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Analyzing the Impact of Electric Vehicles on Power Losses and Voltage Profile in Power Distribution Systems

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Abstract

As the number of electric vehicles (EVs) within society rapidly increase, the concept of maximizing its efficiency within the electric smart grid becomes crucial. This research presents the impacts of integrating EV charging infrastructures within a smart grid through a vehicle to grid (V2G) program. It also observes the circulation of electric charge within the system so that the electric grid does not become exhausted during peak hours. This paper will cover several different case studies and will analyze the best and worst scenarios for the power losses and voltage profiles in the power distribution system. Specifically, we seek to find the optimal location as well as the ideal number of EVs in the distribution system while minimizing its power losses and optimizing its voltage profile. Verification of the results are primarily conducted using GUIs created on MATLAB. These simulations aim to develop a better understanding of the potential impacts of electric vehicles in smart grids, such as power quality and monetary benefits for utility companies and electric vehicle users

Introduction

The number of electric vehicles (EVs) are rapidly increasing within society today, since they are environmentally friendly, cost effective, and reduce local emissions. EVs have the power to drastically reducing the carbon footprint that traditional vehicles leave behind. While they host a variety of good qualities, one of the problems that arises with EVs lies in the infrastructure. There are several public EV charging stations all over the country that an EV user can use whenever they need it. This, however, could create a major issue within the power distribution system - a large-scale electric grid that controls and organizes multiple power inputs.

Researchers have published several papers on integration of EVs and their impacts on power distribution systems. The various papers we studied includes [1], in which a power grid research group in China has proposed a vehicle to home application, which effectively exhibits how the loads for EVs fluctuate on a day-to-day basis and justifies the need for the government to provide a tariff for EV users so that there is an incentive not to charge at peak times. The authors for [2] analyze how the burden that PEVs place on a smart grid changes as the number of vehicles and charging periods vary. In [3], a research group analyzed the benefits and issues of inducting electric vehicles into the smart grid, including the role of the EVs batteries and cost-benefit analysis. The researchers in [4] discuss the possibility of creating an independent and automatic charging schedule for EVs in the power grid. The authors of [5] utilized both the vehicle-to-grid (V2G) and grid-to-vehicle (G2V) method to analyze how it would affect a smart charging schedule for PHEVs. The authors propose an outline of how EVs can be optimally integrated into the power grids by analyzing electric vehicle supply equipment and EV data specific to China in [6]. The authors of [7] have created distribution algorithms that optimize renewable energy sources and charging times respectively. The research cited in [8] explains the vehicle to grid process and based on the potential grid system in California. It also discusses the environmental impacts that the use of the grid that make the system possible. Many research papers also covered how vehicle to grid (V2G) operates in the power grid with regards to EVs. The economic and social significance of introducing the vehicle to grid system and the operation management and strength of providing electric vehicles to the system is discussed in [9]. The authors of [10] studied the cost that goes in creating vehicles to grid systems and the most optimal hours for charging. Multiple factors such as battery cost, efficiency, charging times, and power were optimized for its best and worst cases to determine the cost of electric vehicles. Much of the literature we have studied have also researched the EVs effect on the electric grid in general. Going in depth about the PG&E 69 bus system and using a MATLAB model to display simulated results of the potential system was researched in [11]. The paper cited in [12] analyzes the effect of EVs on the large scale by using a micro-grid in which the vehicles automatically charge and discharge when they meet specific criteria. The authors of [13] focus on the depth of the electric vehicle degradation when being driven compared to being used in a vehicle to grid system. This is important to compare the battery degradation to determine when the high and low peaks are with electric vehicles charging and discharging.

Although several papers have been published on the subject, we aim to address the potential best and worst impacts of EVs on power distribution systems in terms of power losses and voltage profile. The purpose of this paper is to find the best location for the EVs that maintains its ideal minimum power loss and optimal voltage profile through a series of case studies. We are working with the well-known PG&E 69 Bus Distribution System in this project. The problem within the system arises when there are too many inputs. This causes the system to become overloaded and have a large amount of power loss. This occurs when too many EV users are charging their cars at the same time. In order to prevent this, this research focuses on how the power losses of the smart grid can be minimized by finding the optimal voltage profile as well as the location of the vehicle charging stations.

The paper is organized as follows: Section II discusses the modeling of electric vehicles, Section III looks at the problem formulation, Section IV analyzes the system under study, Section V displays the implementation and results, and Section VI conducts the comparative studies with regards to the previously given case studies while Section VII becomes the concluding paragraph

Modeling Electric Vehicles

The main concept that we are exploring in this paper is the ability to distinguish between the potential of the most and least efficient outcomes for electric vehicles within the power distribution system. This was conducted in order to exhibit how big of an impact the location of the busses as well as the battery capacity of the vehicles can make in terms of the overall power loss and how we can utilize this to accurately optimize the data so that the power losses are minimized. In order to accurately model the data, a MATLAB GUI was created to reflect minimum and maximum power losses. Instead of inputting random battery capacity numbers in to test the GUI, we created a unit EV to serve as a standard, singular battery capacity for the code. To create the unit EV, we compiled the nineteen most popular EVs sold in 2019 and recorded the number of vehicles sold as well as its battery capacities [14]. Then we created a ratio that was representative of the specific number of a particular EV model sold against the total number of EVs sold. For example, Tesla sold 154840 units of its Model 3. Compared to the 326644 EVs sold in 2019, the Tesla Model 3 comprises of 47.4% of the total EVs sold in 2019. This number was then multiplied with its corresponding battery capacity according to the specific model chosen. This process was repeated with the remaining nineteen vehicles and added together to create the unit EV. The chart of EV data we have compiled is shown in Table 1. This data was sourced from reference [14]. Equation (1) shows the general equation used in this research to obtain the unit EV,

$$Unit\ EV = \sum \left(\frac{M}{T} \times BC \right) \tag{1}$$

where M is the number sold of a specific model, T is the total number of EVs sold across all models and BC is the corresponding battery capacity for M. We have simplified the number of EVs in Table 1 to make the data easier to analyze. The specific unit EV calculated for this data set was 60.19.

Table 1. Most popular EVs sold in US in 2019

EV Model	Total Sold in 2019 (Unit EV in Thousands)	Power Capacity (kW)	Energy Capacity (kWh)
Tesla Model 3	154.84	7.7	82
Prius PHEV	23.63	3.7	8.8
Tesla Model X	19.43	16.5	100
Chevy Bolt	16.31	55	60
Tesla Model S	15.09	11.5	100
Nissan Leaf	12.37	6.6	40
Honda Clairty Plug-In	10.28	120	25.5
Ford Fusion Energi	7.48	3.7	9
Chrysler Pacifica Hybrid	5.81	6.6	16
BMW 5-Series Plug In	5.44	3.7	12
Audi e-Tron	5.37	150	95
Chevy Volt	4.92	7.2	18.4
VW e-Golf	4.86	7.2	38.5
BMW i3	4.85	50	42.2
Kia Niro Plug-In	4.05	3.3	9
Mitsubishi Outlander Plug-In	2.81	3.3	12
Jaguar I-Pace	2.59	90	90
Mercedes GLC 350c Hybrid	246	4	8.7
Porsche Panama S E-Hybrid	1.96	7.2	14

Problem Formulation and Solution Algorithm

This section presents the formulation of optimization problem to get the potential best and worst cases and the solution algorithm used to solve it.

Optimization Objective Function

Power distribution losses at peak load is used as an index to get the best and worst scenarios. Therefore, the optimization objective function becomes the summation of the power that was lost in power lines within the grid as shown in equation (2)

$$P\_Loss = \sum R_{ij} \times I_{ij}^2 \qquad (2)$$

In this equation R_{ij} is the resistance and I_{ij} is the current of the power line connecting bused i and j together, calculated using Newton-Raphson Power Flow algorithm [15]. The number of EVs integrated in the system was varied as a decision variable to find the optimum power losses.

Optimization Algorithm

The problem of optimal integration of EVs in different power system locations is a mixed integer, nonlinear optimization problem. Several methods can be used to solve this problem and each has its own pros and cons. Tabu search is a simple to implement method that theoretically guarantees convergence to the optimal solution and that is why it has been used in this research. It encompasses the idea that the best value in a set of data is sought out within local neighborhoods. Essentially, it searches for the optimum value within one neighbor and compares it to that of another local neighbor. This process is repeated using memory structures, until a single optimum value is extracted. We utilized this method to find the best power loss within our data, more information on how the method works could be found in [16].

Developed MATLAB GUI

Figure 1 displays the GUI that was developed and used to obtain the results for this research.

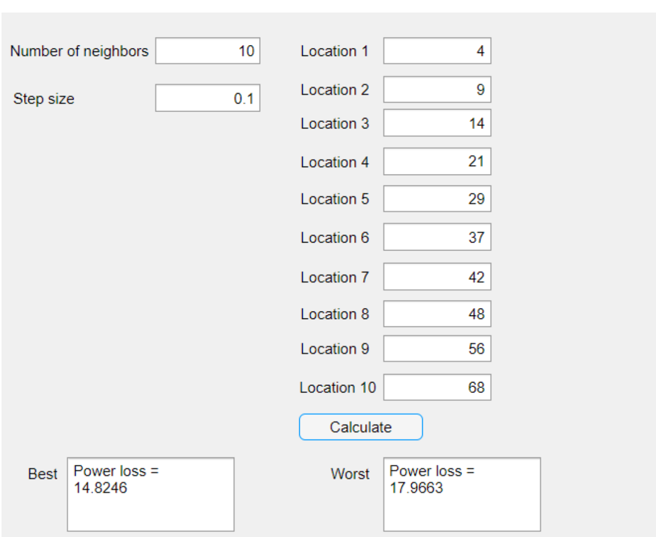

Figure 1. The Developed MATLAB GUI

A GUI was meant to obtain the best and worst power loss for the EVs given the number of neighbors, step size, and locations. The number of neighbors determines how many options the GUI should check during the search process, ten neighbors were used for the study. The step size is the amount of charge that will be applied during the search. Lastly, the ten locations decide what areas of the PG&E 69-node distribution network will have either a charge or discharge. All the other locations that are not part of those from the GUI will not be altered and have zero charge. The GUI will create neighbors by randomly selecting a bus location from the ten provided by the user. It will then proceed to either add or subtract the unit EV multiplied by the step size at the random location. Addition represents the EVs charging, and subtraction represents the EVs discharging. This process is done to generate as many neighbors as the user wants and calculates a power loss for each neighbor. The power losses from the given neighbors are then compared to the current best and worst power loss of the system. If there is a better or worse power loss the neighbor replaces it. Otherwise, the current best or worst power loss stays the same. This iteration is done 100 times where it then outputs the graph of the locations and voltages that produced the overall best and worst power losses and displays the best and worst power loss values on the GUI.

System under study

The power distribution system that has been used in this research for case studies is the PG&E 69-node distribution network shown in the following figure. More information about the system can be found in [17]

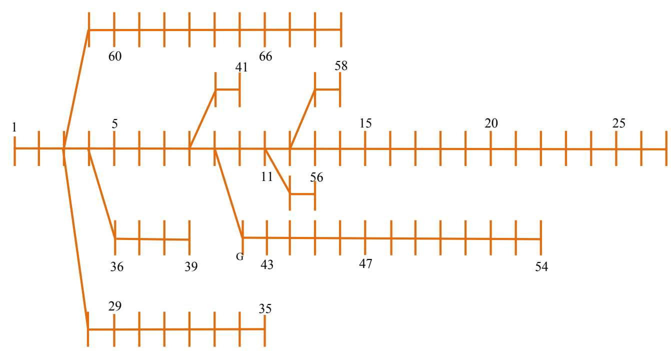

Figure 2. The 69-Bus power distribution system.

Each bus has some loads connected to at and the whole system is connected to the power transmission network at bus 1. When EVs are connected to the system buses, they have a charge or discharge rate. Our goal is to find the best and worst possible power loss that is caused by the EVs. In this study, we created a variable labeled as unit EV as calculated in (1). The unit EV represents the charge and discharge rate (in kilowatts) of multiple EVs in a bus. Finding the unit EV allows us to consider various electric vehicles charges and discharge rates at a given bus instead of just one. This is used to determine how much charge or discharge is at each given bus. Then, with the given values, we use Tabu search to study the best and worst power loss with the EVs and compare it to a grid with no EVs at all. The location where the EV is charging and the amount charging both affect the power loss of the system. For the case studies we use ten fixed bus locations, but the buses are selected at random and whether the unit EV increases or decreases is also randomized. This determines which bus locations has the most impact on the power loss and whether increasing or decreasing the charge/discharging rate affects the amount of power loss that is taking place in the grid system. This data is necessary to determine what the worst and best-case scenario of EVs discharging or charging compared to a system with no unit EVs is. For the studies we will be focusing on EVs only discharging for one case and the EVs charging for other cases during peak power load.

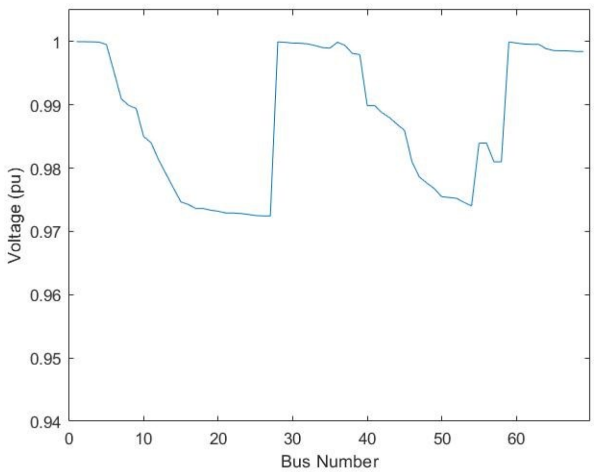

Figure 3. Voltage profile of system with no EVs

Figure 3 shows the voltage of the system with no EVs charging or discharging at any busses. The x axis represents the bus location and the y represent the bus voltage in per unit.

Implementation and Results

Implementation and Results

In this section, we discuss and present the best and worst cases for a case that we have fixed location of EVs. The grid system that is in use is the PG&E 69-node distribution network. This network is a standard bus distribution for our current grid systems. In this study, we created a variable labeled as unit EV. The unit EV represents the charge and discharge rate (in kilowatts) of multiple EVs in a bus. Finding the unit EV allows us to consider various electric vehicles charges and discharge rates at a given bus instead of just one. The unit EV was found by obtaining the 2019 sales percentages of the nineteen most popular EVs among each other and multiplying their charging rates to their respective sale percentages as explained in Section II.

The case that was chosen for this study was a unit EV of 0.5 as the change of increase or decrease for the neighbors and altering the fixed bus locations which are 4, 9, 14, 21, 29, 37, 42, 48, 56, and 58. The voltages in the fixed bus locations all start with a unit EV of 15 charging or discharging and 100 iterations will be done in the tabu search while finding five neighbors for each iteration and picking the respective best or worst neighbor based on their power losses. All the other busses have a unit EV of 0 signifying there is no charge or discharge taking place in those busses. There will be two cases one the first being a case where the bus locations are only providing a discharge and the second is when the bus locations are only providing a charge. Also, a system with no EVs discharging or charging was provided to compare the impact of unit EVs charging and discharging in a grid system. The following provided is the data for the system with the no EVs charging or discharging. The minimum voltage is 0.972433 pu, maximum voltage is 1 pu, and power loss is 31.2643 kW.

Best Impact Case Study

The best impact case study takes into account the grid system when the EVs are only discharging. Provided will be the best and worst case scenario in terms of power loss with worst being a great power loss and best being little power loss when the system is only discharging.

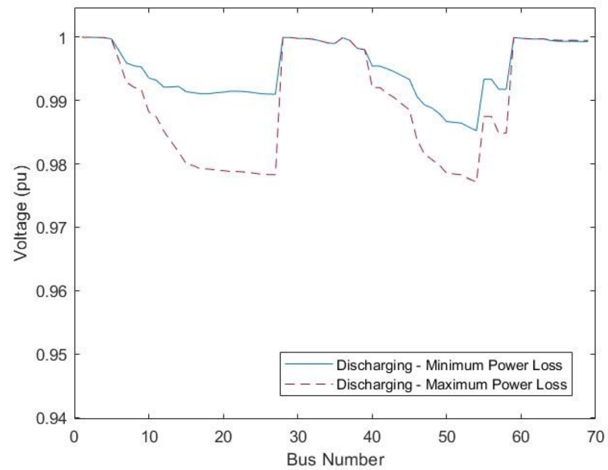

Figure 4. Voltage Profile of system with EVs discharging,

The above graph shows Figure 4. The x axis is the bus locations and the y axis represents per unit voltage. The x and y axis will be the same for all the other graphs. This is one of the best possible power losses that can be created with the given bus locations from a system with EVs only discharging. The power loss obtained will be the lowest out of the four cases provided. The following provided is the data for the system with one of the best possible power losses with EVs only discharging. The minimum voltage is 0.985263 pu, maximum voltage is 1 pu, and power loss is 12.513 kW. This is one of the worst possible power loss that can be created from the given bus locations. The power loss obtained will be the second lowest out of the four cases provided. The following provided is the data for the system with one of the best possible power losses with EVs only discharging. The minimum voltage is 0.977103 pu, maximum voltage is 1 pu, and power loss is 17.9963 kW.

Worst Impact Case Study

The worst impact case study takes into account the grid system when the EVs are only charging. Provided will be the best-case and worst-case scenario in terms of power loss with worst being a great power loss and best being little power loss when the system is only discharging.

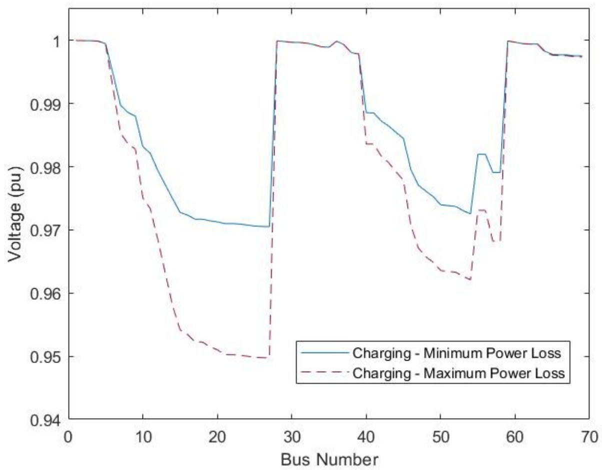

Figure 5. Voltage Profile of system with EVs charging

Figure 5 exhibits one of the best possible power losses that can be created with the given bus locations from a system with EVs only charging. The power loss obtained will be the third lowest out of the four cases provided. The following provided is the data for the system with one of the best possible power losses with EVs only charging. The minimum voltage is 0.970522 pu, maximum voltage is 1 pu, and power loss is 36.576 kW. Also showing one of the worst possible power losses that can be created with the given bus locations from a system with EVs only charging. The power loss obtained will be the fourth lowest out of the four cases provided. The minimum voltage is 0.949749 pu, maximum voltage is 1 pu, and power loss is 82.9797 kW.

Comparative Studies

In this section we can change the locations of EVs and present a few case studies for best and worst results. For the following case studies, we will be keeping the unit EVs the same and their neighbor differences, but the busses will be changed. This will give us an idea of how the bus locations impact the power loss and voltages of our system.

Case Study 1

For Case Study 1, the bus locations will be 26, 27, 35, 39, 41, 53, 54, 56, 58, and 69. Below are the graphs obtained from the study.

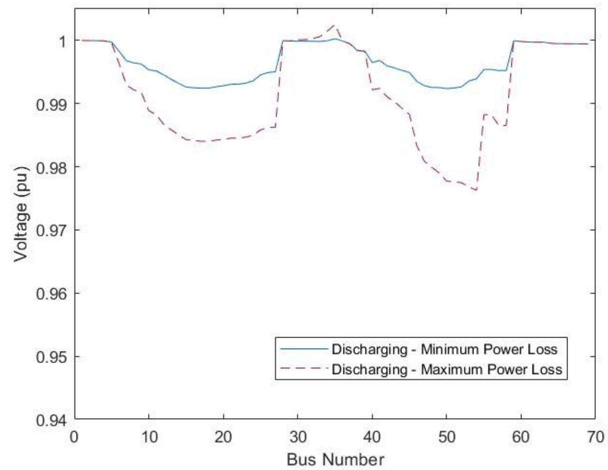

Figure 6. Case study 1, voltage profile of system with EVs discharging

The above graph, Figure 6, is the data for the best impact case study 1 with one of the best possible power losses with EVs only discharging. The minimum voltage is 0.992385 kV, maximum voltage is 1.00029 kV, and power loss is 11.3786 kW. Also displays the data for the best impact case study 1 with one of the worst possible power losses with EVs only discharging. The minimum voltage is 0.976253 pu, maximum voltage is 1.00252 pu, and power loss is 21.6975 kW.

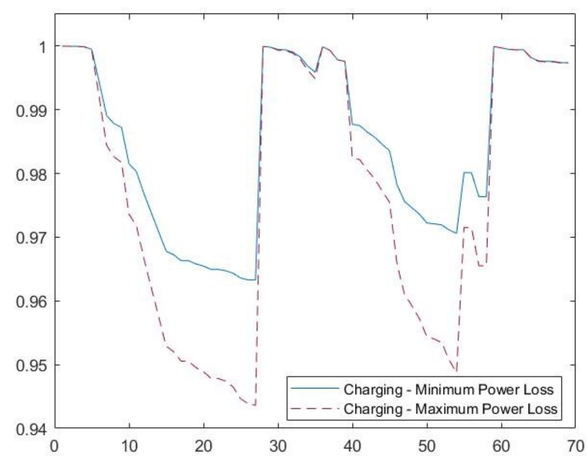

Figure 7. Case study 1 voltage profile of system with EVs charging,

Figure 7 displays the data for the worst impact case study 1 with one of the best possible power losses with EVs only charging. The minimum voltage is 0.96328 pu, maximum voltage is 1 pu, and power loss is 45.939 kW. The data for the worst impact case study 1 with one of the worst possible power losses with EVs only charging is shown in Figure 7 as well. The minimum voltage is 0.943611 pu, maximum voltage is 1 pu, and power loss is 106.7618 kW.

Case Study 2

For Case Study 2 the bus locations will be 2, 3, 5, 28, 36, 42, 55, 57, 59, and 60. Below are the graphs obtained from the study.

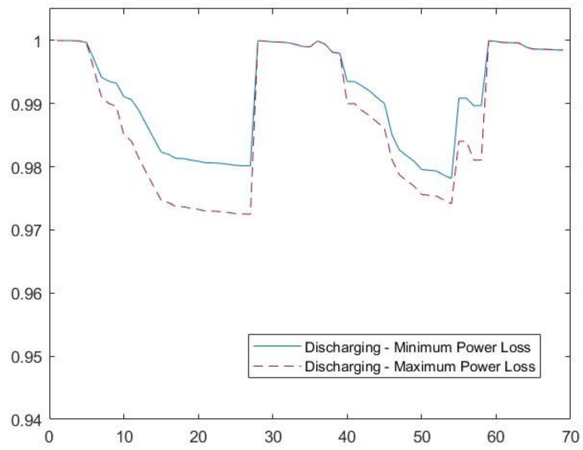

Figure 8. Case study 2, voltage profile of system with EVs discharging

Figure 8 shows the data for the best impact case study 2 with one of the best possible power losses with EVs only discharging. The minimum voltage is 0.978139 pu, maximum voltage is 1 pu, and power loss is 19.9064 kW. Also, shows the data for the best impact case study 2 with one of the worst possible power losses with EVs only discharging. The minimum voltage is 0.972499 pu, maximum voltage is 1 pu, and power loss is 30.9977 kW.

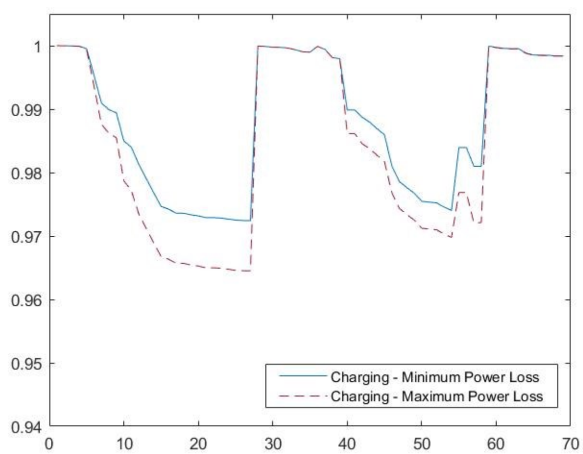

Figure 9. Case study 2, voltage profile of system with EVs charging

Figure 9 is a representation of the data for the worst impact case study 2 with one of the best possible power losses with EVs only charging. The minimum voltage is 0.972416 pu, maximum voltage is 1 pu, and power loss is 31.3414 kW. Also shows the following provided is the data for the worst impact case study 2 with one of the worst possible power losses with EVs only charging. The minimum voltage is 0.964501pu, maximum voltage is 1 pu, and power loss is 52.1625 kW.

Comparison of Results

Table 2 displays the difference in all the data that was obtained from the case studies. The best possible power loss came from case study 1 with a loss of 11.39 kW. The worst possible power lost also came from case study 1 with a loss of 106.76 kW. The lower the power loss, the higher the voltage minimum. Likewise, the higher the power loss, the lower the voltage maximum. We also discovered was that case study 2 had the highest best power loss but the lowest worst power loss. The data seems to be correlated where if one power loss is higher the other would be lower.

Table 2. EV Bus Locations Impacts on Results

Case Study	Bus Location	Cases	Power Loss (kW)	Voltage Minimum (pu)
No EVs	N/A	---	31.26	0.97
#1	26,27,35,39,41,53,54, 56,58, and 69	Best	11.38	0.99
		Worst	106.76	0.94
# 2	2,3,5,28,36,42,55,57, 59, and 60	Best	19.91	0.98
		Worst	52.16	0.96

Different Amounts of EV Charge

In this comparison we kept the busses the fixed bus locations the same which are 4, 9, 14, 21, 29, 37, 42, 48, 56, and 58 but changed the percentage of charge of the unit EV when finding neighbors. The percentage unit EV shown in the table is the percentage of EVs load with respect to the total load power. The power loss below is based on a system where the EVs are only discharging and selecting the best of the possible power losses. This helps us determine the impact of changing the amount of charge in the EVs. We have organized our results in Table 3 below.

Table 3. EV Integration Level impacts on Results

EV Percentage (%)	Cases	Power loss (kW)	Voltage Minimum (pu)	Voltage Maximum (pu)
10	Best	14.90	0.98	1
	Worst	63.06	0.96	1
20	Best	13.60	0.98	1
	Worst	68.85	0.95	1
30	Best	12.68	0.99	1
	Worst	76.31	0.95	1
40	Best	11.71	0.99	1
	Worst	79.84	0.95	1
50	Best	11.43	0.99	1
	Worst	88.50	0.95	1
60	Best	11.13	0.99	1
	Worst	95.50	0.94	1

From the data collected, the higher the EV percentage, the greater the difference between the best and worse power losses. This makes sense as the charge is represented as negative for our MATLAB GUI so there is a positive correlation between voltage minimum and unit EV but a negative correlation between unit EV and power loss.

Conclusion

The data obtained from the MATLAB GUI shows the possible best and worst cases while considering factors such as buses and the number of EVs charging or discharging. These factors play a great role in determining how much power loss will take place in the system and how the voltage profile would be affected. When the EVs are at the best possible case, they effectively support the claim that EVs will reduce the overall power loss in the system. The worst scenarios from our data can be avoided if we consider the busses giving us lower worst possible case scenarios at the expense of a slightly higher power loss for an overall better outcome. Overall, the data effectively exhibits how the power losses and voltage profile of a power grid are affected with regards to specific scenarios. It also showcases how the best-case scenarios can be effectively utilized to reduce the burden on the power grids in terms of real-world implications. These case studies could provide the framework for how reducing the power losses and optimizing the voltage profile could provide general monetary benefits and better power quality for the increasing number of EV users in the future.

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