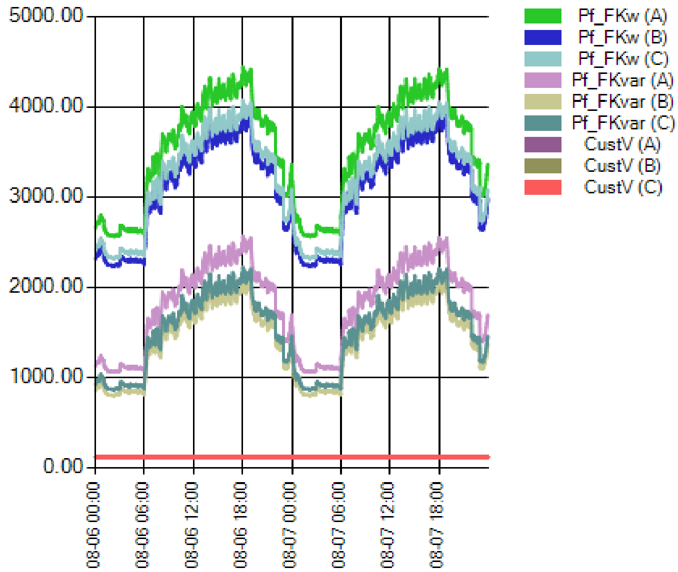


Figure 4-9. Power Flow Comparison with DC Fast Charging only

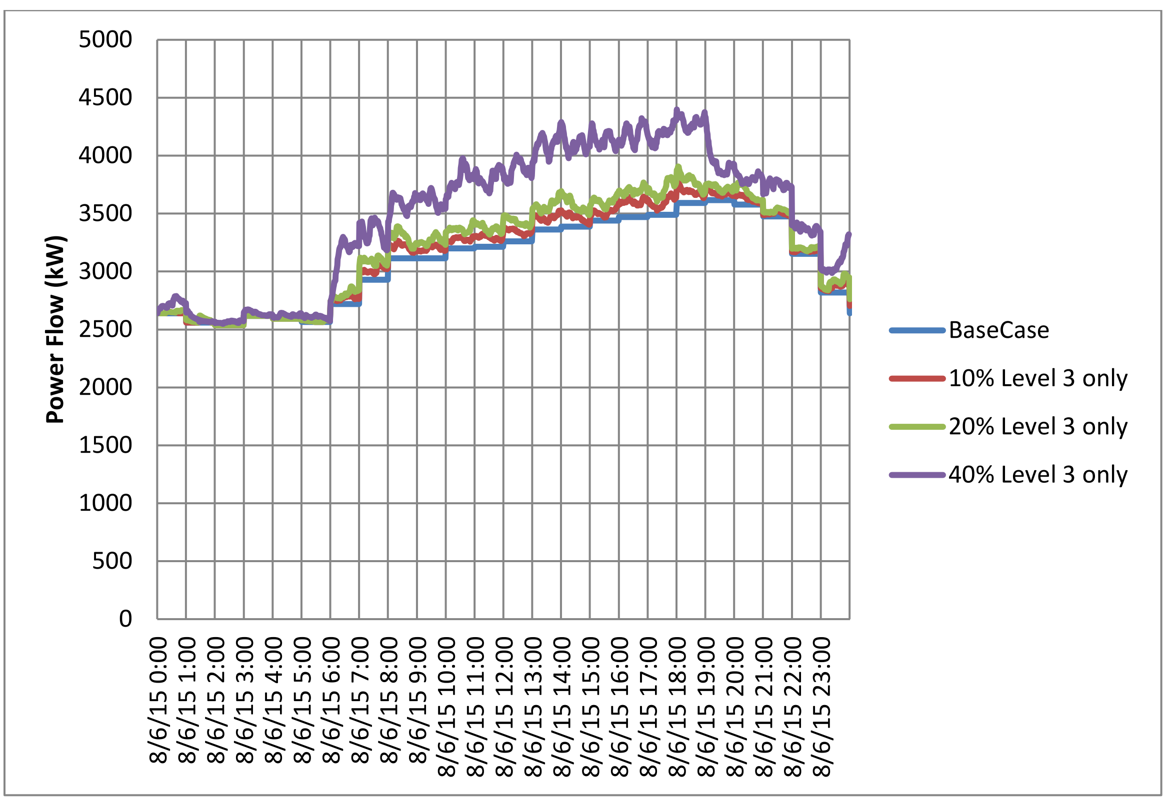


Figure 4-10. Voltage Distance Comparison for Range of EV penetrations and only DC Fast Charging

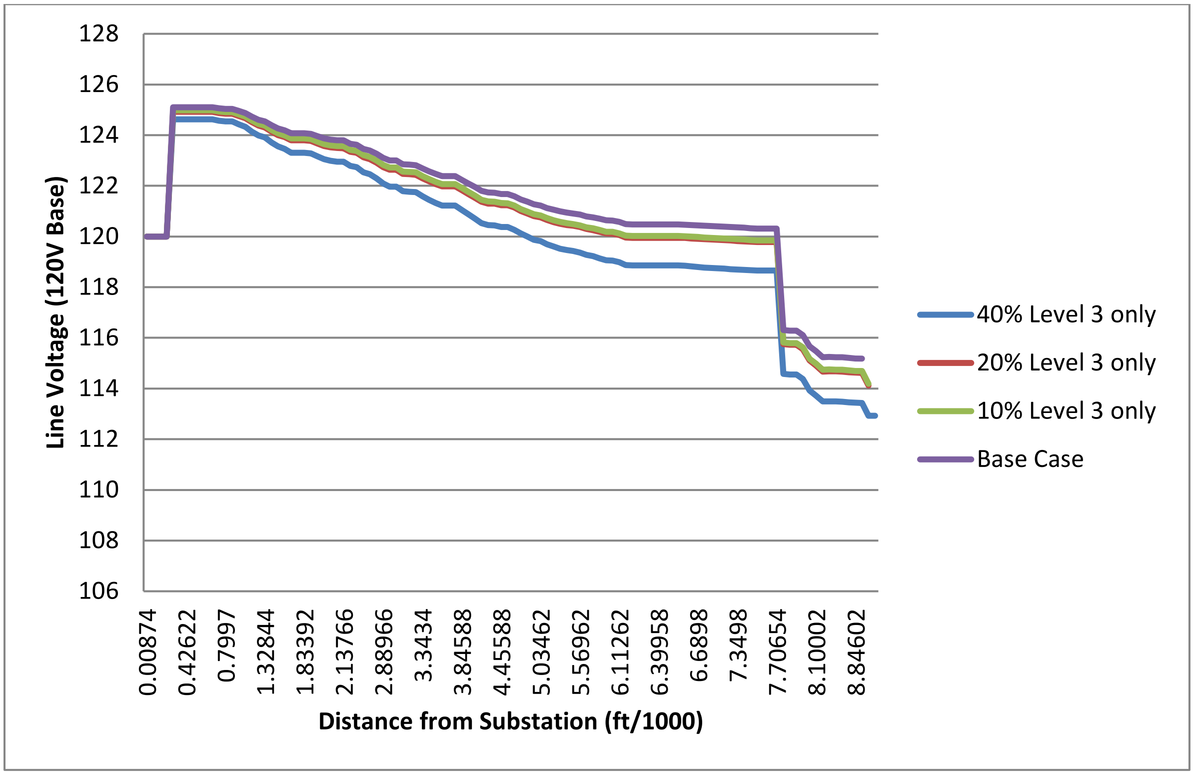


Figure 4-11. Line Segment 2 Voltage Distance Plot Comparison (DC Fast only)

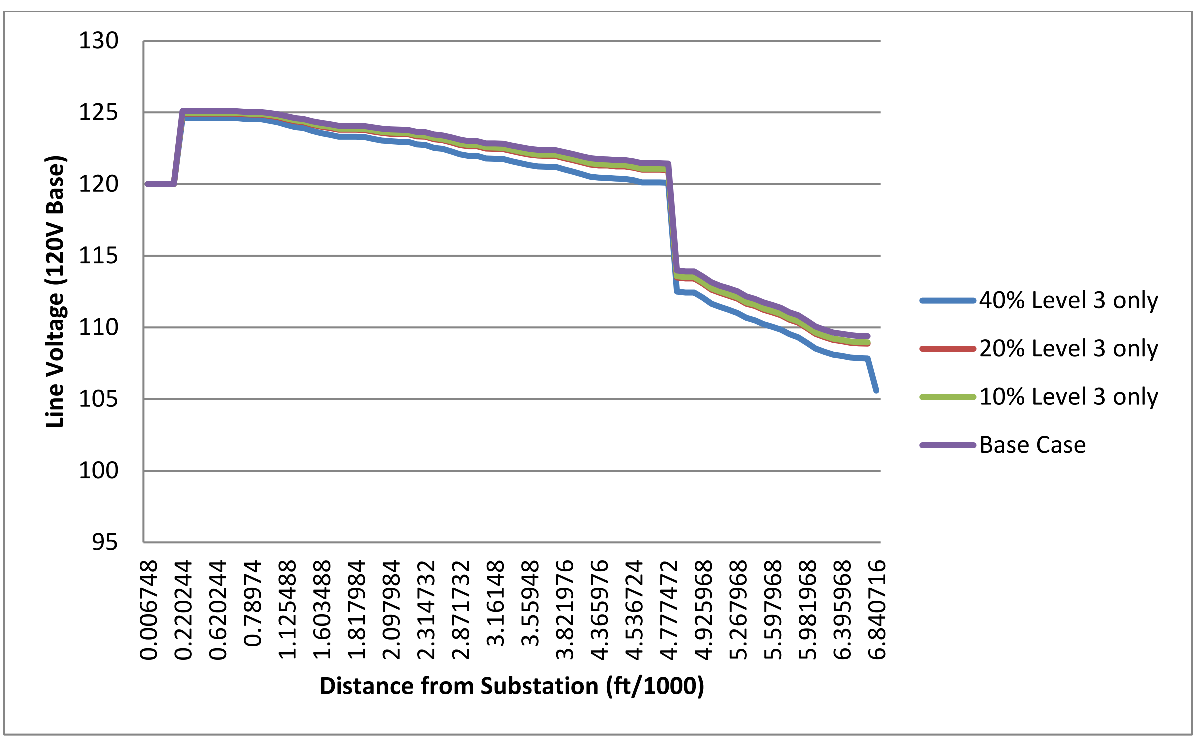


Table 4-10. Max and Min Power Flow Results with 40 percent Penetration (DC Fast Charging only)

Feeder Power Flow Results (Customer Voltage) LV3 40%			
	Phase A	Phase B	Phase C
Max Bus Voltage (120V Base)			
Bus Voltage (V)	117.9	118.5	118.8
Time	8/6/15 2:17	8/6/15 2:17	8/6/15 2:17
Min Bus Voltage (120V Base)			
Bus Voltage (V)	115.5	116.6	117.1
Time	8/6/15 19:00	8/6/15 18:00	8/6/15 18:00
% Difference	2.04	1.60	1.43
Feeder Power Flow Results (Real Power Per Phase)			
	Phase A	Phase B	Phase C
Max Real Power Flow (Kw)			
Power (KW)	4,443	3,935	4,071
Time	8/6/15 18:00	8/6/15 18:00	8/6/15 18:00
Min Real Power Flow (KW)			
Power (KW)	2,561	2,230	2,318
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

Table 4-11. Voltage Distance Results for 40 percent penetration of EVs with only DC Fast Charging

Min Voltage on line at peak load					
	Base case		40% Penetration LV3		%diff
Seg1	Voltage	Distance from Feeder (ft)	Voltage	Distance from Feeder (ft)	
A	115.18	8,915	113.43	8,915	1.52
B	122.57	7,715	121.13	7,715	1.17
C	114.91	8,915	113.39	8,915	1.32
Seg2					
A	109.39	6,834	105.59	6,841	3.48
B	121.36	4,926	120.18	4,926	0.98
C	119.17	6,834	117.98	6,834	1.00
Seg3					
A	119.90	10,687	118.20	10,687	1.42
B	122.08	11,240	120.61	11,240	1.21
C	121.96	11,420	120.53	11,420	1.17
Seg4					
A	120.22	11,593	118.56	11,593	1.38
B	122.87	11,593	121.44	11,593	1.17
C	122.72	11,593	121.33	11,593	1.14
Seg5					
A	119.93	9,387	118.24	9,387	1.40
B	122.46	8,397	121.01	8,397	1.19
C	122.64	8,546	121.23	8,546	1.15

4.2.3.2 Distribution Equipment Violations

Upon analysis of the results of the violations checker tool, it is evident that some transformer overloads occur at the time the load from the charging stations is greatest. The cumulative load from the DC Fast charging stations is the greatest at 1:55 p.m. on August 6, 2015, with a peak value of 2,480kW. At this time there are some overloads on the three-phase transformers connecting the charging stations to the grid. There are four, three-phase transformers overloaded at this time with a margin of violation of 31 percent in the worst case. This effect was anticipated as the worst case peak load at a single transformer could be as much as almost 1MW in the worst case alignment of peak loads from all 20 connected DC Fast charging units. There are also 50 instances of overloaded three-phase lines as a result of the DC Fast charging stations at 1:55 p.m. Some of the overloaded lines loaded beyond 200 percent of the rated capacity. This does not take into account the number of overloads at the feeder peak load time 6:00 p.m. The overloaded three-phase lines at the peak charging time is a source of concern and would necessitate line upgrades.

At peak load the substation transformer SubTr1 is overloaded by a margin of 31.1 percent compared to 24.3 percent in the previous case. There are 24 instances of three-phase line overloads at peak load. The three-phase line overloads are as high as 105 percent in the case of the 15ft section of line which is overloaded in all of the previous scenarios. Excluding the latter section of overloaded line, the average overload margin for the three-phase lines at peak is about five percent. There are two overloaded single phase lines at peak load. The most significantly overloaded single phase line is violated by a margin of 30.6 percent in this scenario which increased from 29.2 percent in the previous scenario. The second overloaded single phase line is only overloaded by about one percent. There are 72 instances of overloaded single phase distribution transformers in this case, two more than in the base case. Table 4-12 summarizes the percent increase in overloads from the base case. The table outlines increase in number of overloaded components from the base case, in addition to the margin by which the components are overloaded compared to the base case.

Table 4-12. Summary of Distribution equipment violations relative to the base case values of Tables 4-10 and 4-11

Summary of Distribution Equipment Violations increase from base Case						
	10% DC Fast		20% DC Fast		40% DC Fast	
	Quantity	% increase	quantity	% increase	quantity	% increase
Single Phase Distribution Transformers	0	1	0	2	2	15
three-phase Distribution Transformers	0	2	0	2	0	3
Step Transformer 1	0	0	0	1	0	2
Step Transformer 2	0	0	0	1	0	1
Station Transformer	0	0	0	2	0	9
three-phase lines	2	3	0	8	49	128
1 Phase Lines	0	4	0	4	1	5

4.3 Combined Level 2 and DC Fast Charging

This scenario analyzes various levels of EV penetration and accounts for the presence of a robust DC Fast public charging infrastructure in the system with Level 2 home charging options. This scenario presents the most realistic scenario for large scale EV adoption. To model the Level 2 charging, the loads from the Level 2 units are broken into nine load types to simulate the loads to an acceptable degree of accuracy. Three load profiles are used, low SOC, medium SOC, and high SOC. An assumed 9.5 hour away from home time developed the charging start times. Corresponding with the temporal departure distribution, it is found that the hours of 4, 5, and 6 p.m. are the most likely for the arrive and plug model, plug in, and charge times assuming that the amount of charge events for each hour is uniformly distributed. This scenario creates an economically feasible number of DC Fast charging stations with a greater number of vehicles in the high initial SOC range for Level 2 charging.

4.3.1 Combined Level 2 & DC Fast Charging with 10 Percent Penetration

This analysis has a 10 percent penetration level of EVs in the population is assumed with Level 2 chargers added to the feeder spatial geography in conjunction with DC Fast charging stations. Assuming 10 percent EV penetration, it is determined there are 258 Level 2 charging units placed on the feeder along with three DC Fast charging stations. Also, there are nine low initial SOC charge events uniformly distributed across the three-hour charge starts time interval (three for each hour), 120 medium SOC events, and 159 High SOC events. For this analysis, the focus is on the combined charging impact three stations will be assumed present in the system on the feeder and the results of the power flow and present violations will be analyzed.

4.3.1.1 Power Flow

This analysis reflects a 10 percent penetration of EVs in the system. The power flow conducted for this scenario reveals a peak load increase to 4,143.86 kW from 3,616 kW in the base case. The peak load shifts from 7 p.m. in the base case to 6:26 p.m. Figure 4-12 references the power flow graph. A summary of the results of the power flow is referenced in Table 4-13. The difference in the load profile characteristic is noticeable when compared to the base case power flow. A graphical comparison can be referenced in Figure 4-13. There is no substantial bus voltage variation at the feeder. The minimum bus voltage with a 120V base measured at the feeder bus is found to be 124.8V. However due to the increased loads downstream, the downstream line voltage decreases causing low voltage violations on loads. The low voltage issues become evident upon conduction of the voltage distance study for the feeder.

An analysis of the voltage distance relationship for the distribution lines is conducted. The most significant decrease in measured line voltage occurs on the A phase of line segment 2 with a percent decrease of 4.046 percent and a minimum line voltage of 104.96 V. A graphical comparison with the base case can be referenced in Figure4-14. The second most significant increase occurs on line segment 1 with a percent decrease of 4.019 percent on phase C and minimum voltage level of about 110V. A plot of the voltage distance relationship can be referenced in Figure 4-13 below. A summary of the effect of the results of the voltage distance study compared with the base case for the five line segments is shown in Table 4-14. The low voltage level on line segments 1 and 2 are significant enough to require compensation.

Figure 4-12. Power Flow of Feeder 19-14-13 with 3 DC Fast Charging Stations 258 Level 2 Units and 10 percent EV Penetration

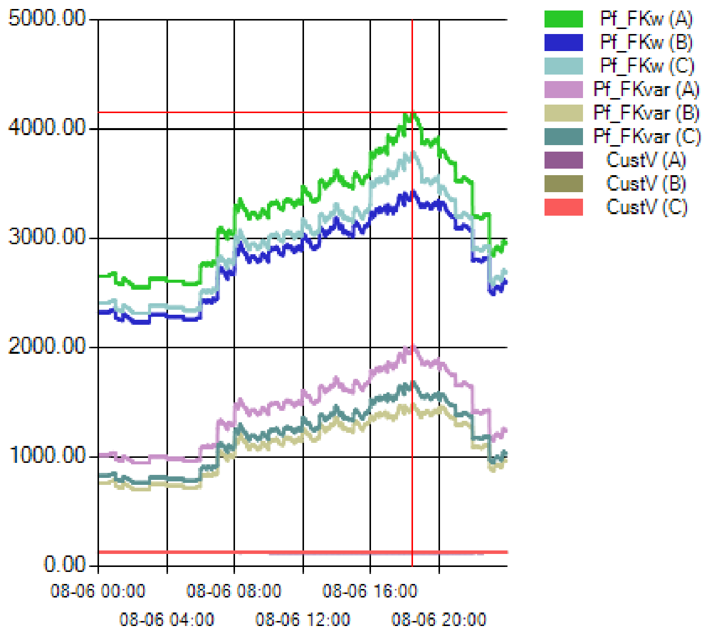


Figure 4-13. Voltage Distance Plot for the Feeder (line segment 1) with 10 percent EV penetration with Level 2 & DC Fast Charging

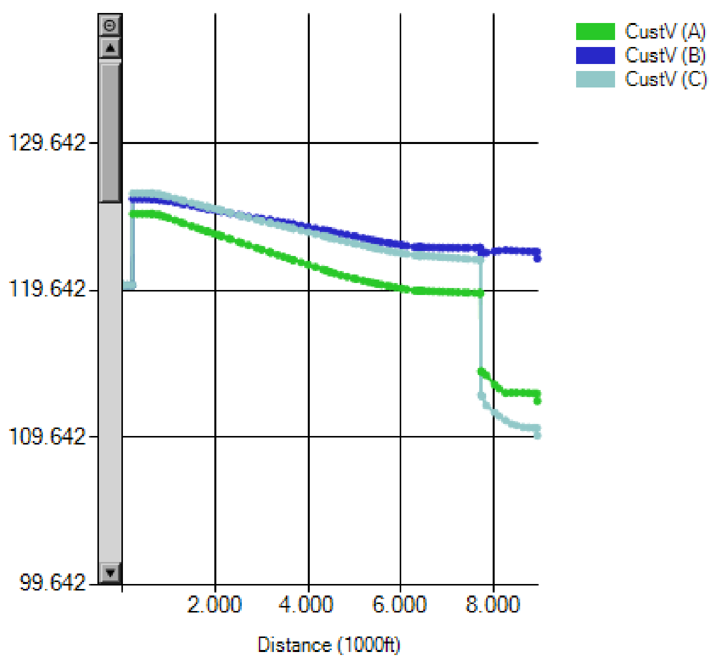


Figure 4-14. Voltage Distance Plot Comparison (Phase A, Line Segment 2, 10 percent Penetration Combined Level 2 and DC Fast Charging)

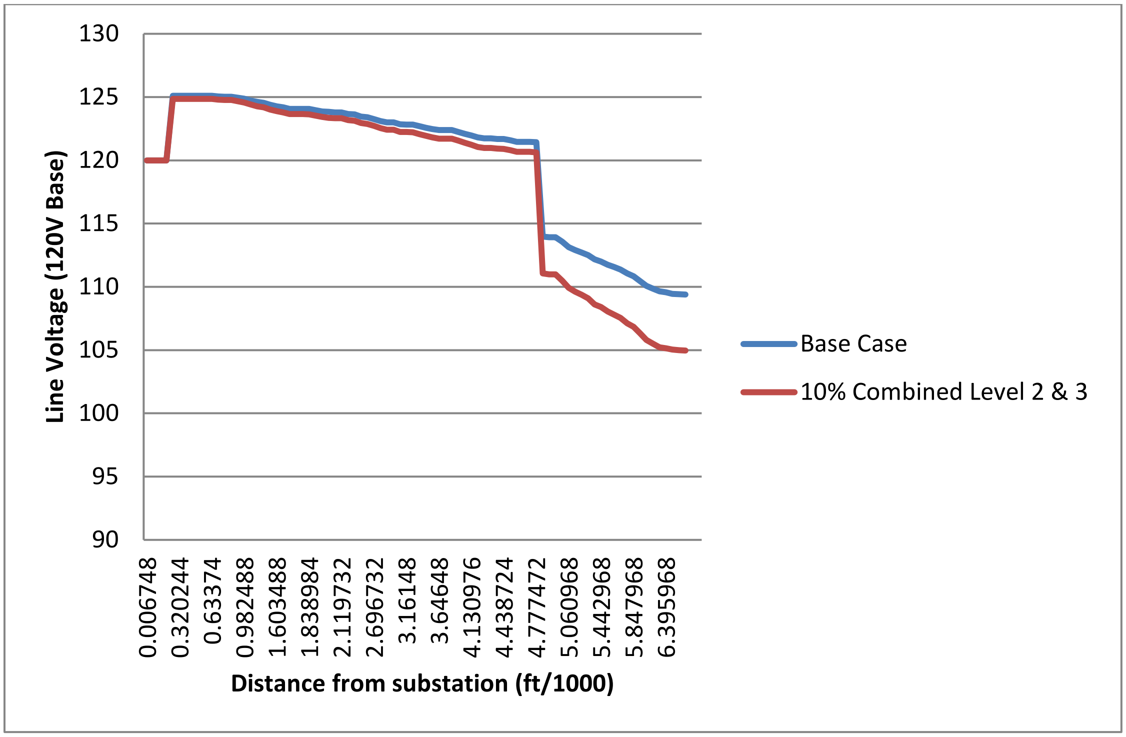


Table 4-13. Power Flow Results Summary for 10 percent EV Penetration with Level 2 and DC Fast Charging Scenario

Feeder Power Flow Results LV2 & LV3 10%			
	Phase A	Phase B	Phase C
Max Bus Voltage (120V Base)			
Bus Voltage (V)	126.21	126.78	127.03
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00
Min Bus Voltage (120V Base)			
Bus Voltage (V)	124.89	125.91	126.27
Time	8/6/15 18:32	8/6/15 19:59	8/6/15 18:32
% Difference	1.06	0.69	0.60
Feeder Power Flow Results (Real Power Per Phase)			
	Phase A	Phase B	Phase C
Max Real Power Flow (Kw)			
Power (KW)	4,150	3,428	3,786
Time	8/6/15 18:32	8/6/15 18:32	8/6/15 18:32
Min Real Power Flow (KW)			
Power (KW)	2,551	2,229	2,312
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

Table 4-14. Voltage Distance of feeder distribution lines with 10 percent EV Penetration, Base Case Comparison

Min Voltage on line at peak load					
	Base case		10% Penetration LV2 & LV3		%diff
Seg1	Voltage	Distance from Feeder (ft)	Voltage	Distance from Feeder (ft)	
A	115.18	8,915	112.64	8,915	2.21
B	122.57	7,715	122.18	7,715	0.32
C	114.91	8,915	110.29	8,915	4.02
Seg2					
A	109.39	6,834	104.97	6,834	4.07
B	121.36	4,926	120.61	4,784	0.62
C	119.17	6,834	117.89	6,762	1.07
Seg3					
A	119.90	10,687	119.02	10,687	0.73
B	122.08	11,240	121.67	11,240	0.34
C	121.96	11,420	120.96	11,420	0.82
Seg4					
A	120.22	11,593	119.35	11,593	0.72
B	122.87	11,593	122.48	11,593	0.32
C	122.72	11,593	121.65	11,593	0.87
Seg5					
A	119.93	9,387	119.05	9,387	0.73
B	122.46	8,397	122.06	8,397	0.33
C	122.64	8,546	121.66	8,546	0.80

4.3.1.2 Distribution Equipment Violations

The violations checker found that numerous single phase distribution transformer overloads occur as a result of adding these chargers to the system. There were 70 instances of single phase distribution transformer overloads present in the system base and the margin of violation was on average lower than in this scenario. At peak load the number of single phase distribution transformers in the overloaded state total 83 on the feeder. With the introduction of Level 2 chargers to the system, distribution transformer overloads are numerous and by margins sometimes exceeding 300 percent over rating on the most heavily loaded transformers. There are also 29 overloads that occur on the three phase lines at peak load as a result of introduction of Level 2 and DC Fast chargers. These three phase distribution line overloads are violated by a margin of almost 100 percent in some cases. The system overloads and analyzes violations primarily at the peak load to identify the point of most significant impact. The number of overloads is significant enough to warrant expansion in the event of large scale adoption of Level 2 EVSE and DC Fast charging stations

The substation transformer SubTr1 is overloaded in this case by 25.7 percent with a measured current of 166.7A. There are two step transformers in overload. The first has overloads on phases A and C, which are overloaded by 103 percent and 249 percent respectively. This step transformer is the component over which the steep drop seen on the A and C phase of line segment 1 in the voltage distance plots. In the base case this component is only overloaded by 127 percent on the C Phase and 44.6 percent on the A Phase. The increase in overload margin is mainly due to the numerous Level 2 charger loads added to residential locations downstream from the transformer. The second step transformer is overloaded on the A, B, and C phases by 85 percent, 4.4 percent, and 8.6 percent respectively. The effects of this step transformer in the line segment 2 voltage distance plot where the voltage drops steeply is shown in Figure 4-14. In the base case, only the A and C phases of this step transformer are overloaded by margins of 167 percent and 9.9 percent respectively. The margin of overload on the C phase is higher in the base case due to the residential load profile. The increase in margin of violation on the A and B phases are due to the addition of the Level 2 charging units. There are instances of low voltage violations at the loads around feeder as a result of the charging stations. The service point violation criteria for low voltage are set at 114V. Some of the load service points have measured voltages as low as 90V at peak.

4.3.2 Combined Level 2 & DC Fast Charging with 20 percent Penetration

In this scenario the number of Level 2 charge events in the system doubles the load of each charge event. This effectively simulates two vehicles plugging in at about the same time with similar initial SOCs for each charge event. This keeps the proportions of charge events distributed similarly as before, but doubles the load of the nine charge scenarios in the database for the system. The number of DC Fast charging stations on the feeder will likewise double from three in the previous 10 percent case to six charging stations on the feeder.

4.3.2.1 Power Flow

Upon conducting the power flow, it becomes evident that the increase in penetration of EVs yields a significant increase in the peak load on the feeder. The simplified “arrive and plug” model used in the analysis with uncontrolled domestic charging yields a model in which most of the home charging load occurs between 5 p.m. and 9 p.m. The peak load occurs around 6 p.m. with a value of 4,720 kW, 30.5 percent higher than the base case peak load. This stark increase in peak load is due to the concentration of Level 2 charging occurrences around peak load hours. A graphic representation for the power flow from the feeder for a single day can be observed in Figure 4-15. The jagged and erratic characteristic in the plot is due to the DC Fast charging station loads. A summary of the peak load results from the power flow can be referenced in Table 4-15.

The voltage distance study for the 20 percent scenario found significantly low voltages at the tail ends of the distribution line segments resulting from the increased penetration of EVs. Table 4-16 shows a tabular summary of the results of the voltage distance analysis. The most dramatic case is on line segment two where the percent difference from the base case equates 9.8 percent with a line voltage of 98.6V. The voltage distance plot for line segment 2 is referenced in Figure 4-16. Figure 4-17 shows a comparison of the A phase of line segment 2 voltage distance characteristics.

Figure 4-15. Power Flow for the Feeder with Level 2 and DC Fast Chargers and 20 percent EV Penetration

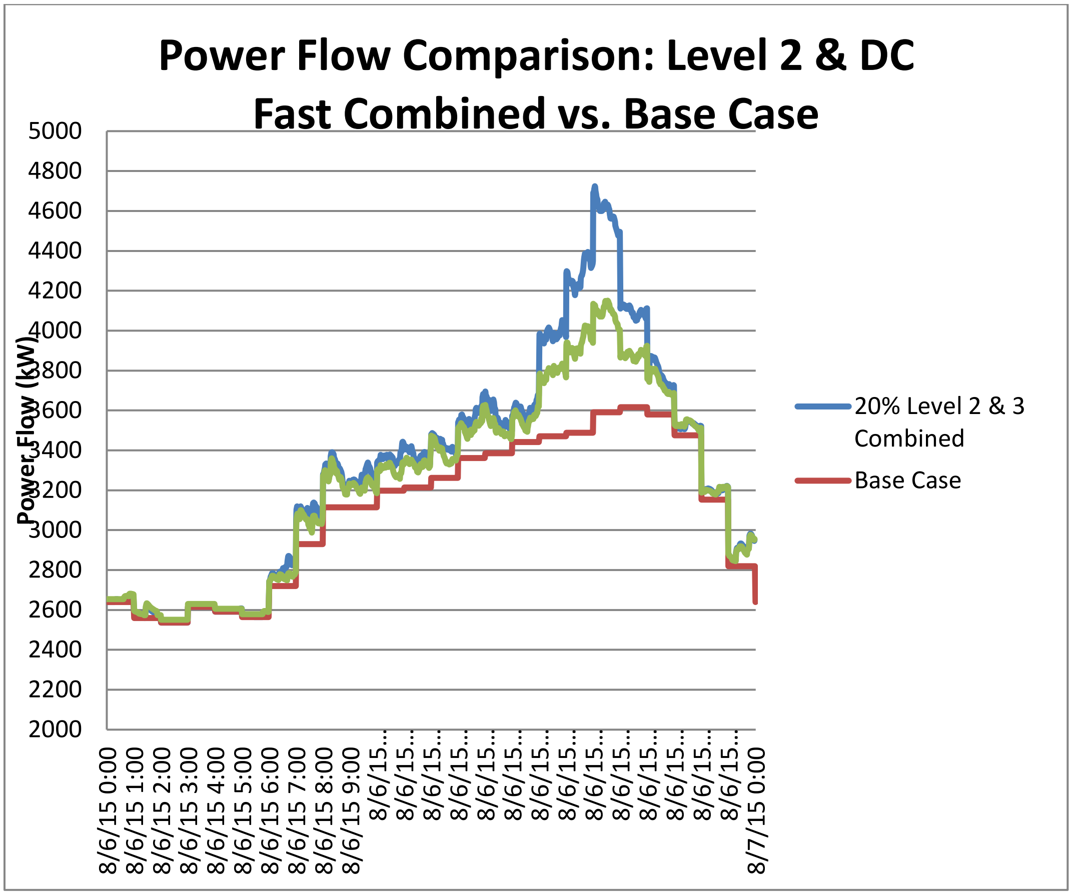


Figure 4-16. Voltage Distance Plot for Feeder (Line Segment 2) with 20 percent penetration of EVs with Level 2 and DC Fast charging scenario

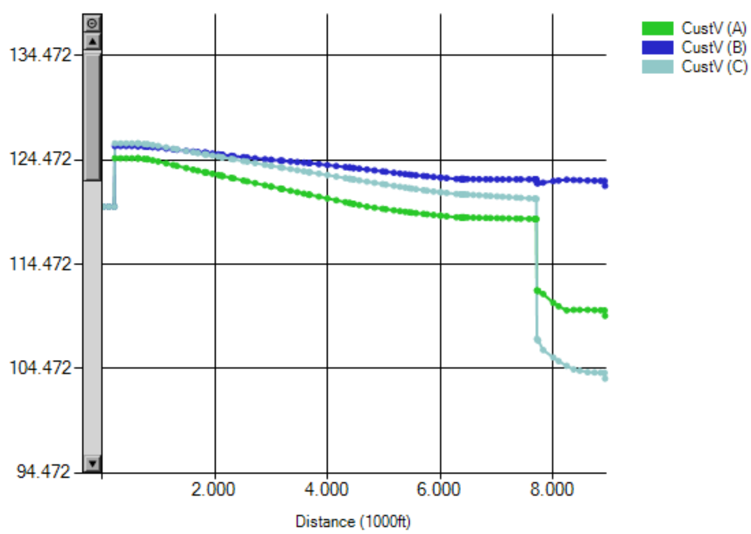


Figure 4-17. Voltage Distance Plot for Feeder (Line Segment 2) with 20 percent penetration of EVs with Level 2 and DC Fast charging scenario

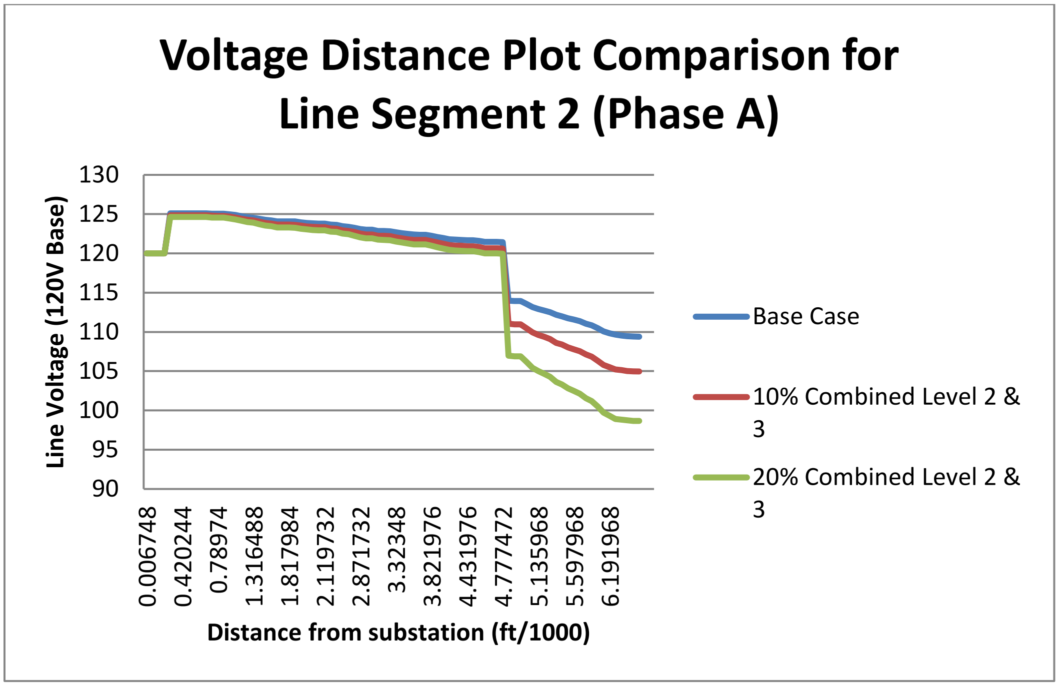


Table 4-15. Power Flow Results for Feeder for 20 percent EV Penetration with Level 2 & DC Fast Charging Scenario

Feeder Power Flow Results LV2 & LV3 20%			
	Phase A	Phase B	Phase C
Max Bus Voltage (120V Base)			
Bus Voltage (V)	126.23	126.8	127.04
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00
Min Bus Voltage (120V Base)			
Bus Voltage (V)	124.62	125.79	126.04
Time	8/6/15 18:03	8/6/15 18:03	8/6/15 18:03
% Difference	1.29	0.80	0.79
Feeder Power Flow Results (Real Power Per Phase)			
	Phase A	Phase B	Phase C
Max Real Power Flow (Kw)			
Power (KW)	4,724	3,671	4,319
Time	8/6/15 18:03	8/6/15 18:03	8/6/15 18:03
Min Real Power Flow (KW)			
Power (KW)	2,537	2,215	2,298
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

Table 4-16. Voltage Distance results for 5 Line Segments, with 20 percent EV Penetration, with LV2 and LV3 Charging Scenario

Min Voltage on line at peak load					
	Base case		20% Penetration LV2 & LV3		%diff
Seg1	Voltage	Distance from Feeder (ft)	Voltage	Distance from Feeder (ft)	
A	115.18	8,915	110.06	8,915	4.44
B	122.57	7,715	122.26	7,715	0.25
C	114.91	8,915	104.08	8,915	9.42
Seg2					
A	109.39	6,834	98.67	6,834	9.80
B	121.36	4,926	120.17	4,784	0.99
C	119.17	6,834	116.79	6,762	1.99
Seg3					
A	119.90	10,687	118.39	10,687	1.25
B	122.08	11,240	121.74	11,240	0.28
C	121.96	11,420	120.14	11,420	1.49
Seg4					
A	120.22	11,593	118.72	11,593	1.25
B	122.87	11,593	122.56	11,593	0.25
C	122.72	11,593	120.70	11,593	1.65
Seg5					
A	119.93	9,387	118.42	9,387	1.25
B	122.46	8,397	122.13	8,397	0.28
C	122.64	8,546	120.83	8,546	1.47

4.3.2.2 Distribution Equipment Violations

This scenario shows significant equipment violations that occur at peak. There are a concerning number of distribution line overloads that occur at peak load on the system. At peak load there are 70 instances of three-phase line overloads. Some of these are overloaded by a margin of over 150 percent. There is one instance of violation on a three-phase underground feeder cable, overloaded at peak by 2.3 percent. There are 14 instances of single phase lines overloaded by margins up to 200 percent.

The substation transformer SubTr1 is overloaded in this scenario by a margin of about 33 percent, which is a 7.6 percent increase from the 10 percent penetration scenario. There are 90 instances of single phase transformer overloads that result from the increased penetration of Level 2 EVSE in the system Several of the single phase distribution transformer overloads exceed 100 percent over rating. There are the same 2 step transformers overloaded as in the 10 percent scenario. The first is overloaded on the A and C phases by margins of 175 percent and 419 percent respectively. The second step transformer is overloaded on A, B, and C phases by margins of 127 percent, 12.88 percent, and 14.4 percent respectively. The effect of the overloaded step transformer on the line voltage is evident in the voltage distance plot in Figure 4-17. A tabular summary of the increases in percent overloads and the quantity of overloaded components for both the 10 and 20 percent penetration scenarios can be referenced in Table 4-17.

Table 4-17. Summary of increased equipment violation with increased EV penetration

Summary of Distribution Equipment Violations increase from base Case				
	10% LV2 LV3		20% LV2 LV3	
increase from base case	Quantity	% increase	quantity	% increase
Single Phase Distribution Transformers	13	165	20	315
three-phase Distribution Transformers	0	29	0	29
Step Transformer 1	1	-82	1	-40
Step Transformer 2	0	122	0	292
Station Transformer	0	4	0	11
three-phase lines	28	21	69	78
1 Phase Lines	2	82	13	175

4.3.2.3 Cost / Benefit Analysis

There are costs to consider in the form of system upgrades that need to be considered for moderate penetrations of EVs in the distribution system. However, these costs provide potential benefits for the utility in the form of increased reliability and a possible decrease in peak demand by developing tailored service classifications for loads with EVSE.

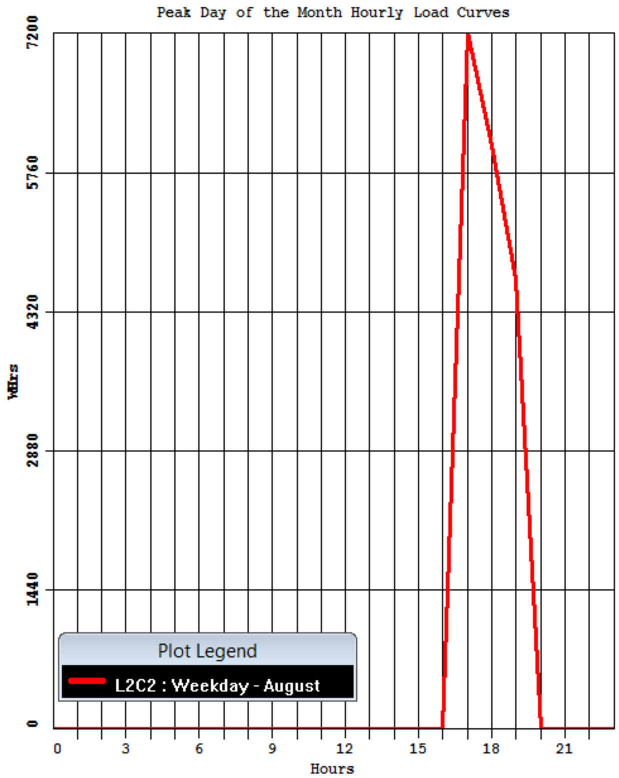
Some of the costs in this scenario and penetration level include the need to increase the size of single phase transformers serving residential loads due to the demand from home charging activity in the system. Other costs associated include the increase in line capacity to serve the increased peak load to prevent outages and lost load costs. Voltage control in the form of power factor correction downstream from the feeders is necessary to alleviate the low voltage violations present at service points downstream from high demand loads like the DC Fast charging stations.

There are potential benefits for the utility and the customers as well. The potential exists to develop new time-of-use or market based service rates for residential customers with EVSE, which could incentivize off peak charging. Requiring time-of-use rates or EVSE tailored rates for residential customers with EVSE could reduce peak demand due to home charging. Another potential benefit for increasing system capacity through upgrades lies with increasing system reliability and reduced costs due to lost loads.

4.4 Level 2 Home Charging Only

Creating a scenario of no DC Fast public charging helped to gain an idea of the impact home charging has on the distribution system. A model that simulated Level 2 charging activity analyzed the effect of domestic charging on the distribution system. Several new load classifications were added to the DEW database to simulate Level 2 charging of vehicles with low initial SOC, medium initial SOC, and high initial SOC. The transportation model developed and described in Chapter 3 determined that home charging is likely to start between the hours of 4 p.m. and 6 p.m. Without the presence of DC Fast charging stations in the system, a greater number of samples exist in the low and medium initial SOC classification than in the high initial SOC classification when compared to the case of combined DC Fast (public) and Level 2 (home) charging available scenario. A one-hour time resolution is used for this analysis due to the nature of the Level 2 load profile not being as erratic as the DC Fast charging station load profiles. Figure 4-18 shows an example of a low initial SOC Level 2 load profile.

Figure 4-18. Low initial SOC Level 2 load profile from DEW



4.4.1 Level 2 only on system 10 percent penetration

In the 10 percent penetration case, 258 Level 2 EVSE loads are placed around the spatial geometry of the feeder semi-randomly. The number of Level 2 EVSE loads added to each load bus in the system coincides with the number of pre-existing residential loads on the load bus. In this case, the quantity of Level 2 EVSE loads added to each distribution transformer does not outnumber the quantity of pre-existing residential loads. In most cases the number of Level 2 EVSE loads added on each transformer equate about half or less than half the number of residential loads on the transformer. This is based on the idea that there are an average of 2.2 vehicles per household in the geographic area of interest in this study.[20] Not all single phase transformers on the feeder have Level 2 EVSE loads applied. The Level 2 units used in this analysis are 208/240V 30A units rated at 7.2kW.

4.4.1.1 Power Flow

The power flow conducted for the two-day time interval used in this study found that a 10 percent presence of Level 2 EVSE yields an increase daily peak load on the feeder to 3831.05 kW at 6:00 p.m. on August 6, 2015. When compared to the base case daily peak load of 3616.35 kW at 7:00 p.m., one can see that a shift in peak load occurs and an increase in peak load of almost six percent. The power flow for the feeder is shown in Figure 4-19. A graphical comparison of the power flow to the base case is referenced in Figure 4-20. Table 4-18 shows a tabular summary of the power flow results.

This scenario conducted a voltage distance analysis and found that the greatest change in line voltage from the base case occurs on the C phase of line segment 1, with a two percent drop in voltage from the base case. The line segment 1 voltage distance plot for this scenario can be referenced in Figure 4-21. The A and C phase voltage distance plots are shown in Figure 4-23 and Figure 4-24 respectively, for a direct comparison to the base case for the varying penetration levels in this section. A tabular summary of the comparison of the voltage distance analyses for the five line segments for the 10 percent penetration scenario can be referenced in Table 4-19.

Figure 4-19. Power Flow Results for 10 percent penetration for Level 2 EVSE only case

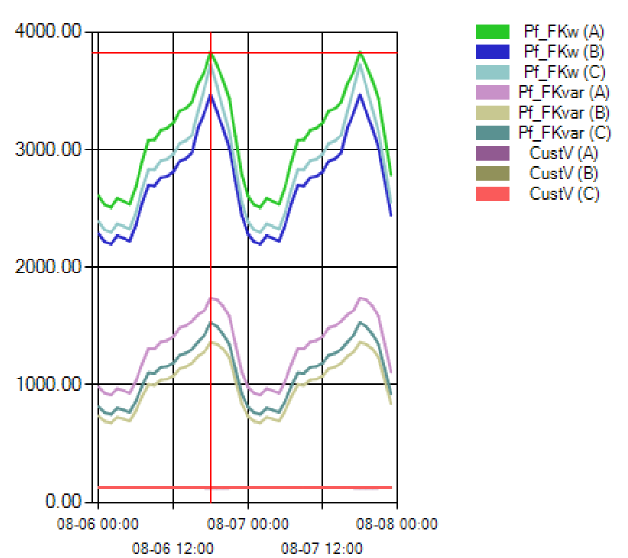


Figure 4-20. Power Flow for Feeder with 10 percent Penetration of EVs and Only Level 2 Home Charging

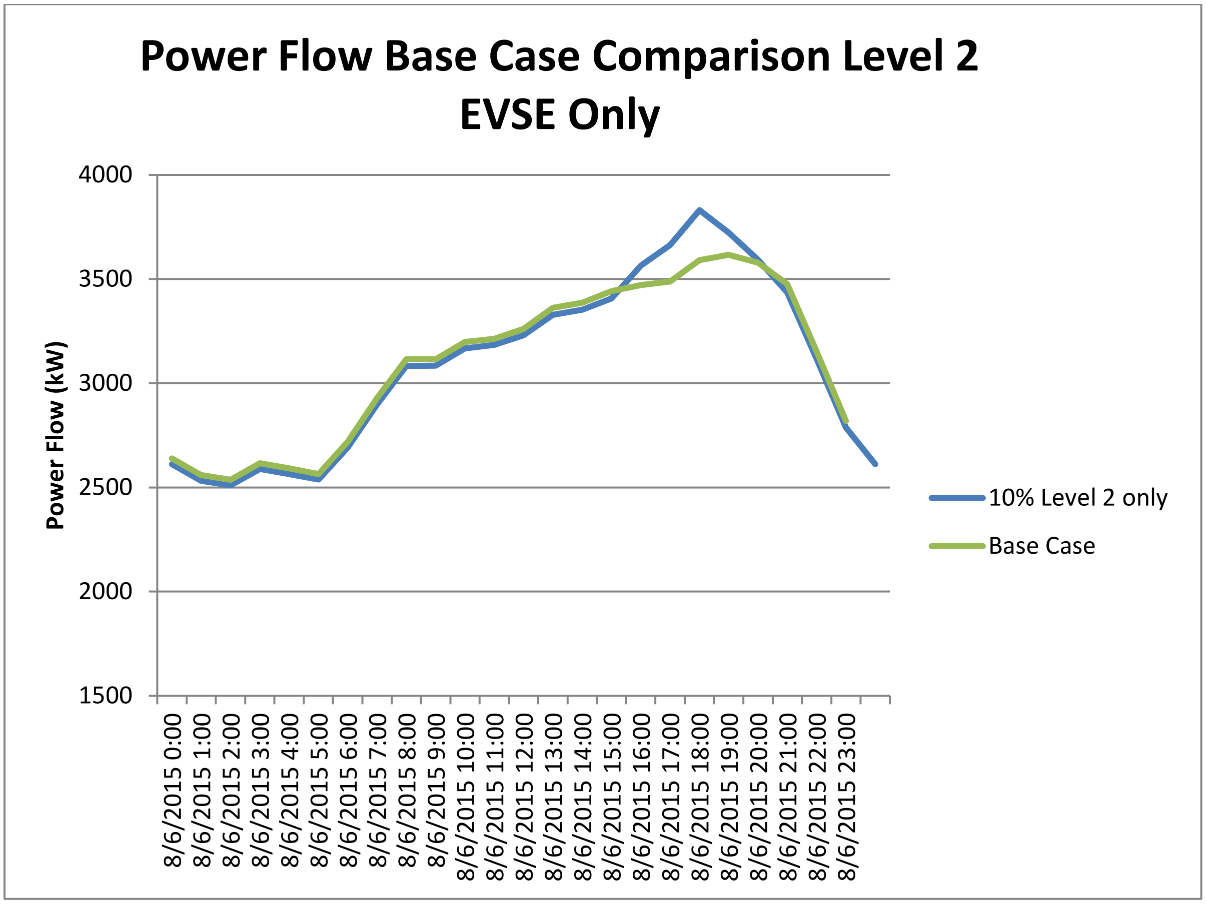


Figure 4-21. Voltage Distance Plot (Line Segment 1) on the Feeder with 10 percent Penetration and Level 2 Only

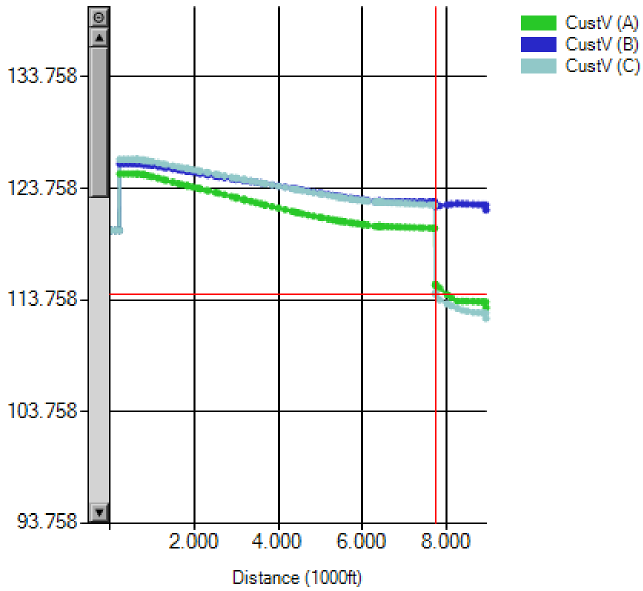


Table 4-18. Summary of Results of Power Flow for 10 percent EV Penetration and Level 2 Home Charging Only Scenario

Feeder Power Flow Results LV2 10%			
	Phase A	Phase B	Phase C
Max Bus Voltage (120V Base)			
Bus Voltage (V)	126.24	126.8	127.04
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00
Min Bus Voltage (120V Base)			
Bus Voltage (V)	125.03	125.97	126.35
Time	8/6/15 18:00	8/6/15 18:00	8/6/15 18:00
% Difference	0.96	0.66	0.54
Feeder Power Flow Results (Real Power Per Phase)			
	Phase A	Phase B	Phase C
Max Real Power Flow (Kw)			
Power (KW)	3,831	3,468	3,726
Time	8/6/15 18:00	8/6/15 18:00	8/6/15 18:00
Min Real Power Flow (KW)			
Power (KW)	2,510	2,198	2,298
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

Table 4-19. Voltage Distance results for 10 percent EV penetration with Level 2 charging only Scenario

Min Voltage on line at peak load					
Base case			10% Penetration Level 2 only		%diff
Seg1	Voltage	Distance from Feeder (ft)	Voltage	Distance from Feeder (ft)	
A	115.18	8,915	113.58	8,915	1.39
B	122.57	7,715	122.18	7,715	0.32
C	114.91	8,915	112.61	8,915	2.00
Seg2					
A	109.39	6,834	108.87	6,834	0.47
B	121.36	4,926	121.07	4,784	0.24
C	119.17	6,834	118.77	6,834	0.33
Seg3					
A	119.90	10,687	119.80	10,687	0.079
B	122.08	11,240	121.66	11,240	0.35
C	121.96	11,420	121.50	11,420	0.38
Seg4					
A	120.21	11,593	120.11	11,593	0.09
B	122.87	11,593	122.48	11,593	0.32
C	122.72	11,593	122.22	11,593	0.41
Seg5					
A	119.93	9,387	119.83	9,387	0.08
B	122.46	8,397	122.03	8,397	0.35
C	122.64	8,546	122.18	8,546	0.38

4.4.1.2 Distribution Equipment Violations

Upon analysis of the results of the distribution violations checker it is evident at peak that the addition of the Level 2 chargers to the system contribute to a significant increase in distribution equipment overloads. At peak, the overload for substation transformer SubTr1 is by 23.5 percent. There are numerous single phase distribution transformers overloaded by margins exceeding 100 percent and 98 single phase transformer overloads at peak in total. There are two overloaded step transformers in the system, each on the A and C phases. The first is overloaded by 93 percent and 196 percent on the A and C phases respectively. The second is overloaded by 177 percent and 10 percent on the A and C phases respectively. The second overloaded step transformer is where the steep voltage drop occurs in the A and C phase voltage distance plots as shown in Figure 4-23 and Figure 4-24 respectively. One can see from the voltage distance plots and the tabular summary that the voltage on the downstream three-phase lines becomes substantially low due to the introduction of Level 2 charging EVSE.

Additionally, there are three sections of three-phase distribution lines in the system overloaded by as much as 80 percent at peak due to the addition of the Level 2 charging infrastructure. There are two adjoined sections of single phase distribution line overloaded at peak load by margins of 36.5 percent and 7.1 percent respectively.

4.4.2 Level 2 only on system 20 percent penetration

In this scenario, the load classes that represent the Level 2 charging load are doubled in load value. This simulates multiple vehicles plugging in within the same hour with similar initial SOC values. This scenario is essentially the same as the 10 percent scenario, but with more charge events occurring on the distribution transformers. This keeps the distribution of charge events the same as the previous scenario.

4.4.2.1 Power Flow

The power flow is conducted on the circuit for this scenario. The peak load is found to increase to a value of 4211kW from 3831 in the 10 percent penetration case. A graphic representation of the power flow is referenced in Figure 4-22, with a tabular summary of the power flow to be observed in Table 4-20. Figure 4-23 shows a graphic representation of a comparable power flow between the base case, 10 percent penetration, and 20 percent penetration cases.

Additionally, this analysis determined the influence of charging stations on the line voltage. The voltage vs. distance from substation plot for line segment 1 can be observed in Figure 4-24 for phase A and Figure 4-25 for phase C. These voltage distance plots show the voltage on components along about two miles of distribution lines. The drop seen near the tail of the plot shows the voltage on phases A and C dropping to around 111V on phase A and 109V on phase C. This drop occurs as a result of adding the Level 2 charging units to the line. The drop in voltage occurs over a 167kVA 13.2/7.62: 4.16/2.4kV step transformer. The lines downstream from this transformer are particularly loaded with Level 2 chargers especially at peak. The low voltage on the lines is due to the increase in peak load from the Level 2 charging loads as shown in the power flow plot of the lines after the transformer and referenced in Figure 4-25. When compared to the voltage at peak load in the 10 percent penetration case and base case the voltage drop is due to the increased penetration of EVs with the Level 2 home charging model. The steep voltage drop occurs over the step transformer at peak load due to the high demand. Figure 4-16 shows a plot of the voltage of the component throughout the course of the day.

Figure 4-22. Power Flow for Feeder 19-14-13 with 20 percent penetration with Level 2 only.

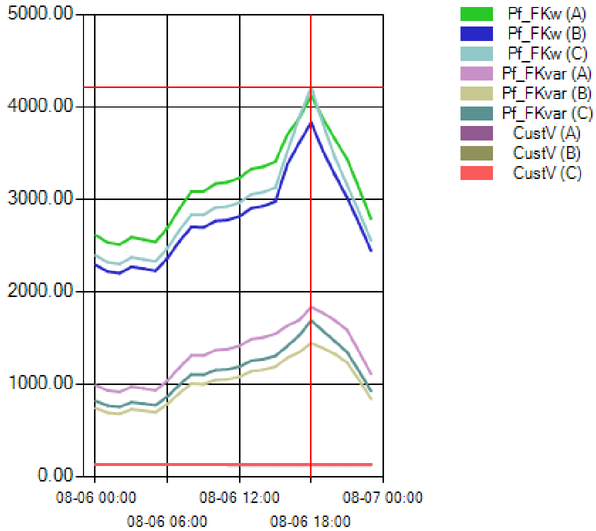


Figure 4-23. Power Flow Comparison for the Level 2 Charging Scenarios

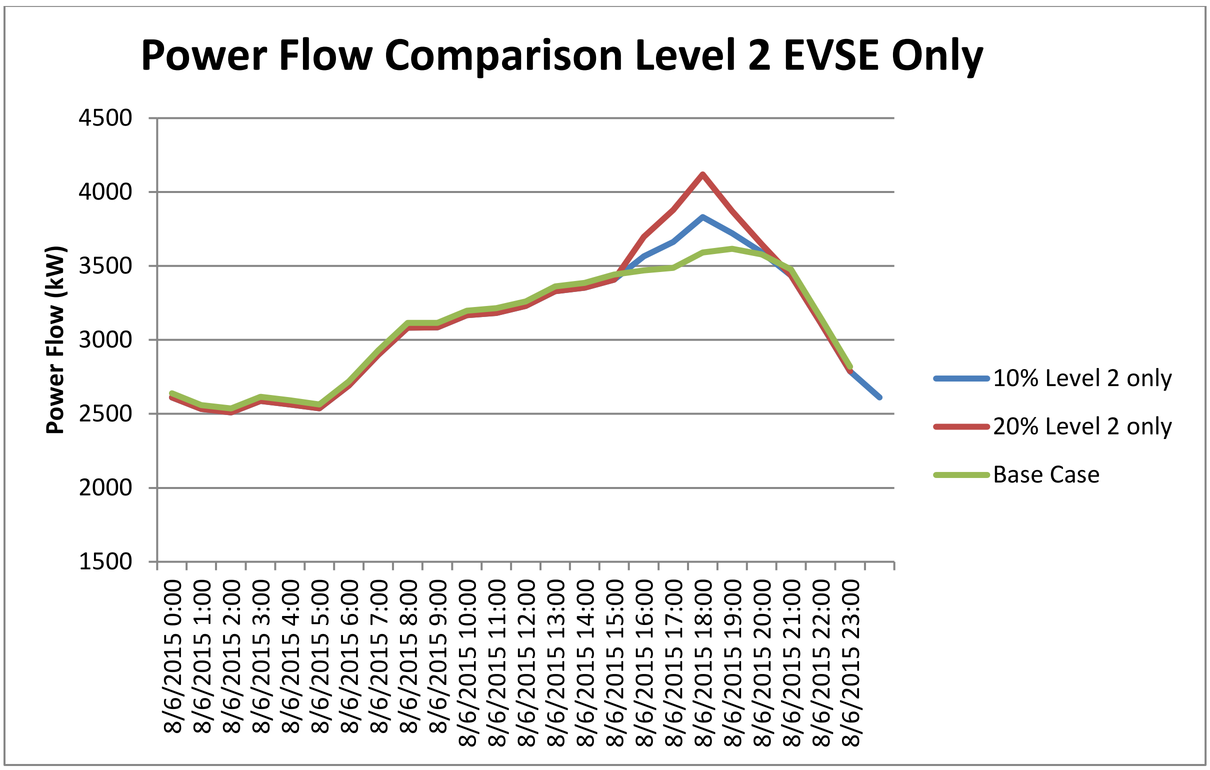


Figure 4-24. Voltage vs Distance from Substation Plot with Level 2 charging comparison. (Line Segment 1 at Peak load)

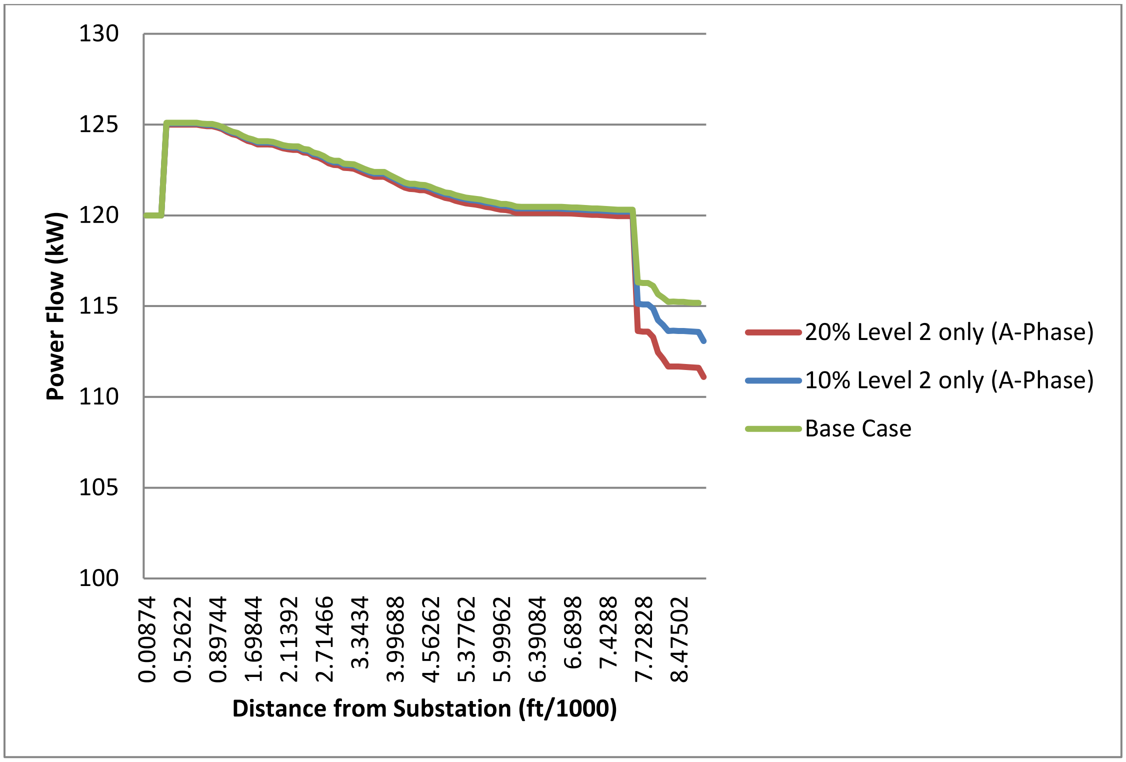


Figure 4-25. Voltage Distance Plot Comparison for C Phase of Line Segment 1

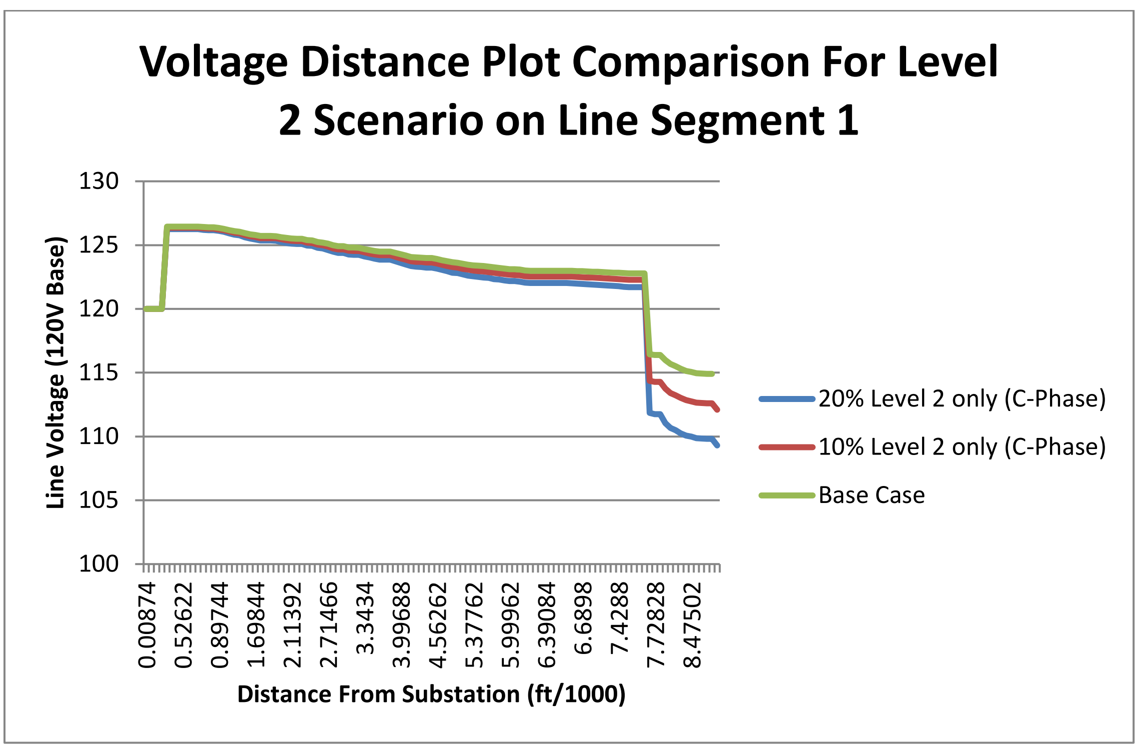


Figure 4-26. Voltage vs Time of Step Transformer Where voltage drop occurs in plot Figure 4-24)

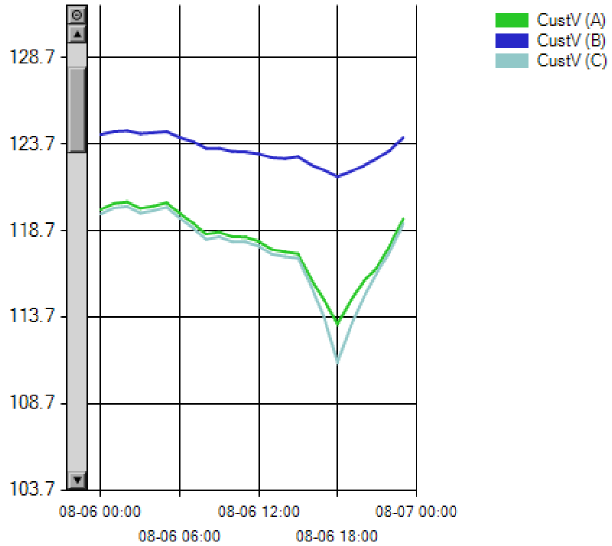


Table 4-20. Power Flow Results Summary for 20 percent Penetration and Level 2 Charging Only

Feeder Power Flow Results LV2 20%			
	Phase A	Phase B	Phase C
Max Bus Voltage (120V Base)			
Bus Voltage (V)	126.24	126.8	127.04
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00
Min Bus Voltage (120V Base)			
Bus Voltage (V)	125.0	125.92	126.25
Time	8/6/15 18:00	8/6/15 18:00	8/6/15 18:00
% Difference	0.99	0.70	0.61
Feeder Power Flow Results (Real Power Per Phase)			
	Phase A	Phase B	Phase C
Max Real Power Flow (Kw)			
Power (KW)	4,119	3,831	4,211
Time	8/6/15 18:00	8/6/15 18:00	8/6/15 18:00
Min Real Power Flow (KW)			
Power (KW)	2,510	2,198	2,298
Time	8/6/15 2:00	8/6/15 2:00	8/6/15 2:00

Table 4-21. Minimum line Voltage Values at Peak Load (5 line sections)

Min Voltage on line at peak load					
	Base case		20% Penetration Level 2 only		% Diff
Seg 1	Voltage	Distance from Feeder (ft)	Voltage	Distance from Feeder (ft)	
A	115.18	8,915	111.61	8,912	3.10
B	122.57	7,715	121.76	7,715	0.66
C	114.91	8,915	109.82	8,915	4.43
Seg 2					
A	109.39	6,834	108.16	6,834	1.12
B	121.36	4,926	120.74	4,784	0.51
C	119.17	6,834	118.32	6,834	0.71
Seg 3					
A	119.90	10,687	119.55	10,687	0.29
B	122.082	11,240	121.21	11,240	0.71
C	121.96	11,420	120.97	11,420	0.80
Seg 4					
A	120.22	11,593	119.863	11,593	0.30
B	122.87	11,593	122.0667	11,593	0.65
C	122.72	11,593	121.6484	11,593	0.87
Seg 5					
A	119.93	9,387	119.5817	9,387	0.29
B	122.46	8,397	121.5898	8,397	0.71
C	122.64	8,546	121.6616	8,546	0.80

4.4.2.2 Distribution Equipment Violations

The violations checker analyzed the overloads on the distribution system components that result from the addition of Level 2 EVSE to the system. As a result of increasing the penetration of EVs in the system there are 106 instances of single phase distribution transformer overloads that occur on in the system, 36 more than in the base case. There is a 28 percent overload on the substation transformer SubTr1. In this instance, the station transformer overload is less severe than in the combined 31 percent overload for Level 2 and DC Fast 20 percent penetration case. The two step transformers mentioned in previous scenarios are each overloaded on the A and C phases. The first overload is by 151 percent and 282 percent on the A and C phases respectively. The second overloaded on the A and C phase is by 189 percent and 11 percent respectively. The exacerbated overloads are due to the excessive peak load created by the concentration of Level 2 charging loads on the system around peak load hours.

There are eight sections of three-phase distribution lines overloaded at peak load in this scenario, which compose four individual sections of line. The most significantly overloaded line is overloaded by a margin of nearly 100 percent. There are nine overloaded lengths of single phase lines at peak load in this scenario, the most severely overloaded exceeds 45 percent over rating. A tabular summary of the increase in distribution equipment violations resulting from the increase in penetration of EVs is referenced in Table 4-22.

Table 4-22. Summary of increase in distribution equipment violations from base case

Summary of increase in equipment violations				
	10% Level 2		20% Level 2	
	quantity	% increase	quantity	% increase
Single Phase Distribution Transformers	28	15	36	233
three-phase Distribution Transformers	0	2	0	4
Step Transformer 1	0	29	0	115
Step Transformer 2	0	50	0	62
Station Transformer	0	2	0	6
three-phase lines	2	8	3	28
1 Phase Lines	0	12	8	20

4.4.2.3 Cost / Benefit analysis

There are costs associated with the adoption of EVs in the NYS power system due to the large number of equipment overloads evident at peak. First, an increase in the capacity of residential single phase transformers are necessary to account for the additional loads from residential EVSE. Another associated cost involves the distribution line upgrade to accommodate the increase in peak load from Level 2 EV charging.

Adoption of time-of-use rates by residential customers with installed EVSE would present a benefit by shifting and reducing the peak load presumably shifting vehicle charging loads to off peak hours. While this strategy would require customers to choose time-of-use rates, most NYS utilities currently offer residential these rates to customers.

4.5 Comparisons

One of the focuses of this project is to determine the potential effects of DC Fast DC fast charging on the power system. The simulated distribution system added charging stations analogous to gas stations for various penetrations of EVs in the system to test the effect of a robust DC Fast charging infrastructure. The public DC Fast charging stations were supplemented in the simulation by Level 2 home charging using an uncontrolled "arrive-and-plug" model as discussed in Chapter 3. Table 4-23 shows a comparison conducted between the latter scenario and one in which only Level 2 home charging is available based on their daily peak loads and the percent increase from the base case.

Table 4-23. Daily Peak Load Comparison of Scenarios

Daily Peak Load & Increase from Base Case Comparison				
	10% Pen		20% Pen	
Combined LV2 & LV3	Peak Load (kW)	% increase	Peak load (kW)	% increase
Phase A	4,150	14.77%	4,724	30.63%
Phase B	3,428	8.53%	3,670	16.21%
Phase C	3,785	15.45%	4,318	31.71%
Level 2 Only				
Phase A	3,831	5.94%	4,119	13.91%
Phase B	3,468	9.82%	3,830	21.27%
Phase C	3,726	13.64%	4,211	28.45%

One can ascertain from the table that the daily peak load is greatest in the combined Level 2 and DC Fast scenario on the A and C phases. The Level 2 home charging only scenario has the highest daily peak loads on the B phase. The case of combined Level 2 and DC Fast charging has the highest total daily peak load in this analysis. This is largely due to the coinciding high load characteristics in the daily load profiles of the DC Fast charging stations, Level 2 home charging models, and base case daily load profile for the system around 6:00 p.m.

The peak loads alone cannot provide an accurate comparison for the effects of these two scenarios as voltage imbalance on the distribution lines presents an issue. To address voltage imbalance in the system due to additional chargers, the ends of line segments 1 and 2 are compared for both cases as shown in Table 4-24.

Table 4-24. Line Voltage Imbalance Scenario Comparison

Voltage Imbalance comparison				
Line Voltages (120V Base)	Segment 1		Segment 2	
Combined LV2 % LV3	10% Pen	20% Pen	10% Pen	20% Pen
Phase A	112.64	110.06	104.97	98.67
Phase B	122.18	122.26	120.61	120.17
Phase C	110.29	104.08	117.89	116.79
Level 2 Only				
Phase A	113.58	111.61	108.87	108.16
Phase B	122.18	121.76	121.07	120.74
Phase C	112.61	109.82	118.77	118.32

Upon observing the voltage imbalance comparison table, it is evident that the line voltage imbalances in each case are greatest in the combined Level 2 and DC Fast charging scenario. Based on this result one may conclude that the scenario of combined Level 2 home-charging and DC Fast public charging has a greater potential impact on the system. The impact on distribution equipment overloads is another important aspect in determining which scenario has the most significant impact. Table 4-25 provides a tabular summary of the number of equipment overloads for comparison of each scenario.

Table 4-25. Summary of Distribution Equipment Violations Scenario Comparison

Comparison of Distribution Equipment Overloads					
	Combined LV2 &LV3		Level 2 only		Base Case
	10% Pen	20% Pen	10%	20%	
Single Phase Distribution Transformers (Quantity)	83	90	98	106	70
three-phase Distribution Transformers (% overload)	173	173	146.2	148.3	144
Step Transformer 1 (greatest % Overload)	85	127	196	282	167
Step Transformer 2 (greatest % Overload)	249.4	419.4	177	189	127.4
Station Transformer (% Above Base OA Rating)	26	33	23.5	28	22
three-phase lines (Quantity)	29	70	3	4	1
1 Phase Lines (Quantity)	3	14	1	9	1

The table shows the combined Level 2 home and DC Fast public charging scenario has a greater impact on distribution equipment overloads in many aspects. As expected, there are more severe single phase distribution transformer overloads that occur in the Level 2 home charging scenario due to greater demand from home charging without public charging options. The severity and quantity of three-phase overhead distribution transformer overloading is higher in the combined Level 2 and DC Fast scenario caused by an increased daily peak load and the high three-phase demand of the charging stations. The step transformer 1 overload is greater in the Level 2 only scenario due to the many residential customers downstream from the transformer. The increase in daily peak load from Level 2 charging in the residential areas exacerbates the overloads. The demand is lower in the combined case because the demand from home charging is offset by the public charging options. However, the step transformer 2 is far more overloaded in the combined case due to high demand downstream and low and imbalanced voltage on the severely overloaded phases, as shown in Table 4-24 with a per unit voltage of only 0.821 per unit (pu). The substation transformer is more severely overloaded in the combined case due to the higher peak load as referenced in Table 4-23. When comparing the number of three-phase line overloads in the system, it is important to note that in the 20 percent case, the number of overloads given in the table is not representative of the number of overloads present at peak load. Rather, the number given represents the number of three-phase line overloads present at the time when the cumulative loads of the charging stations on the feeder is the greatest, which is 1:55 p.m. Obviously the impact of the combined charging scenario is greatest on three-phase line overloads due to the high demand of the DC Fast charging stations. The impact on single phase distribution line overloads is greatest in the combined scenario as well when the low line voltage resulting from the increased peak load pairs with the demand of the Level 2 charging loads fed by the single phase distribution lines in residential areas.

The conclusion, based on a comparison of impact on daily peak load, distribution equipment, and voltage imbalance, is that a scenario where charging is uncontrolled in both Level 2 home and DC Fast public charging applications will have a greater effect.

5 Conclusions

5.1 Work Presented

The research conducted in this project examines the effect of EV charging on the NYS distribution system. To best test the effect of EV charging on the grid, realistic stochastic transportation models used data from the NHTS to accurately determine when the vehicles are most likely to charge and the initial SOC of the vehicles upon plugging in. The transportation model developed load profiles for DC Fast charging stations in conjunction with Level 2 home charging models for various scenarios and EV penetration levels. Models compared the potential cost of a public DC Fast charge for comparison home charging methods and determined that under some rate structures, the cost of a DC fast charge is comparable to a Level 2 home charge. Almost all scenarios studied the cost of charging and found an EV is lower than the cost of fuel for an internal combustion engine vehicle. DEW software simulated the NYS distribution system and conducted analysis on the feeder for various penetrations of EVs and charging scenarios using DEW, power flows, voltage distance, and equipment violations. For the purposes of testing, using the most heavily loaded feeder on the most heavily loaded substation explored the potential worst case for the simulated distribution system. This report explains and summarizes the effects of these tests throughout.

The impact of EV charging is significant on the NYS distribution system, even in moderate penetrations. Testing the simulated system with varying penetrations of EVs found that an increase in the penetration of EVs yields greater violations on some distribution equipment. The effects of the increased penetrations of EV charging include daily peak load increase, daily peak load shift, voltage imbalances on the lines, distribution line overloads, low voltages at service points, quantity of overloaded distribution transformers increases, and overloaded station transformers.

In this study, there is special emphasis given to DC Fast charging and its potential impacts in a distribution system. To substantiate the importance of studying this constantly evolving technology, an in depth study explored the DC Fast charging station's impacts on the distribution system. In Chapter 4, a study looked at the simulated system with a robust DC Fast charging infrastructure, assuming a 20 percent usage rate, but ignored the impact of home charging on the distribution system. It found that at high penetrations, these charging stations have the potential to create numerous substantial overloads on three-phase distribution lines as well as significantly shifting peak loads, as discussed in Chapter 4 Section 2. These findings are further supported as the effects of home charging on the distribution system are accounted for in addition to the DC Fast public charging. In the worst case scenario the addition of Level 2 charging caused a greater number of three-phase lines to overload, especially when the loads from DC Fast charging stations are greatest. Additionally, significant voltage imbalances become evident at peak load hours on the three-phase distribution lines due to the introduction of Level 2 home charging. However, this imbalance could be corrected.

There was another thorough analysis on a charging scenario where only Level 2 home charging is available and no public charging options exist. The study determined that the impacts of home charging alone are significant, even at moderate EV penetration levels especially when looking at the effects on single phase distribution transformers, voltage imbalance, and peak load increases. A comparison between the combined Level 2 home charging with DC Fast public charging scenarios and the Level 2 home charging only scenario determined which charging scenario has the greatest impact on the distribution system based on each charging scenario's impact on daily peak load, voltage imbalance, and distribution equipment violations. As discussed in Chapter 4 Section 5, the scenario combining Level 2 home charging with DC Fast public charging stations has the most significant impact on the system overall.

5.2 Possibilities for Future Work

There are a multitude of possibilities to explore in an effort to better understand the potential future impacts of EVs. A few aspects in particular may be advantageous to address as EVs continue to gain ground in the automotive market in the U.S.

First: Addressing the possibility of no home charging option for EV owners is very realistic for metro areas where home charging is not a possibility for EV owners. For these individuals, public charging would be a necessity and would increase the potential usage rate of public DC Fast charging or Level 2 charging within an area. In fact, the Matlab program created load profiles for the charging scenarios analyzed in this study designed with the capability of defining a percentage of the EV population with no home charging.

Second: Investigating various controlled charging strategies for EV charging, which are well studied and documented. Most of these strategies offer advantages in the form of increased reliability, peak load shifting, and increasing predictability. A possibility to expand on this topic exists in the form of exploring strategies for implementation that have the potential to be widely adopted.

Third: Exploring the potential of adding battery backup to public charging stations. High efficiency (80-90 percent) lithium ion batteries have the possibility for use in conjunction with time-of-use rates. increasing the charging station owners profits. As of now, the cost of energy storage remains too high, however, the benefits of such technology will be significant once the cost is non-prohibitive. Each year battery technology improves and as they become more cost effective, the batteries could control demand charge, store energy at low market price, and discharge to charge vehicles when electricity costs are high, thus increasing profit margins and shifting the peak load from charging stations to off peak hours.

5.2.1 Potential Marketing Opportunities

With an ever growing number of EVs on the road and a current deficit in EV tailored marketing in the U.S., particularly on the East Coast, here are several potential marketing opportunities in New York. In the event of a rapidly increasing number of EVs in the State, a potential marketing opportunity for a substantially funded company could include, franchising the DC Fast charging infrastructure in such a way as to be ahead of the curve with DC Fast charging stations in areas with the highest numbers of EVs. Particularly in areas with limited home charging options for residents, piloting the project with a few stations strategically placed by matching the number of units at a station with the estimated number of EVs in the given region. Another opportunity would create a specialized service for Level 2 and DC Fast charger installation at facilities to support the rapidly growing EV charging market. Such a business would delve into the electrical contracting side of the market. Additionally, filling the need to build these charging stations early could present an opportunity to grow a small business. Finally, coordinating with EV manufacturers, utilities, and charger manufacturers to develop a standardized home smart charging network with an essential cyber security system in place.

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