Electric Vehicle Charging Impact on Distribution Conductor Model and Mitigation Techniques

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Electric Vehicle (EV) charging is one of the largest growing electricity demand sectors that is being added into the electric grid. The bulk electric system, which will carry the majority of the current load, is a specific infrastructure which is regularly monitored for load changes. In contrast, distribution systems do not have the same supervision and therefore can be treated as a black box. The distribution system is important for stability of the grid and in order to predict how much EVs will impact the main grid, a simulator for a distribution line was created to determine substation transformer loading and line loading. In addition, four charging cases for the EVs were created to investigate different charging scenarios. Finally, load mitigation techniques were investigated to offer potential solutions for the overloading of aged infrastructure.

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1.0 Introduction

Electric Vehicles (EV) are a mode of transportation in which electric torque provides a clean and exciting way to travel. An increase of these vehicles being integrated onto the national electric grid is occurring in not only in the United States but in other countries worldwide, this large amount of charging, or big charging, will become a prevalent issue due to aging infrastructure, lack of capacity on distribution lines, and transformer overloading. These are long-term issues which will need to be addressed with or without the EV revolution. Many research articles describe the effect on the bulk electric system, while the distribution system is not as researched. Typical distribution systems are not monitored in the way the transmission system is currently monitored and yet this will most likely be where the bottleneck in power consumption will occur. These systems can be extremely unique due to the age and design differences through the years; therefore, simulations of individual lines are required to determine the impact. Section two of this thesis contains a relevant literature review of EV charging, encompassing harmonic considerations and loading scenarios. Section three describes the creation of the simulator used in this research and the parameters input to create the loading charts. Next, the simulator takes into account four peak charging scenarios and compares them to line and transformer limits, while also considering the potential for two-way power flow in section four. Section five investigates two mitigation techniques: charge scheduling and reconductoring. The charge scheduling section creates a potential algorithm that would be implemented using a master-slave configuration and the associated IEEE standards. Then, the reconductoring section describes the steps and considerations needed for completing this task with reference to the National Electric Safety Code.

Finally, in section six, the conclusions are presented and the best-case scenario for EV charge

mitigation is presented.

2.0 Literature Review of Electric Vehicle Charging Methodologies

A review of relevant literature is necessary to facilitate the research method required to perform a research on EVs and distribution systems. Therefore, a survey of academic literature covering topics such as the EV charging technology and consequences of large-scale power consumption is paramount. The following three subsections stipulate current methodologies present in the previous categories. With the advent of EVs came an influx on information about research, application, and projections on this technology. In the last year alone, 2018, over 6,828 articles were published within the IEEEXplore article archive, exhibiting a large volume of publications [1]. These articles cover different facets of EVs, particularly the technological application. Using the Google Trends application, the term 'EV Charging' did not start to see a spike in popularity until 2010, while its counterpart 'Electric Vehicles' has seen a steady interest since data collection started in 2004 [2]. EVs are not only focused heavily upon in academia, but also in the government and sector. A number of cities in the United States (US) are beginning to create legislation for EV charging, and also states are attempting to create legislation with a focus on charging locations, such as in Pennsylvania with Senate Bill 596 [3]. This bill is directed toward utility response to transportation electrification. The working title, "An Act amending Title 66 (Public Utilities) of the Pennsylvania Consolidated Statutes, in restructuring of electric utility industry, providing for transportation fueling infrastructure development," describes exactly what the goal is: create the ability to refuel (charge) EVs and other alternative fuel vehicles. As EV penetration increases, potentially more problems could arise in terms of technology and application. Utility-scale phase balancing and infrastructure capabilities are two of the main concerns with EV charging, and many electric utilities are facing a similar problem as more EVs

penetrate their service areas. Big charging, which is the focus of this thesis, will be defined as the phenomena of large power draw that an electrified fleet will require to continue consistent operation. Electric power utilities constantly need to be ahead of technological revolutions within the industry. Therefore, there is a need for these utilities to create simulation cases for potential impacts on the future. EVs are no different, and the rate of penetration onto these distribution grids as well as the number of vehicles charging simultaneously will become imperative in mitigating the effects of the technology change to create and maintain a safe and reliable system.

2.1 EV Charging Technology

The first step to understanding the complexities of big charging is to understand the technology behind the charging itself. The type of charger is critical because the voltage level of the charger directly influences the amount of output power the device can provide. These chargers can also have design problems that can be described as potential harmonic interference. Finally, the component that is being charged, the battery, also needs to be studied at a high-level.

2.1.1 EV Charger Types

In order to enable the EV to operate, its batteries have to be charged beforehand. Although that sounds simple, this step already presents a first big challenge, the missing standardization of the charging plugs. For example, Tesla vehicles use a different charger than a Chevrolet Bolt. In addition, there is no standardization between countries either. In the US, there are four main

charging apparatus that exist for vehicles. Each charger has its own caveats which make them unique.
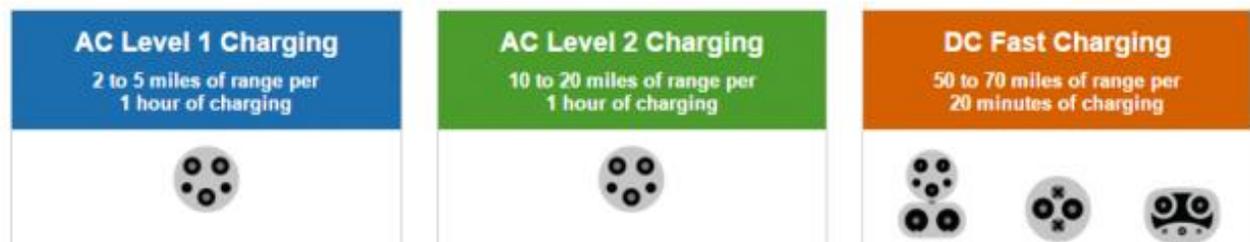
Figure 1: EV Charging Levels [4]

The four charging levels are 120 Volts (V), 240 V, 480 V, and DC fast charging, seen in fig 1 above [4]. The Level 1 charger, 120 V, has the slowest recharging time due to the lower voltage and power output. These are typically chargers that come with the EV and plug into standard residential and commercial power outlets. The Level 2 charger, 240 V, is the most common of the four. This is the type of charger used in public charging spaces and is relatively faster than the Level 1. The last AC charger is the Level 3 charger, or 480 V. 480 V is a voltage typical for commercial properties and would most likely be located there. The last charger is the dc fast charger. These chargers are typically used in Tesla automobiles and use a higher dc current to charge the vehicle in the quickest time of the four. In general, one of the first steps in big charging will thus be to develop a standard for EV charging. At the moment, Level 2 and dc fast charging are the de facto standards but could shift to another undeveloped charging scheme in the future. Regardless of the standard, the charger of the future could be affected by underlying problems, such as increased harmonic interference or battery degradation by the act of charging which will be addressed in the following sections.

2.2 Potential Harmonic Interference from Charging

Once the charging scheme has been established, a concern from the chargers is potential harmonic interference that charging and discharging can create on distribution-level architecture. Harmonic content is exacerbated by phase unbalance, as mentioned in [5]. Each residential area is typically connected via a single phase, and with different amounts of charging loads on each line, there could be a large amount of unbalance that occurs at the substation feeding the line. In [6], a study for EV Level 1 chargers was created, and as the number of chargers increased, the voltage unbalance could increase to two percent, which is still within the five percent allowable distortion that is set forth in the standard IEEE 519-2014 [7]. Another study done as part of the Los Angeles smart grid regional demonstration showed that the Level 2 chargers have been staying within the IEEE 519-2014 standard harmonic range while the Level 3 chargers were not at the time of the study [8]. Even with a large number of chargers being deployed, [9] hypothesizes that there could be harmonic cancellation with a large number of different charger types being used at the same time. As shown in Fig. 2 below, there can be a resultant wave from different harmonics combining that affects the hypothetical 60 Hz wave. The original shape is present but contains disturbances that can damage equipment.
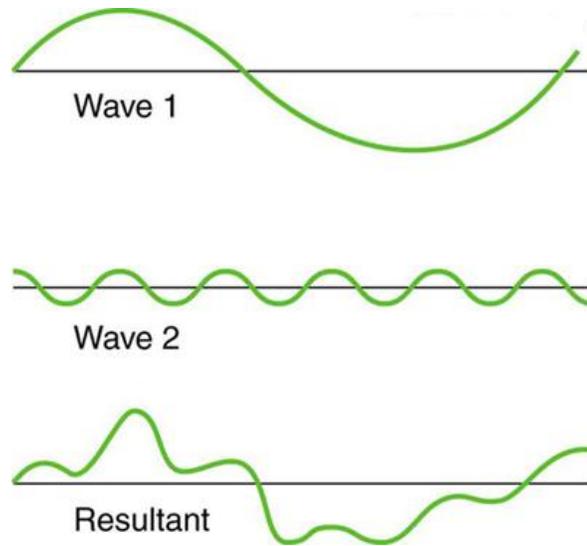
Figure 2: Harmonic Distortion Example [10]

The harmonic cancellation would occur through the use of different frequencies, creating destructive interference cancelling the different waveforms. Therefore, the overall impact could become mitigated. This is an interesting approach in that there is an assumption that no charger standardization will occur in the future. Finally, [11] suggests there is no issue with chargers, since there can be power electronic topologies that can be added to them to create a smaller impact on distribution systems. Due to the small penetration level, it will be crucial to determine to what extent these charging schemes will create for impacting the grid.

2.3 Batteries and Charging

The heart of EVs are their battery systems. Typical EVs use lithium-ion batteries due to their relatively high-power density compared to other battery solutions [12] and they are the cornerstone of electrical torque. For the purpose of this paper, batteries will be treated as a black

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box power source and the chemical properties will not be investigated. Nevertheless, these batteries need a steady power supply in order to charge properly, as stated in [12] since batteries are sensitive in regard to charging, and the stochastic nature of some renewable resources can be damaging. For example article [13] addresses there is a load scheduling problem with wind power, a stochastic renewable source. The amount of charging that the battery can do in this situation requires a large amount of computational power, which is undesirable when attempting to predict a random-nature energy source. The large amount of computational power is due to the randomness of the charge and the inability to count the charge after a period of battery degradation. Direct stochastic renewable energy charging is not ideal, and therefore requires a direct connection to a stable power source, such as the grid or a filtering intermediary step.

One of the largest challenges to current battery technology is the degradation of the lithium-ion batteries. Repeated charging and discharging at deep levels (greater than 50 percent) can damage the batteries. To combat this, EVs usually contain twice as many batteries as to not discharge greater than half of the total capacity [12]. Although the doubling of battery size completes the task, the added weight also has an impact on the efficiency of the EV. Therefore, charging becomes even more important with the weight of the batteries and total potential charge. Heavier EVs can show a decreased range but still contain a large number of batteries. A balance between weight and capacity is necessary for the most economical vehicle operation.

2.4 EVs and the Grid

Once the charging technique has been determined, the next crucial step is determining the affect big charging will have on the grid. There have been quite a few different studies created for

the EV impact and the grid, but for brevity, urban charging and the EV scheduling problem will be reviewed. Urban charging is becoming more and more critical due to the ongoing trend of cities transforming into megacities, which means a population of ten million people or more. Having more places gain a higher penetration of EV's creates a scheduling problem for charging to ensure the grid will not become overloaded at a certain time of the day. Both of these topics are described in the following sections.

2.4.1 Urban Charging

Urban charging can be considered the charging of EVs in densely populated areas, such as in a city. Most of the data that has been collected for the EV scheduling problem comes from urban charging studies. A study that was done on the University of California Los Angeles (UCLA) campus [14] shows that there are peaks for charging amounts that occur around the start of the workday and at the end of the workday. These times are not surprising as these are times that people have finished commutes and errands during the day and are looking to charge while being busy in buildings. Fig. 3 shows the energy consumption trend from the study. Another article, [15], provides a similar study but in the Toronto area, where the same result was achieved for typical plug-in times. Understanding where the demand for charging is located and its peak will help predict load distributions for utilities and power generation quantities. Figure three shows a consumption chart similar to the other research articles. The peak time is in the morning, which is consistent with when residential load increases due to people waking up. The only inconsistency with the previous research with this graph is the lack of an evening peak for when people report home. One explanation is that this could be on a weekend day, where the people could be home during the day and not at work or completing errands.
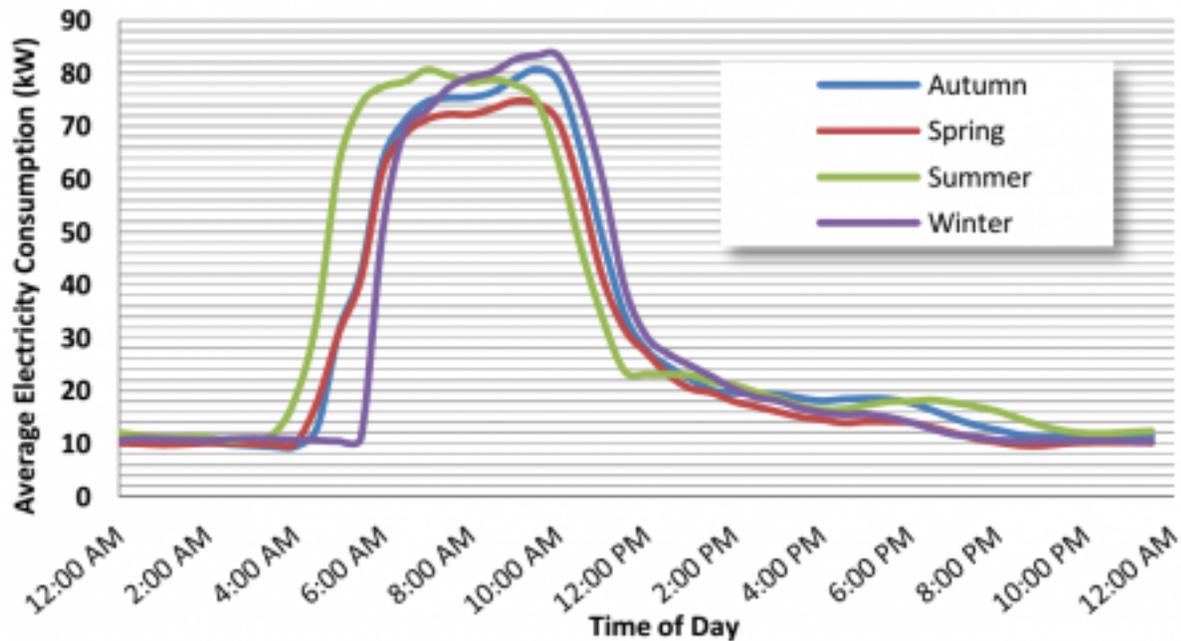
Figure 3: Example Electricity Use Chart [16]

2.4.2 The EV Scheduling Problem

Once the different load profiles are created in an urban setting, the necessity for load scheduling arises. From previous data collections, there are peaks in consumption in the morning and evening, in proximity to the start and end times of a typical workday. These peak loads can then be extended in time if the EV chargers are then activated in locations of work or retail. The EV scheduling problem is focused upon in [13], [17], [18], and [19]. These four articles give a brief overview of the problem and potential solutions. [11] describes the scheduling necessary to charge with a wind turbine, while [17] described the use of a fuzzy controller to schedule when to charge or discharge with a centralized controller. The article [18] uses hardware-in-the-loop (HIL) as well as real-time digital simulation (RTDS) to simulate power flow using three states (charging, discharging, and no charging) and ranks the power flow by priority of low charge. Finally, [19]

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describes a control algorithm that can be used for parking garages with two cases for charging: all vehicles charge at the same time or stagger the charging. These four articles give a brief look into the EV scheduling problem of when to charge the vehicles if there is a large influx of power demand in a relatively small amount of time caused by these vehicles. With big charging, the scheduling problem is going to become critical in redirecting the amount of power needed for the charging of a large fleet of EVs. The most common control is the centralized controller which determines the power flow needed for all of the vehicles and evenly distributes power to vehicles in an order determined by their individual state of charge on each battery. This approach not only smartly charges the vehicles but does so in a manner that the utilities should not become overwhelmed by a large fluctuation of required power on local infrastructure.

2.5 The Role of Big Charging

With a large penetration of EVs on the road, there will be a large power demand as well. This is the EV charging conundrum: how will the exponentially increased power demand be handled in technological and governmental realms? There will be negative consequences to the increased demand, as well as positive impacts. Negative consequences can include large generation mismatch, phase balancing problems, overutilized infrastructure, and increased emissions impact. On the other hand, there are still some positive impacts to the large-scale topic. Positive impacts can include grid stability and duck curve mitigation using the batteries as a distributed energy resource (DER). Both of these sides will be discussed in the following sections.

2.5.1 Negative Consequences

Negative consequences are just as they sound: they have a negative impact on the affected subject matter. The four main problems that can be seen include large generation mismatch, phase balancing problems, unavailable infrastructure, and increased emissions impact. Generation mismatch comes from the inability for a generation source and a load to be able to be matched, so there is neither a lack nor excess of power [20]. With the data collection on EV charging habits, generation providers will be able to ramp to the desired generation level depending on trends. This is not unlike current energy market predictions, where historical data is used to predict what the load will be the next day.

Phase balancing problems and harmonic problems are intertwined issues. The phase unbalance that can be created by EV charging is created through different penetration levels throughout a distribution system. For example, a single phase of a three-phase distribution network could have 20 EV chargers that activate at relatively similar times. Another phase of the same network could have no chargers activating at that time, leading to the first phase having a much larger power draw [10]. Power is transmitted from the substation in the three phases and if one phase is heavily loaded, there could be power quality issues closer to the sources. As years have progressed, this has been a concern for residential feeders before the wide-scale adoptions of EVs [21]. One way to mitigate this would be to use the EV scheduling problem to even the distribution feeders to create a better power factor. The power factor is a factor which relates the total power in watts to the apparent power in volt-amps. The closer to one the power factor is, the better power quality becomes, and lower losses occur. If the factor is pushed closer to one, then the generation and quality problems should desist.

Another major problem that could happen is overutilized infrastructure [22]. On the East Coast of the US, the infrastructure tends to be older due to the West Coast settlements being newer and initial technological implementation on the East Coast. For example, this is why states such as California have such advanced utility power programs with solar photovoltaics (solar PV) and EV integration. The main problem will be the aged grids of the East, not necessarily the West. Power lines can only handle so much current, so there is a push to create higher voltage distribution lines to allow for more current and power transfer. This will be a long process, due to the amount of distribution lines and associated equipment (such as transformers, circuit breakers, and insulators) being replaced to accommodate the voltage change as well as the associated costs. In order to conquer the infrastructural issues, change is inevitable. More lines, generation, and overall equipment will be necessary in order to handle the load that will be to come with the advent of big charging.

The last major problem that could occur is increased emissions impact [23]. Internal combustion engines will have emissions due to combustion of fuel no matter what type of fuel or catalytic converters are used. With the switch to EVs, there is still a cost to the electricity consumption. Nuclear energy, a low-emission source, has an undecided future in more than one country. With nuclear closures potentially occurring in the US, the current fuel replacement is with natural gas. Natural gas releases half the emissions as a similar coal fuel, but if the electricity is from a fossil fuel, one emissions source is just replaced with another. This creates a need for low-carbon sourced fuels to become more needed. Not all renewable energy sources can be considered clean, creating the important distinction between the renewable resources. As low-carbon renewables are needed, their impact will also be felt, leading to positive consequences.

2.5.2 Positive Impacts

Consequences do not necessarily need to be negative, so positive consequences can exist. Two main positive outcomes from EV charging are grid stability and duck curve mitigation. Both of these come from using batteries as a distributed energy resource (DER). With increased loading on the power system, a method of peak shaving using the EV batteries could be used [22(28)]. Peak shaving is an operation occurring at high load demand intervals in which batteries can be deployed, creating a lower demand on traditional generation sources. Peak shaving has two main benefits: stability and money saving. The article [24] describes the financial benefits of time-of-day pricing, meaning at high demand times that the price of electricity will increase and discourage people from using it at that time. Peak shaving can help with the financial side by storing energy in the EV battery and using the battery during high-priced electricity times. Technology-wise, peak shaving allows for power equalizing over time. This can be accomplished using a vehicle-to-grid (V2G) electronics topology, as described in [25]. This will allow for the power to flow into and out of the EV batteries to create a more stable grid. The paper [26] also proposes a similar approach to stabilizing the grid by injecting more power in times of fluctuations or peak consumption times. Battery types also need to be considered when creating stabilization methods, as different configurations can create different responses, as mentioned in [27]. One example of different responses would be the difference between lithium-ion batteries and lead acid. Lead acid batteries typically have a slower response time than the lithium-ion, so an immediate power gap closure would not be satisfied as fully as with the original battery.

In addition to grid stabilization techniques, the duck curve could potentially also be mitigated by battery technology. The duck curve is the penetration curve of solar energy over time, and how it can create a steep ramp of baseline generation coming online as more solar PV is

introduced [28]. One way to approach the duck curve is to think of it as an inverted peak, and baseline generation is generation that typically does not turn off, such as nuclear, natural gas, and other non-stochastic generation fuel sources. Figure 4 shows the visualization of the duck curve.
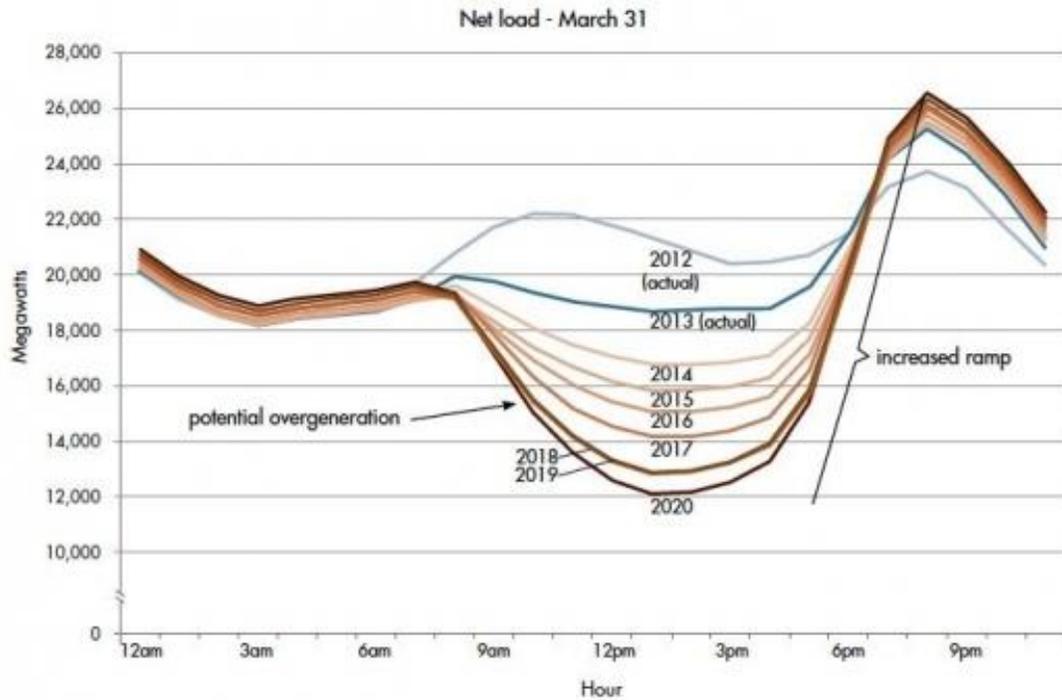

Figure 4: Duck Curve of Overgeneration [28]

As shown, there is an over-generation of solar which causes the dip in baseline and increases for every year when more solar PV is introduced into the system. Once there is a fluctuation in irradiation of the panels, the generation can sharply drop off or ramp up, creating non-ideal situations where the baseline generation cannot compensate for the load [28]. One way the batteries in EVs could help mitigate this problem would be to use the V2G adaptation and push energy back onto the grid until the baseline generation can reach an equilibrium with the loads on the system. The mitigation of the duck curve can also be considered a grid stabilization effort. Grid

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stabilization is crucial to provide safe and reliable service to customers and having more stabilization techniques will help with the transition from traditional generation to stochastic sourced energy production.

3.0 Data and Projections for Distribution Simulation Environment

EVs have more positive consequences than negative consequences, as determined in the literature review. Since they will be integrating into the grid in the upcoming years, an analysis of load growth and impact is necessary to ease into a smooth transition. In order to create a simulation, a determination of regressions and predictions is necessary in order to project the potential loading of the distribution lines.

3.1 EV Penetration Projection

EV penetration rates are not unlike the rates presented from the integration of cellular devices. The curve begins slowly as the first adopters push the technology forward. As time goes on, the adoption takes on an exponential curve. This curve was created using penetration amounts already seen through 2018 and reflects the current trend. These can be seen in Table 1, shown below.

Table 1: EV Purchase Rates through 2018 [29]

Year	EVs Purchased	Percentage Deviation from Previous Year
2011	27,500	
2012	55,000	200
2013	96,000	75
2014	119,000	24
2015	115,000	-3
2016	157,000	36
2017	200,000	27
2018	361,000	81

The table shows how in the early 2010's there was a slow rate of EV purchasing and as 2020 approaches the exponential behavior. The exponential regression resulting from this table, for the purpose of predicting the EV purchasing rate is modeled by equation 1:

$$x(t) = 27609e^{0.3806t} \tag{3-1}$$

where,

$X_{EV}(t)$ is the EV's purchased in year t and

t is the year.

The regression completed on this dataset gave a coefficient of determination of 0.9246, leading to a highly correlated dataset.

3.2 Battery Size Projections

A similar process in determining the EV purchasing projections can also apply to the battery size of the vehicles in the future. Table 2 describes the trend for miles per battery from the years 2015 until 2019.

Table 2: Battery Size Historical [30]

Year	Miles per Battery
2015	119
2016	122
2017	156
2018	159
2019	190

Unlike the EV purchase rate, the batteries have not been growing as exponentially, but rather linearly. Every four years sees an increase in seventy miles per battery. Therefore, in 2030, the average battery can hold approximately 400 miles worth of charge. The dataset for this conclusion is statistically insignificant due to such a small population, but the assumption will be used moving forward. Therefore, the battery projection for capacity can be estimated using equation 2:

$$x_{Battery}(t) = 190 + \frac{70t}{4} \tag{3-2}$$

where,

$X_{Battery}(t)$ is the EV battery capacity in miles per battery in year t + 2019 and

t is the year after 2019.

3.3 Home Load Projections

In this specific simulation, the average home will contain a load of size 15 kVA for the peak. This number was achieved through estimating the load of a medium-large home which uses electricity to heat. This is a potential overestimation, but the worst-case is necessary to stress the system. Each year the simulation adds a compounded three-percent increase in base load in addition to the EV load which is added due to additional loads and efficiency gains. Therefore, the home load projection can be modeled as in equation 3:

$$x_{Home}(t) = 15,000(1 + 0.03)^t \qquad\qquad (3-3)$$

where,

$X_{Home}(t)$ is the home baseload in year t + 2019 and

t is the year after 2019.

This projection equation will be used in conjunction with the EV load equations, which are determined in section 3.4. Distribution circuits also use a multiplier called a diversity factor. This factor assumes that no two loads are the same and is multiplied to get the load at a certain time.

Over ten loads, the diversity factor approaches 0.54, which is the factor used in this distribution line simulation.

3.4 EV Load Projections

EV chargers in the public right-of-way are typically a level two charger, which charges at a maximum of 7.2 kW. Therefore, this charging level will be used in order to determine the peak charging level that the EV fleet will create. The EV load projections are then projected using three charges cases: low, medium, and high. Before these three cases are determined, the use of combustion engine vehicles is studied to apply to EV use.

3.4.1 Combustion Engine Vehicle Use Study

In a medium-size city such as Pittsburgh, a typical commute for a vehicle is 20 miles one way, as determined in the Siemens City Tool analysis from 2018 [31]. Therefore, the round-trip average for driving is 40 miles per day. Typical combustion engine vehicles typically show 'low fuel' at the eighth tank level which is no different than in EVs. With this information, the three cases for charging will be after one trip (360 miles left), half a battery (200 miles left), and at one-eighth of a battery (50 miles left). In addition, the average number of cars per household in the Pittsburgh region is approximately two, and it can be assumed then that each load center will house two vehicles. In order to determine the actual number of EVs per line, the average number of vehicles bought per year is used with the number of EVs bought per year. The number of total

vehicles per year is around 17 million, while the EV penetration rate changes. Using this relationship, the number of EV's per line can be projected.

3.4.2 High Charge Projection

The high charge projection assumes that each EV will be recharged at the end of the day, after completing one trip. In order to create the worst-case scenario for loading of the distribution lines, this case is considered the highest and most severe due to the entire EV fleet charging at the same time.

3.4.3 Medium Charge Projection

The medium charge projection decides that the EVs are charged only when half the battery is left, and not every load is on at the same time. The time for half battery, assuming only daily commute, is every five days, so the EV load is assumed to be at one-fifth on any given day. This is a considerable decrease compared to the high charging case, and still high compared to the low charging case in 3.4.4.

3.4.4 Low Charge Projection

The low charging projection assumes that the owner will only charge when one-eighth of the battery remains, or one daily commute. This assumes that the charging will occur every eight or nine days, so the load is at one-ninth of its maximum potential. This is the best case for highly

loaded lines as it spreads the amount of charging needed to the last minute and can be scheduled easier for line congestion relief.

3.5 Equipment Parameters for Simulation

Line parameters needed for the simulations are outlined in the sections below. There are two categories of parameters: physical and nominal. The physical parameters describe the physical properties of the cables, such as radius and resistance. The other type of parameter, nominal, describes the voltage levels and line lengths that are used in the simulation. In addition to the line parameters, equipment on the system also needs parameters. The last piece needing a value is that of the transformer feeding the line from the substation. The individual transformers on the line are not considered since they can be arbitrarily added.

3.5.1 Physical Line Parameters

In order to simulate the different distribution lines that could be used, three cables of interest were selected. These three cables have parameters outlined in Table 3. Common cable sizes have a bird-themed codename which they can be easily referred. The first cable of interest has the highest power transfer of the three and has the codename of Dove. The second cable, codename Oriole, has a lower amount of power that can be transferred due to a lower ampacity. The third cable, codename Penguin, acts as the common neutral for the other two cables in the simulation. In theory, there should not be current on the neutral, but it acts as a pathway for line faults and helps with balancing the loads.

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Table 3: Physical Line Parameters [32]

Attribute	Cable 1	Cable 2	Cable 3
Conductor Size	556.6 kCMIL	336.4 kCMIL	4/0
Conductor Codename	Dove	Oriole	Penguin
Conductor Type	26/7 ACSR	26/7 ACSR	4/0 Aluminum
Geometric Mean Radius	0.0308	0.025	0.0101
Resistance per Mile	0.1917	0.309	0.5914
Ampacity	735	545	370
Diameter	0.927	0.741	0.563

3.5.2 Nominal Line Parameters

The nominal line parameters describe the values which are not set for the lines through the physical characteristics, such as the voltage and the line length. In this research, two-line voltage and length sets are used, as seen in Table 4.

Table 4: Nominal Line Parameters

Line Voltage (kV)	Line Length (mi)
13.2	14
2.4	6

These two combinations can be seen as the average line length in a system and the voltages are in line-to-ground, typical for distribution applications.

3.5.3 Transformer Parameters

Distribution lines need a source of power, and this is typically provided by a substation. Each line has its own specific circuit breaker and not necessarily its own transformer. For the intents of this research, the line will be afforded its own transformer at the size of 10 MVA. This is not uncommon for a single-line size. Transformers can be run at higher power output than the size that is specified, but this will shorten the life instead of creating failure conditions at the onslaught of the high-power output.

4.0 Simulation of Distribution Feeder

This section describes the simulation results using the simulator and parameters outlined in section 3. In total, 64 charging and discharging simulation cases were completed in total. Constants throughout the simulations include the pole geometry, transformer rating, load sizes, and neutral conductor type. This helped to reduce the number of variables to allow for a closer comparison of different simulation cases.

4.1 User Interface for Data Input

Since the parameter values were set in the previous section, the simulation can occur. The simulator uses a Graphical User Interface (GUI) as an interface for data placement. This can be seen in the example shown in fig. 5. Here, the inputs that are required create a versatile simulator. The individual loads per mile per phase allow for unbalanced or balanced simulation and assumes each load of a specific type uses an average kVA load. The transformer is modeled in the substation terminal end where the line originates. Next, there are individual line parameters required to calculate mutual and self-inductances within the system. The four charging cases outlined in section 3.4 are selectable. The final areas are for line length and voltage in the line-to-ground configuration and pole geometry.

Figure 5: Distribution Simulator Interface

4.2 Balanced Load, Dove Conductor Charging Simulation

The first set of simulations that was completed uses a balanced system with dove as the primary conductor Figure 6, below, shows the comparison of loading percentage by charge case for four separate simulations. The first two lines represent the transformer loading percentage with two-way charging on and off. The last two lines represent the line loading with the two-way power flow switching on and off as well. This specific charging level was 13.2 kV line-to-ground. At this

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voltage level, the two-way flow does not make much difference, as seen in the chart. This could be attributed to a large load existing on the lines before the charging is accounted for. Charge case three shows overloading conditions in both the transformer and line loading, and the bottleneck is in both. The step from case two to three shows a large increase in load, which is expected for the amount of increased charging.
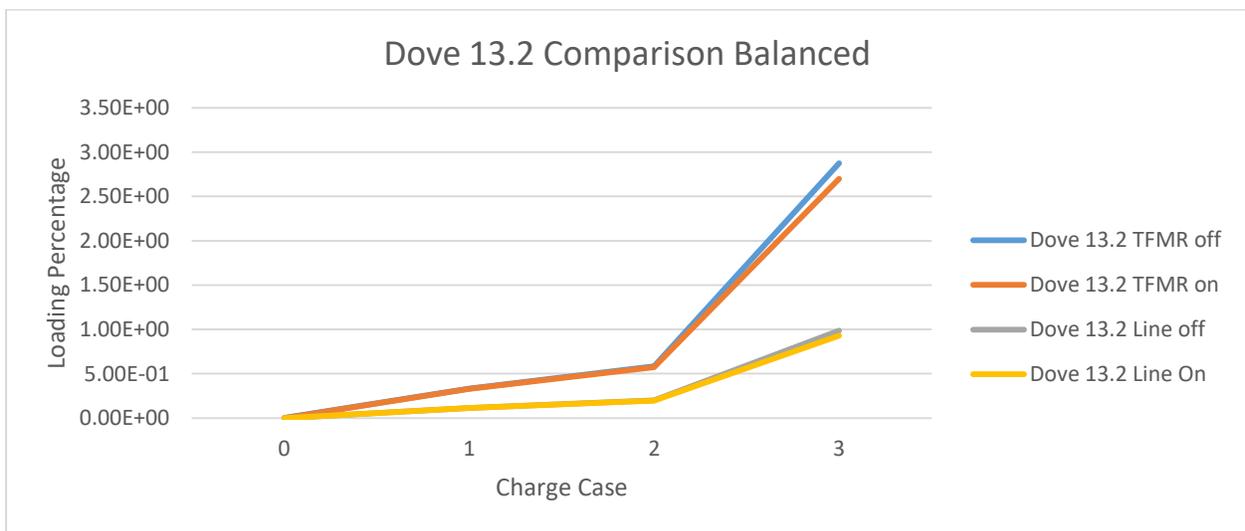
Figure 6: 13.2 kV Dove Conductor Balanced System

In addition to the dove conductor size at the 13.2 voltage level, an analysis at the 2400 V level was also conducted. Figure 7, below, shows the comparison of loading percentage by charge case for four separate simulations. Again, the first two lines represent the transformer loading percentage with two-way charging on and off and the last two lines represent the line loading with the two-way power flow on and off as well. This definition is valid for all of the simulations below. At this voltage level, the two-way flow makes more of a difference due to a higher penetration rate

and lower loading allowances. The graph shows that at lower voltage, the penetration levels are much higher due to the lower loads that already existed. Two-way power flow has a much greater impact due to a combination of lower existing load and higher EV loads. In this case, a two-way power flow existing on the line would be beneficial for total line loading since the line loading in this case is so relatively high.
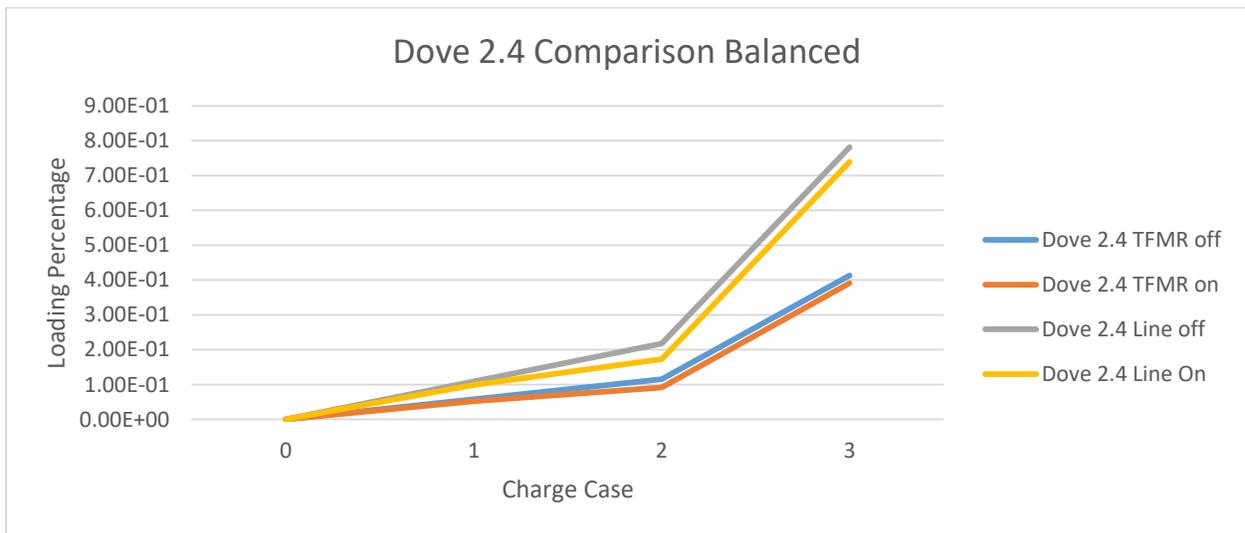

Figure 7: 2.4 kV Dove Conductor Balanced System

4.3 Unbalanced Load, Dove Conductor Charging Simulation

The second set of simulations that was completed uses an unbalanced system with dove as the primary conductor. Figure 8, below, shows the comparison of loading percentage by charge case for four separate simulations. This specific charging level was 13.2 kV line-to-ground. At this

voltage level, the two-way flow makes more of a difference than the balanced case. As with the balanced case, the two-way power flow is not as effective at the already high line loadings that occur in the 13.2 kV case even with the newly added EV loads. The unbalance does not make much of a difference compared to the balanced simulation due to the number of loads that occur and the rebalancing that can occur with larger commercial and industrial loads on each circuit.

Figure 8: 13.2 kV Dove Conductor Unbalanced System

In addition to the dove conductor size at the 13.2 voltage level, an analysis at the 2400 V level was also conducted. Figure 9, below, shows the comparison of loading percentage by charge case for four separate simulations. As with the balanced case, the two-way power flow is more effective at the line loadings that occur in the 2400 V case with the added EV loads. In this case, the unbalance is much more pronounced due to the smaller loads that can occur on the lower level power lines.

Figure 9: 2.4 kV Dove Conductor Unbalanced System

4.4 Balanced Load, Oriole Conductor Charging Simulation

The third set of simulations that was completed use a balanced system with oriole as the primary conductor. Figure 10, below, shows the comparison of loading percentage by charge case for four separate simulations. This specific charging level was 13.2 kV line-to-ground. This is a similar result to the dove conductor in section 4.3. The lines are overloaded, and overloads create burnouts. The transformer is also at a high overload percentage, almost 2.5 times the rated load. Once again at this voltage level, the two-way flow does not make much difference in the circuit due to the high rate of base load the buildings already harbor.
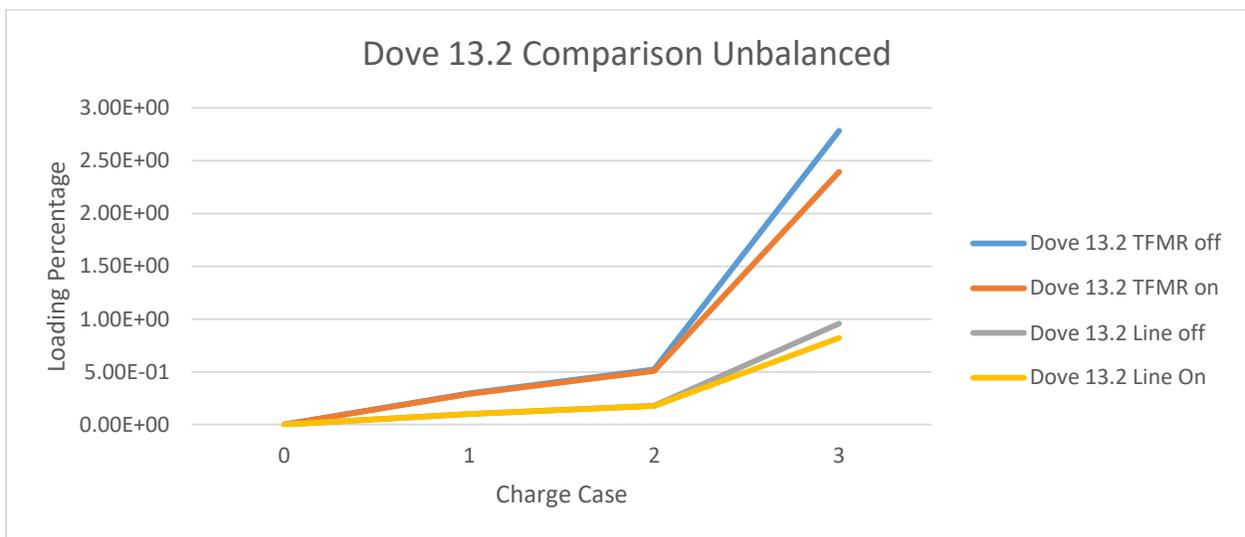
Figure 10: 13.2 kV Oriole Conductor Balanced System

In addition to the oriole conductor size at the 13.2 voltage level, an analysis at the 2400 V level was also conducted. Figure 11, below, shows the comparison of loading percentage by charge case for four separate simulations. At this voltage level, the two-way flow makes more of a difference due to a higher penetration rate and lower loading allowances. The line loading with the two-way power flow is much more drastic in the smaller primary cable, which is consistent with a smaller ampacity. Here, the line loading is the bottleneck in the system, and the transformer is within reasonable loading conditions.
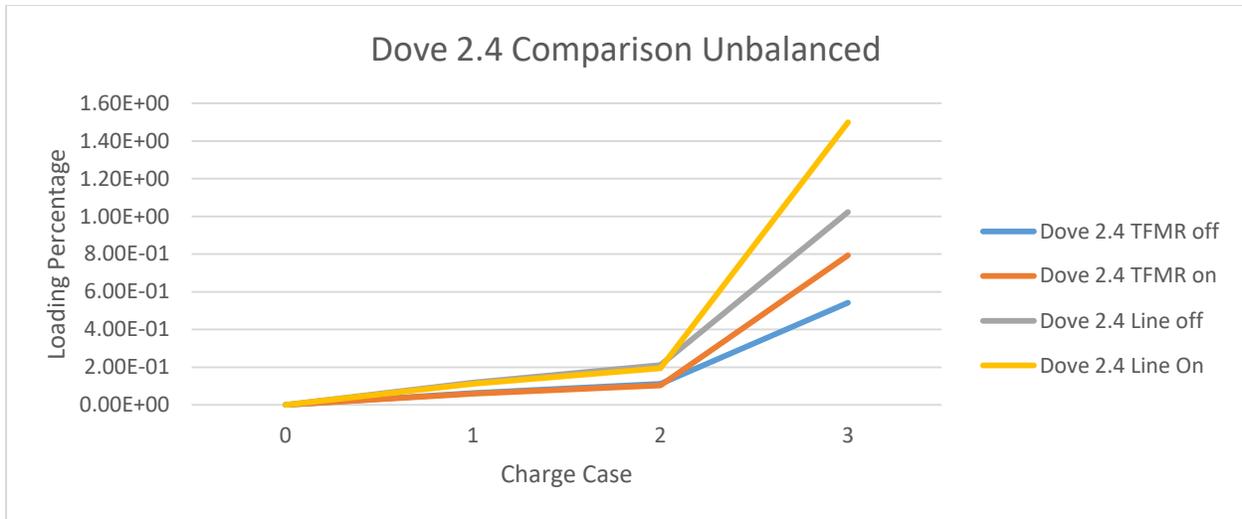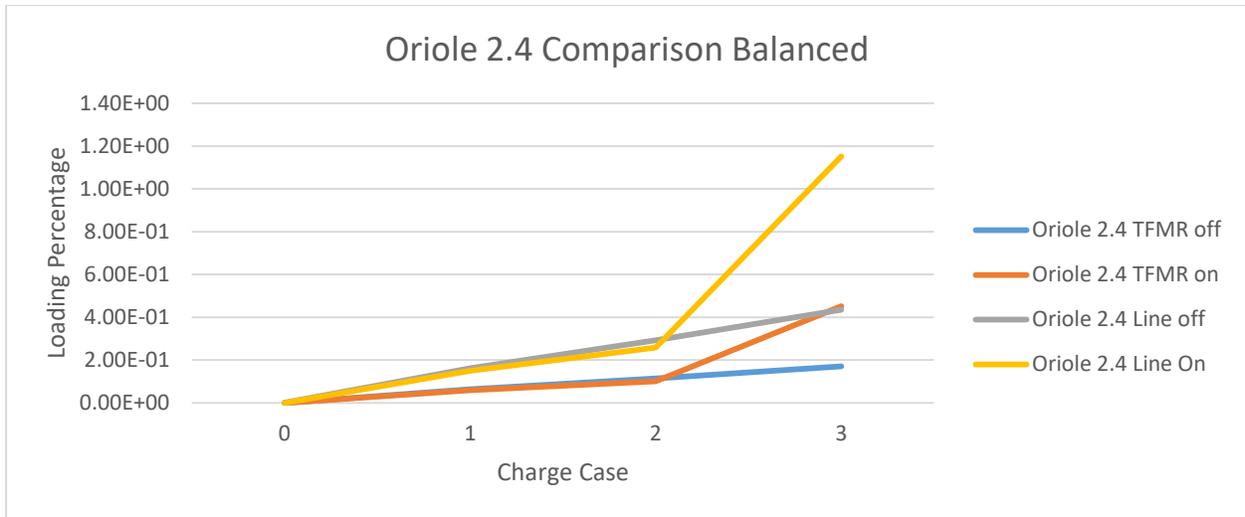
Figure 11: 2.4 kV Oriole Conductor Balanced System

4.5 Unbalanced Load, Oriole Conductor Charging Simulation

The final set of simulations that was completed use an unbalanced system with primary conductor oriole. Figure 12, below, shows the comparison of loading percentage by charge case for four separate simulations. This specific charging level was 13.2 kV line-to-ground. At this voltage level, the two-way flow makes more of a difference than the balanced case, but only slightly. As seen in the previous sections, the two-way power flow is most impactful in lower-level power systems and here there is no discernable overloading conditions.
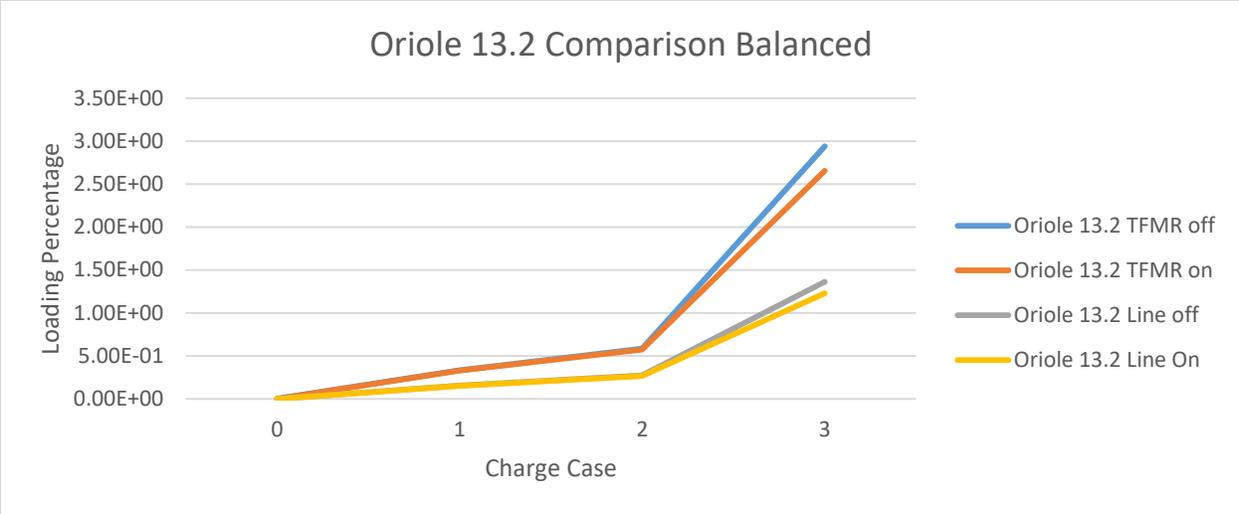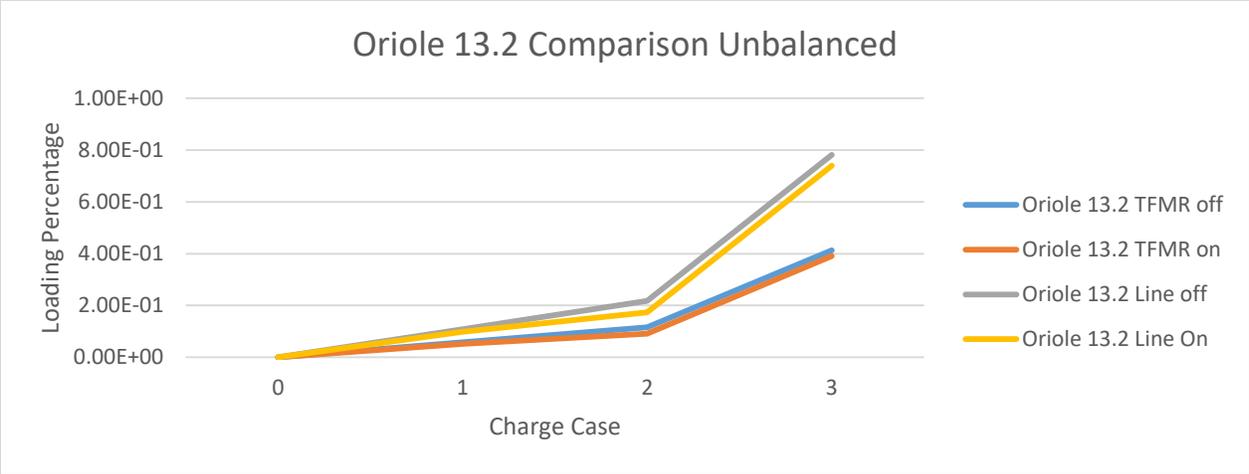
Figure 12: 13.2 kV Oriole Conductor Unbalanced System

In addition to the oriole conductor size at the 13.2 voltage level, an analysis at the 2400 V level was also conducted. Figure 13, below, shows the comparison of loading percentage by charge case for four separate simulations. As seen in the dove conductor, the lower level unbalanced system has more impact in terms of charging and the two-way power flow. The previous four cases in this scheme have the same trend, where the lower voltage power systems are more affected by unbalance and the two-way power flow than the higher-voltage systems.
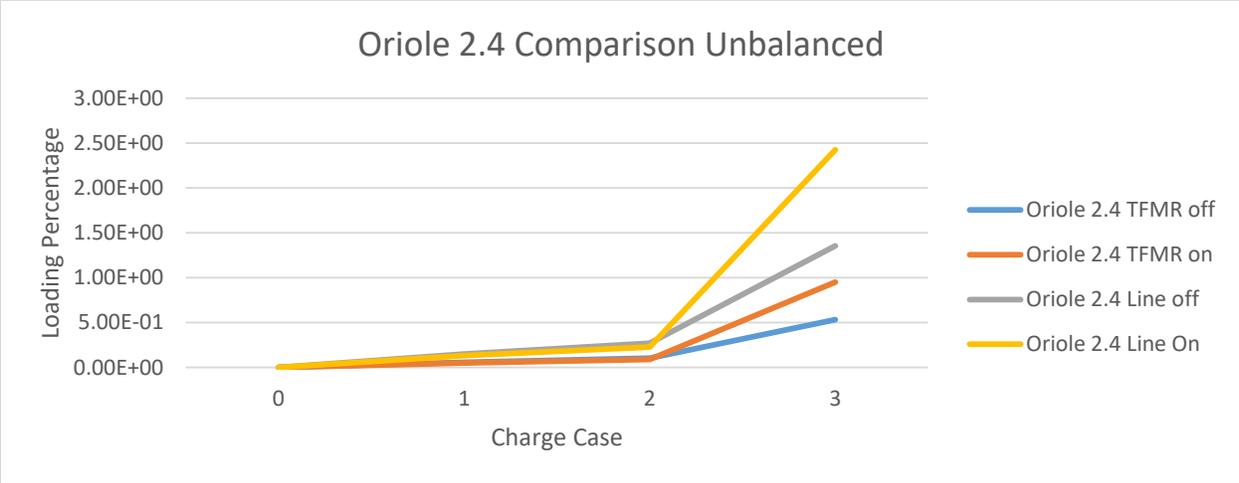
Figure 13: 2.4 kV Oriole Conductor Unbalanced System

5.0 Mitigation Techniques and Challenges

Creating a simulation of the different charging scenarios is not the only pathway to mitigate the impact of EV charging but is just a steppingstone for finding a more robust solution. In the following sections, some techniques for reducing the load are applied to the empirical section previously and some considerations for the different techniques are presented afterwards.

5.1 Mitigation Techniques

In each of the simulation scenarios, the highest EV penetration rate showed that there will be line overloading that will occur. Transformer overloading is also a possibility, but this is not as troublesome as the line loading. Transformers can run short intervals with overloading conditions, as the lifespan will shorten instead of destruction. Lines, on the other hand, will burn if there is too much current on the lines. Therefore, there needs to be a solution to keep the EV charging current as low as possible while satisfying the load demands. From previous sections, the loading was analyzed at the peak, which typically occurs in the early evening. In order to mitigate the excess charging current, two solutions could be used to reduce peak current: charge scheduling, and reconductoring of lines. These two will be described in the following sections.

5.1.1 Charge Scheduling

The first of two solutions to reduce the line current is to schedule the EVs for off-peak times. This could be, for example, completed when a threshold on a line has been met and charging can occur. A potential charging algorithm could be used, as seen in fig. 14, below.
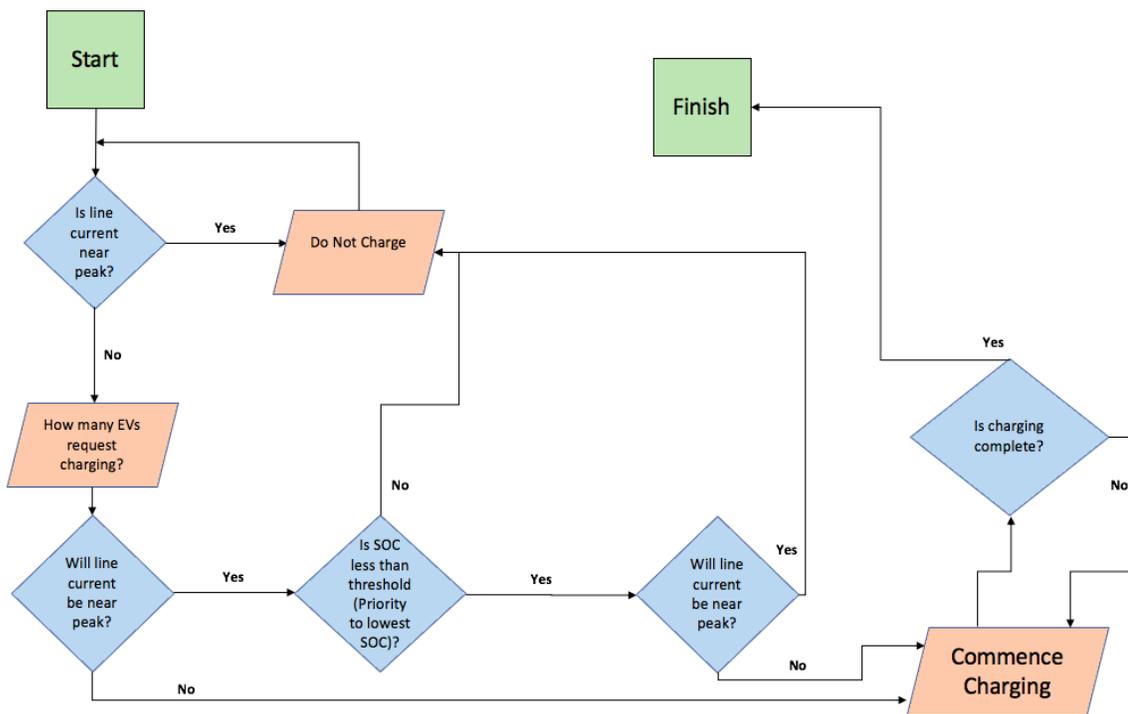
Figure 14: Potential Logic Diagram for Charge Scheduling

Here, the logic begins with when the line current is approaching peak. This can be set by the line properties and the current transformers that exist in the substation end of the distribution line. If the line is very close to the threshold, the charging will not commence. Next, knowing how many vehicles are requesting charging is necessary to know if the line will be overloaded. If it is

not, the vehicle may charge. If the line is close to the threshold, a loop commences taking the charging request and the line data and when there is available room or the state of charge (SOC) is so low that it is critical to charge, the charging will commence or wait. Once the charging starts, the vehicle will continue charging until complete and finally more room will appear on the system for more vehicles. This logic diagram does not consider neither more advanced charging techniques nor two-way power flow. The controller that would be used for such an application would need to be built for the conditions that occur on the individual lines. This approach would be costly, as it would require a master-slave controller system with a controller on each individual EV as well as a SOC charge estimator for the decision making.

5.1.2 Reconductoring of Lines

The second of the two solutions would be to reconductor the lines for higher amperage. The bottleneck in EV charging is the lines, as determined previously. Reconductoring would be the first half of this solution, as the larger cables can have higher amp throughput while the other half would be setting the line to a higher voltage. The higher voltage would create a lower current, and more power can be moved through the distribution lines. This solution would not be as costly as creating scheduled charging, but it would still have costs due to the individual equipment needing to be changed to accommodate different voltage levels. This is a quick and direct way to allow more charging capabilities compared to the controller installation.

5.1.3 Combinational Solution

In addition to the two individual solutions, these solutions can be combined to create a more robust solution than the two separately. The charge scheduling can allow for off-peak charging tied to time of day pricing while the lines will not get close to the limit with new conductors.

5.2 Challenges to the Mitigation Techniques

There are challenges to the two solutions that are not necessarily technically challenging but regulatory challenging. The two-way power flow requires inverters for the individual vehicles, and this can lead to harmonic issues, briefly described in section 2.1.2. On the other hand, reconductoring has its own challenges with archaic infrastructure and national electric safety codes (NESC) surrounding any new construction and rehabilitations. In the next section, each of these are discussed as to why mitigating high currents for EV charging can be such a challenging topic.

5.2.1 Inverter and Controller Challenges

Two-way power was a consideration in this research, where at peak times, the attached EVs would immediately place the amount of energy they pulled back onto the grid to decrease the amount of loading at peak conditions. Two of the main challenges with this idea are controllers and inverters. Controllers will be a costly solution. As described in 5.1.1, each vehicle will require a slave controller that is controlled by a master taking data from each vehicle and each power line

in a system. This would need to be tied to a supervisory control and data acquisition (SCADA) system, which is already tracking the status of different power systems locations of interest. Connecting individual controllers brings another question to the table: cyber security. This is a problem already being seen with the introduction of wi-fi enabled smart meters, which are also tied to utility networks. This work does not consider cyber security but it is necessary to mention as it is becoming a relevant topic for both government, academia, and industry. These individual controllers in the future can be combined into home charging and public charging stations, so each car will not be required to maintain more electronic equipment. These stations would then require internet connectivity in order to transfer the data for commands and therefore public spaces would need to not only receive upgraded electric connections but data connections as well. The electric connections are already required as part of the charger infrastructure and in the future the data connection can be installed in parallel or retroactively.

Inverters for the DC to AC conversion were not as strictly regulated until the IEEE 1547-2018 standard was updated for 2018 [33]. This standard was revised due to a blackout which happened in Southern California, when solar photovoltaic cells tripped off the grid, causing a large shedding of load. This inverter standard can be applied to tripping hazards to the two-way power flow problem, but due to the revised standard, there are many inverters that were sold without the specific thresholds for voltage stability. This can be a challenge until the standard is fully implemented across the system.

The next standard of note is IEEE 519-2014, which describes the harmonic content of a power system and its limits. The official title, "IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems," describes exactly what the standard outlines: acceptable harmonic contents and limits [7]. The standard, originally released in 1981, began the

quantification of harmonics on the system, since electronics were becoming popular and power needed to be regulated. The 1960s and 1970s were littered with blackouts due to voltage collapse and part of the standard which addressed this problem. A first update was released in 1992 and addressed harmonic distortion and set the limits for this phenomenon. The latest edition, 2014, describes statistical analysis on the systems and updates on limits due to the shift to stochastic power sources and high amounts of DC current penetration into the system. Figure 15 below shows the acceptable limits for harmonic contents for currents specifically.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
$< 20^c$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Figure 15: Harmonic Distortion Limits for Current [7]

Figure 15, pulled from the standard edition 2014, only shows odd harmonics due to the cancellation of even harmonics in power systems. Harmonics above the eleventh are typically small and not necessarily considered in such power systems, and the total distortion allowed is five percent for most systems. This could become a challenge due to inverters placing energy onto the system at different times due to potentially asynchronous behavior. This behavior could create

problems since the waveforms could create destructive or constructive harmonics and therefore decrease the voltage peaks to outside of and above acceptable limits for power systems. One way to mitigate this would be to inject the inverter current at specific points in the system's frequency and therefore mitigate the interference. Just as in other cases, this adds cost to the already costly system and cannot guarantee anything.

The final standard of note ties both controllers and harmonic problems together, IEEE 518-1982 [34]. This standard describes the harmonic allowances for controllers. Since one of the components of the controller solution is to check the state of charge of a vehicle, the harmonic output from the vehicle could potentially disrupt the controller. This is an unlikely scenario, but one that is still necessary to address. The standard is from 1982, which is close to being out of date for current applications, but the outlining prerogatives still apply to these chargers. Both of these challenges are only the beginning for technological solutions and are not considered in-depth. Due to the high cost of implementation and technical considerations, the solution in section 5.2.2 is more reasonable with the technology and costs of 2019.

5.2.2 Clearance Challenges

Reconductoring power lines, however inexpensive compared to its technological counterpart, can still be costly. In the United States, there are a set of codes called the National Electric Safety Code (NESC) which dictates how far power lines need to be away from different structures [35]. These distances are called clearances and the code describes many different cases that power lines can exist in, such as near buildings, swimming pools, highways, and other man-made sites. One of the stipulations of this code is that if any work is being done on a pole, it needs to be brought up to the current standard (which is updated every four years) and one pole on each

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side is typically also needed to be brought up to the current code. This is not unlike other building codes where if any type of renovation is completed, the entire building must be brought up to whatever applicable code there is. Reconductoring is one of the actions that can be taken on an electric utility pole where the clearances would need to be changed in order to be legal. This problem becomes prevalent where old infrastructure is dominant: in older cities with aged infrastructure. The NESC, which is updated every four years, has increased distances for conductors since the 1980's, which is new for much of the infrastructure in the United States. A simple reconductoring, which would consist of changing cables, insulators, jumpers, and other wire-related equipment could suddenly change to an entire pole replacement and pole movement. There would not be a route to avoid this potential problem and it would become not just costly but challenging to get the same equipment back into the areas where it once was located. Of course, reconductoring would not be a problem for certain areas where large clearances are already existing but as stated, it will be a main challenge in cities where the lines can be close to buildings or where space prohibits pole movement.

5.2.3 Combinational Solution

The best solutions are typically a compromise between systems, such as the two solutions from section 5.2.1 and section 5.2.2 combined. One way to do this would be to allow areas to be reconductored if the spacing allowed a conversion, while more congested areas adopt a charge scheduler. Dense areas would favor this idea because the main conductors to the area could be replaced for higher current throughput since it would be a main feeder. The smaller offshoots could use a scheduler per each feed and therefore have a smaller cost associated. No solution is the catch-

all for the EV charging, but having multiple solutions working together will have more leniency for future growth.

6.0 Conclusion

Electric Vehicles are a technology which could be likened to the cell phone revolution in the early 2000's. The rate of adoption increased exponentially for phones in the 1990's and early 2000's, and now it is now commonplace for most people to have one just twenty years later. If EV's continue their exponential growth curve, there will be a similar outcome. An exponential adoption curve has already been plotted, as seen in the regression of cars being purchased. There is no sign of slowing and this provides a basis for EV charging analysis for the future. A line simulator is necessary for checking how much current will be needed for a specific distribution line. After analysis of line loading cases, the main constraint that will occur is required amps in the highest charge case in every scenario creating an overload and destroying the distribution lines. In the more realistic charging scenarios, the distribution lines will not become overloaded from charging at the half battery and eighth battery levels. Even if the highest charge case becomes the scenario, three ways can decrease the charging load on each of the lines. Two-way power can inject current back onto the distribution line at peak loading conditions in order to decrease the peak amps. Then, the car can charge at off-peak times. The second solution is to schedule the charging for a time where there is available current on the system to charge the vehicles. This ties into the two-way power flow which would require the electronics to facilitate this solution. The third solution is to reconductor the distribution lines at a higher voltage, which would allow for more current to pass through the system. The final and best solution is a compromise between the three aforementioned solutions, replacing main conductors while the offshoots would be controlled by the charge scheduler and two-way charging. There is no perfect solution to the EV charging

problem which will occur and the best way to combat this problem is to create a combinational

system with as much flexibility as possible.

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