Impact of EV Charging Strategies on Peak Demand Reduction and Load Factor Improvement

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Abstract

A rapid growth in Electric Vehicle (EV) penetration is expected in the near future. EV presents economic and environmental advantages over traditional gasoline vehicles. However, a number of EVs, if charged simultaneously, may pose some serious challenges for electric utilities especially at the distribution level. This paper investigates selected EV charging strategies to mitigate the adverse effect of charging EV on the peak demand. These charging strategies are implemented for different EV penetration levels and charging modes. Simulation results indicate that EV charging time, charging power and penetration levels are significant factors impacting system peak load. Examining different EV charging strategies can help reduce the negative impact of EV penetration on the peak demand and thereby improve system load factor.

***Index Terms*—Electric Vehicles (EVs), EV charging strategies, peak load management, load factor**

1. Introduction

There are an increasing number of Electric Vehicles (EVs) as they have potential to provide cheaper travel costs and environmental benefits [1]. EV can also reduce reliance on imported oil. Savings on oil can be an important contribution to a national economy [2]. Authors in [1] estimate that 10% of U.S. vehicles will include some forms of PHEV (Plug-in Hybrid Electric Vehicles) or PEV (Plug-in Electric Vehicles) by 2020. Electric Power Research Institute (EPRI) predicts that PHEV/PEV will account for 62% of the entire U.S. vehicle fleet by 2050 according to the medium scenario [3]. Although these projections are beneficial in terms of environment and economy, research shows that high penetration of EVs has negative impacts on the electricity grid. Additional EV loads can bring about several challenges, including an increase in system peak demand, transformer and feeder overloads, voltage sags, and voltage unbalance especially at the electric power distribution level [4-6].

Early studies about EV penetration focused on power generation plants to meet the increasing demand [6-8, 9]. Oak Ridge National Laboratory (ORNL) foresees that high EV penetration may result in an increase in system stress conditions in a distribution system, and new generation plants may be required [10]. System-wide analysis may not be suitable to analyze the impact of EV penetration on a local distribution system due to high diversity factor at the distribution level [11].

In [12], authors analyze the impact of EV penetration on load and voltage profiles at a distribution transformer. System losses due to EV charging are discussed in [13] and [14]. Authors in [5] carry out delayed and off-peak charging scenarios and present their impacts on the distribution system and the environment. The impact of time-of-use tariffs on distribution load shapes with PHEV penetration is analyzed in [15]. Authors in [16, 17] propose a demand management algorithm to control EV loads. The problem of increasing peak demand with high EV penetration in a distribution system is considered in [18] and [19]. Authors in [20] calculate the maximum number of EVs that can be charged simultaneously during peak hours, considering voltage drop and transformer overloading.

The number of EVs, their charging power and their plug-in time for charging are essential factors to evaluate the impact of EVs on a distribution system. This paper analyses how different EV charging strategies can help avoid an increase in peak demand at a distribution circuit level. Two EV charging modes are considered, i.e., normal charge and quick charge. A residential distribution system comprising 1,000 houses is simulated in the GridLAB-D environment. EV fleet charging loads are added to the residential load at different penetration levels.

This paper is organized as follows: Section 2 explains the development of residential system load profiles in GridLAB-D. EV charging profiles and charging strategies are presented in Section 3. The charging strategies are implemented using different charging scenarios in Section 4. Results and discussions are presented in Section 5.

2. Residential Profiles for Residential Customers

The residential system load profile is generated in GridLAB-D. This is an open-source power system modeling and simulation tool developed by Pacific Northwest National Laboratory (PNNL) [12, 21]. The GridLAB-D environment provides modeling of each house with their appliances. It uses Typical Meteorological Year (TMY) data of Yakima, WA for outdoor temperature, while indoor temperature is calculated based on internal gains (from lighting, people, appliances, etc.), conduction through exterior walls, roof, fenestration, as well as outdoor temperature.

In this study, a residential distribution circuit serving 1,000 houses is simulated for one week in July. House sizes are assumed to vary from 1500 sqft to 2500 sqft. Number of homeowners vary from 2 to 6. Household appliances include

HVAC units (heating, ventilating, and air conditioning), lighting loads, plug loads, water heaters, refrigerators, clothes dryers, clothes washers, dishwashers and ranges.

Demand for electricity of an appliance depends on its capacity and schedule of usage, which is different for different appliances. Clothes washers, dishwashers, clothes dryers and ranges are called pulsed load appliances [22]. The schedules of pulsed load appliances are used in order to calculate the probability of appliances to be in operation. In each time step, probability is accumulated during the simulation. Appliances are ON when the probability equals to one. Water heaters operate to keep the water temperature in a specified dead band. Plug and lighting load schedules indicate the average demand during the course of the day.

Cooling and heating set points are randomized for each house between 70-75°F (21.1-23.8°C) and 65-69°F (18.3-20.5°C), respectively. The water heater set point is 120°F (48.8°C) with 10°F dead band. Schedules for pulsed appliances are also randomized. The simulated load profile of 1,000 houses is depicted in Fig. 1.

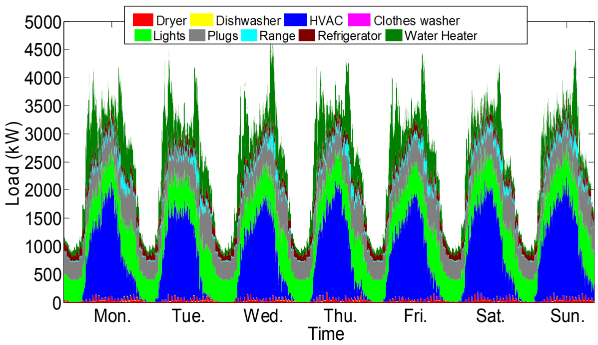

Fig. 1. One-week load profile of a distribution network comprising 1,000 houses in July

As shown, the peak load of 4,761 kW occurs at 6:11 PM on Wednesday. This day will be used for the simulation study described in this paper.

3. EV Charging Profiles and Strategies

Based on the data of residential home arrival time as published in the 2009 National Household Travel Survey [11], EV arrival time in this study is assumed to follow the Gaussian probability distribution model with the mean of 5:30 P.M. and the standard deviation of one hour.

As Chevy Volt is one of the most common EV in the market, Chevy Volt is the EV considered in this study. Two charging options are possible for Chevy Volt: Normal charge from a 120V/16A outlet and quick charge from a 240V/16A outlet. EV charging profiles for normal charge and quick charge are given in Fig. 2 and Fig. 3, respectively, at 10%, 20% 30% and 50% EV penetration levels. Note that the 50% EV penetration level indicates 500 EVs in a distribution circuit with 1,000 houses.

These figures illustrate the additional EV loads when EVs are charged without any strategy. That is, all EVs start charging as soon as they arrive home and stop when the battery is fully charged. This can be considered the worst scenario as many EVs arriving home at similar times and at residential peak load hours. In this study, three EV charging strategies are analyzed, which aim to reduce peak electricity demand due to EV penetration:

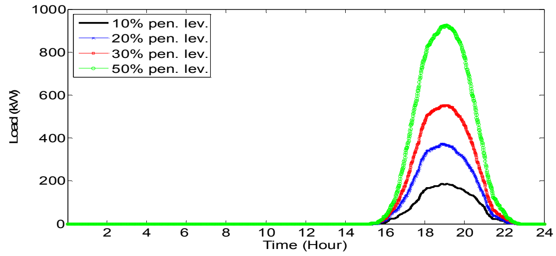

Fig. 2. EV load profiles – normal charge

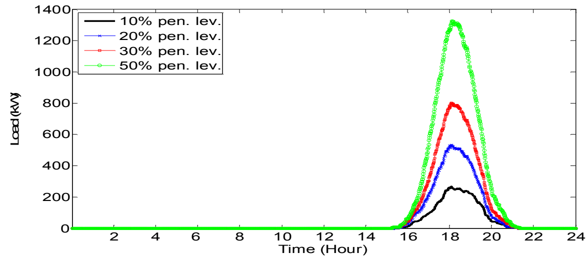

Fig. 3. EV load profiles – quick charge

Charging Strategy 1 (CS-1): EVs are not allowed to charge between 5 P.M. and 7 P.M. The EVs, which arrive home before 5 P.M., start charging and continue until 5 P.M. If their batteries are not fully charged, these EVs will resume their charging at 7 P.M. until batteries are fully charged. The EVs arriving home between 5 P.M. and 7 P.M. will need to wait until 7 P.M. to start charging. The EVs arriving after 7 P.M. can be charged nonstop. This strategy can create demand restrike, i.e., another peak demand at 7 P.M. when all EVs are allowed to resume their charging.

Charging Strategy 2 (CS-2): All EVs stop charging at 5 P.M., 60 % of EVs can resume their charging at 7 P.M., and 40 % of EVs can resume their charging at 8 P.M. This strategy helps reduce the possibility of demand restrike [23].

Charging Strategy 3 (CS-3): This strategy assumes that homeowners wait until midnight for charging their EVs and all EVs start charging at midnight. This allows homeowners to charge their EVs during the lowest demand period.

The impacts of these charging strategies on a distribution system load profile for both normal and quick charge modes are discussed in the next Section.

3. Case Studies

3.1. Impact of Normal Charge on the Load Profile

In this case all EVs are charged in the normal charge mode. They are connected to 120V outlets and charged at 1.9 kW [24]. Four scenarios are considered: EVs are charged without any strategy, and EVs are charged using strategies CS-1, CS-2, and CS-3. Based on the base distribution system load profile as discussed in Section II, distribution system load profiles with EV charging at 10%, 30% and 50% EV penetration levels are shown in Fig. 4, Fig. 5 and Fig. 6, respectively. In all figures, the black line represents the base residential system load profile without EV charging. The green line shows the distribution system load profile with EV – no control charging. The red, blue and magenta lines represent the distribution system load profiles with EV using charging strategies CS-1, CS-2 and CS-3, respectively.

As shown in Fig. 4, Fig. 5 and Fig. 6 in the no-control case (green lines), the system peak load increases proportionally with the EV penetration. The peak load is 4,928 kW at 10% EV penetration, it increases to 5,593 kW at 50% EV penetration level.

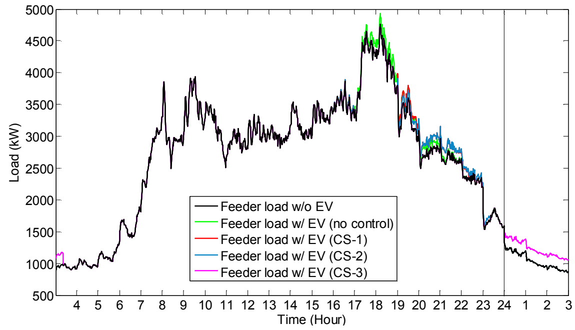

Fig. 4. Distribution system load profile without EV and with EV - normal charge – at 10% EV penetration level.

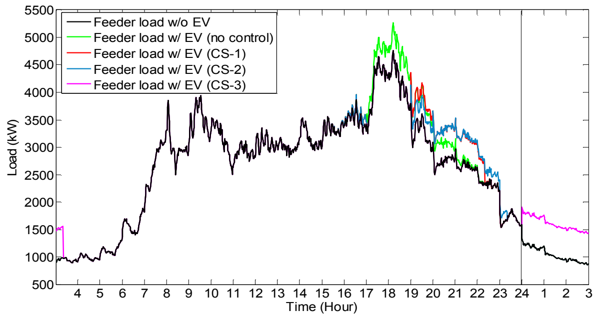

Fig. 5. Distribution system load profile without EV and with EV - normal charge – at 30% EV penetration level.

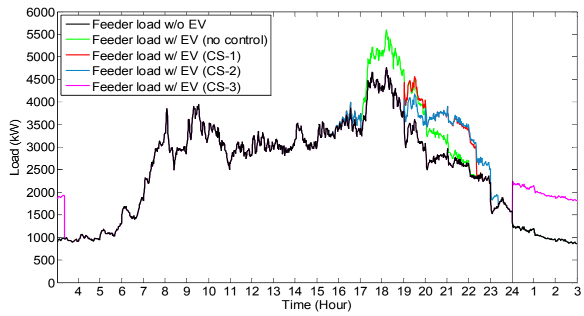

Fig. 6. Distribution system load profile without EV and with EV - normal charge –at 50% EV penetration level

Implementing strategies CS-1, CS-2 and CS-3 can help stop EV charging during peak hours. EVs resume charging at 7 P.M. in CS-1, which may result in demand restrike in the system. In Fig. 4 and Fig. 5, increases are seen for peak load with EV penetration. These small increases are avoided with any of given strategies and do not cause demand restrike. The increase in peak load is much higher at 50% EV penetration as seen in Fig. 6. Normal peak is 4,761 kW at 6:11 P.M. However the second peak whose value is 4,557 kW occurs at 7:29 P.M. with CS-1. The second peak is decreased to 4,177 kW with CS-2. EVs do not add to the total load before midnight in CS-3.

Table 1 summarizes the percentage of a system peak load increase when different EV charging strategies are used in the normal charge mode. As seen, the impact of EV charging on system peak load can be avoided when strategies CS-1, CS-2 and CS-3 are used for any given penetration level.

Table 1. Percentage of a system peak load increase at different EV penetration levels and charging strategies in a normal charge mode

	Without CS	CS-1	CS-2	CS-3
10% EV	3.512	0.000	0.000	0.000
30% EV	10.736	0.000	0.000	0.000
50% EV	17.480	0.000	0.000	0.000

Table 2 summarizes the change in system load factor (defined as the ratio of the average load to the system peak load) when different EV charging strategies are used in the normal charge mode. As shown, load factor improvement is provided with implementation of control strategies due to increased average load and constant system peak load.

Table 2. System load factors at different EV penetration levels and charging strategies in a normal charge mode

	Without CS	CS-1	CS-2	CS-3
0% EV	0.527	0.527	0.527	0.527
10% EV	0.513	0.531	0.531	0.531
30% EV	0.490	0.542	0.542	0.542
50% EV	0.471	0.553	0.553	0.553

3.2. Impact of Quick Charge on the Load Profile

In this case all EVs are charged in the quick charge mode. Vehicles are plugged in to 240V outlets and charged at 3.3 kW. The quick charge mode requires more power to charge during a shorter duration than the normal charge mode. Impact of different EV charging strategies are examined for quick charging mode as shown in Fig. 7, Fig. 8 and Fig. 9 at 10%, 30% and 50% EV penetration levels, respectively.

Overall, the impact of quick charging EV on a distribution system load profile is more than that of normal charging EV. In Fig. 7, the peak load increases to 5,011 kW at 10% EV penetration and in Fig. 8. increases to 5,546 kW at 30% EV penetration. It can be seen that CS-1, CS-2 and CS-3 can help avoid high peak demand successfully even in the 50% EV penetration scenario. However, demand restrike is a greater threat in the quick charge mode.

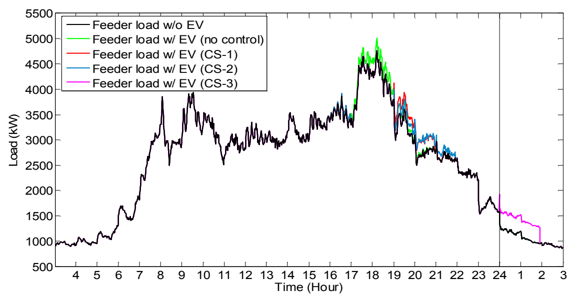

Fig. 7. Distribution system load profile without EV and with EV - quick charge –at 10% EV penetration level.

As evident in Fig. 8, for CS-1 the peak demand is 4,761 kW at 6:11 P.M. without EV and the second peak demand comes up to 4,768 kW at 7 P.M at 30% EV penetration level. At this time, the peak value is 4,376 kW when CS-2 is used. This value is under the original peak load without EV.

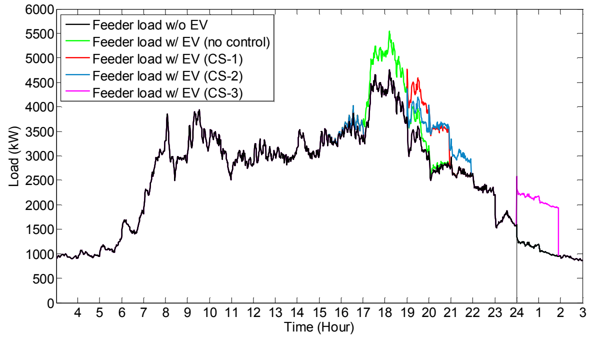

Fig. 8. Distribution system load profile without EV and with EV - quick charge –at 30% EV penetration level.

As illustrated in Fig. 9, the distribution system peak load is 6,067 kW at 50% EV penetration level. While CS-1 keeps the system peak at 4,761 kW at 6:11 P.M., the new peak load increases to 5,251 kW at 7:29 P.M. This implies CS-1 helps avoid the increase in the original system peak load but it causes demand restrike at later hours. As EVs resume their charging gradually in CS-2, CS-2 reduces the second peak to 4,768 kW. The impact of EV charging on the system load is removed completely by shifting the EV charge time to midnight in CS-3.

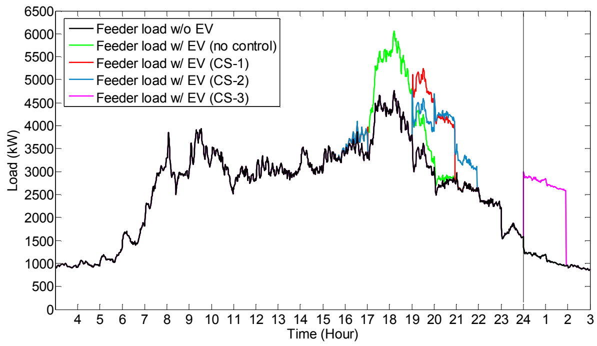

Fig. 9. Distribution system load profile without EV and with EV - quick charge –at 50% EV penetration level.

For the quick charge, the percentage of a system peak load increase is given for different EV penetration levels and charging strategies in Table 3.

Table 3. Percentage of a system peak load increase at different EV penetration levels and charging strategies in a quick charge mode

	Without CS	CS-1	CS-2	CS-3
10% EV	5.269	0.000	0.000	0.000
30% EV	16.500	0.169	0.000	0.000
50% EV	27.454	10.296	0.169	0.000

Naturally peak load increases with level of EV penetration. All strategies (CS-1, CS-2 and CS-3) can help avoide the peaks at 10% EV penetration level. While CS-1 can keep the increase in peak load at a low level for the 30% EV penetration scenario, but the peak load increases 10.2 percent for the 50% EV penetration level. The peak load increases only 0.17% in the 50% EV penetration scenrio with CS-2. EV fleet charging does not increase the system peak load with CS-3.

In Table 4 system load factors are summarized for different EV penetration levels and charging strategies when EVs are charged in a quick charge mode. Without any control strategy, system load factors decrease with EV penetration due to an increase in system peak load. However, with control strategies implemented, the system load factor can be improved as the system peak load with EV can decrease and the average load increases when compared with no EV scenario.

Table 4. System load factors at different EV penetration levels and charging strategies in a quick charge mode

	Without CS	CS-1	CS-2	CS-3
0% EV	0.527	0.527	0.527	0.527
10% EV	0.506	0.532	0.532	0.532
30% EV	0.467	0.543	0.544	0.544
50% EV	0.435	0.503	0.554	0.555

4. Discussion

Home arrival time of most vehicles happens during peak hours. If homeowners begin charging their EVs as soon as they arrive home (no control strategy), the system will see the increase in peak loads. At lower EV penetration levels, this increase may not constitute a big problem, but at higher EV penetration levels this may cause damages to distribution system equipment. In the normal charge mode, 30% penetration level causes 10.7% increase in the system peak. This rate is 17.5% for 50% penetration level. These increases are higher in the quick charge mode, i.e., 16.5% and 27.4% for 30% and 50% EV penetration, respectively.

To deal with the issue of peak load increase due to high EV penetration, this study considers different EV charging strategies to mitigate negative impacts of EV fleet charging. These strategies are simulated for normal and quick charge modes. With a normal charge, any of the given strategies (CS-1, CS-2, CS-3) can avoid higher peak demand for all EV penetration levels. Load factor improvement is also evident. With a quick charge, delaying EV fleet charging to off-peak hours (CS-1) is adequate to avoid increasing system peaks for 10% penetration level. However, demand restrike is experienced at 30% and 50% EV penetration levels. CS-2 and CS-3 can potentially avoid this problem.

5. Conclusion

In this paper, the residential system load profile is modeled for different penetration levels and charging modes of EV. Three charging strategies are considered to mitigate the impact of EV fleet charging on peak demand. These charging strategies are based on shifting charging loads away from peak hours. Simulation results demonstrate that Charging Strategy 1 is effective but there is a risk of demand restrike at high EV penetration levels. Gradually, charging as in Charging Strategy 2 can be a good solution to avoid high peak demand due to EV loads. Midnight charging in Charging Strategy 3 appears to never cause the increase in peak loads due to charging at lowest demand hours. Average system load is increased with EV penetration. These charging strategies also improve the system load factor due to the reduction in the EV penetrated system peak load by shifting the EV loads out of peak hours.

6. Acknowledgement

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