# Investigating the Impacts of Plug-in Hybrid Electric Vehicles on Distribution Congestion

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## *ABSTRACT*

*Smart grids are envisioned to support large penetrations of electrical vehicles driven by economical and environmental signals. Nevertheless, distribution system operators are becoming concerned about distribution congestion that may occur in the network with multiple domestic plug-in hybrid electric vehicles (PHEVs) charging. Therefore, investigating the impacts of high PHEV penetration levels on the performance of distribution networks seems to be essential for system operators and planners. Doing so, in this paper, PHEV characteristics are precisely extracted from valid published reports and surveys. Accordingly, a comprehensive model for investigating the impacts of different PHEV penetration levels on distribution systems for a single year and upcoming years is developed. The proposed model is applied to the IEEE 34-node test feeder, and PHEV impacts on the distribution network characteristics are reported. The results show distribution congestion occurrence for more than 11% PHEV penetration level.*

## INTRODUCTION

Global warming, green house gas emission and fuel resource depletion bring up major concerns for nations. Transportation sector is one of the major sources of these problems. Over the past few years, transportation electrification has been considered as an effective solution to remove negative impacts of conventional vehicles. Plug-in hybrid electrical vehicle (PHEV) technology is an emerging paradigm and a promising solution to tackle the threatening environmental challenges. PHEVs are equipped with rather large batteries and connected into the grid to be charged. Coincidence of PHEV charging and peak load demand would lead to distribution system congestion and likely distribution transformers destruction. Assessing the impacts of widespread charging of PHEVs on distribution systems, PHEV characteristics, i.e. size of battery, state of charge (SOC) of battery, and beginning time of charging, should be determined. These characteristics depend on vehicle type as well as owners' behaviours. Furthermore, to achieve a more practical model for PHEVs, the number of vehicles in a residential distribution network, the PHEV penetration level for upcoming years, distribution of PHEVs in the network, and estimation of household load growth for upcoming years should be extracted from related published reports.

In recent years, various researchers have concentrated on PHEV charging impacts on distribution systems. From a detailed review of the technical literature, it is clear that majority of these studies have used simple assumptions for PHEV characteristics and owners' behaviour. References [1] and [2] assess the impacts of charging PHEVs on a residential distribution network with different charging strategies and various PHEV penetration levels. The results show significant increase in the system peak load. However, results are based on a simple assumption that the starting time of charging is certainly between 5 and 7 p.m.. Also, many researchers considered such various simplified assumptions for the size of PHEVs' battery. For example, in [2-4], authors use the definite size of batteries for all the PHEVs. These assumptions for other PHEV characteristics are also utilized in [5-6] without any firm justification. This may lead to unreliable results. The precise estimation of different PHEV penetration levels impacts on the load demand is necessary for the distribution system operators and planners. Therefore, an accurate model for PHEVs should be developed based on justified characteristics and data.

In this paper, a comprehensive model is proposed to investigate PHEV impacts on residential distribution systems. Precise PHEV characteristics are extracted from related reports. Also, different PHEV penetration levels, vehicle owners' behaviour, and load growth in upcoming years are also considered in the studies.

## EXTRACTING PHEV CHARACTERISTICS

In order to achieve an accurate PHEV model, PHEV characteristics need to be determined precisely. Some of these characteristics such as daily miles driven and plug-in time are related to vehicle owner's behavior. A transportation report of the U.S.A, 2009 national household travel survey (2009 NHTS) [7] is used to extract such characteristics. Other characteristics such as PHEV battery characteristics can be found in the car manufacturer reports [8-9] and related documents [10]. In addition to the mentioned PHEV characteristics, other required data, i.e. number of vehicles per house and load growth in the upcoming years is also achieved here. It should be noted that, after extracting PHEV characteristics, it is essential to determine PHEV distribution in the network based on these characteristics.

## PHEV Battery Capacity

The required energy to charge the battery is directly related to the capacity of battery. Table I shows the energy consumption per mile (ECPM) and size of PHEV battery with different classes and different all electric ranges (AER) [10]. AER is the distance which PHEV can drive on the pure electric mode. (PHEVx indicates a PHEV with AER=x)

TABLE I
ECPM AND SIZE OF BATTERY FOR VARIOUS PHEVS (KWH)

| Vehicle class | ECPM [kWh/m] | PHEV30 [kWh] | PHEV40 [kWh] | PHEV60 [kWh] |
|---|---|---|---|---|
| Compact sedan | 0.26 | 7.8 | 10.4 | 15.6 |
| Mid-size sedan | 0.30 | 9 | 12 | 18 |
| Mid-size SUV | 0.38 | 11.4 | 15.2 | 22.8 |
| Full-size SUV | 0.46 | 13.8 | 18.4 | 27.6 |

Table I clarifies that there is a wide range of batteries for PHEVs. Table II and III show the percentage of each vehicle class and penetration of AERs, respectively.

TABLE II
PERCENTAGE OF EACH TYPE OF VEHICLE IN NHTS 2009 [7]

| Vehicle class | Compact sedan | Mid-size sedan | Mid-size SUV | Full-size SUV |
|---|---|---|---|---|
| Percentage | 51.48% | 10.35% | 23% | 15.17% |

TABLE III
PENETRATION OF PHEVS WITH DIFFERENT AERS [11]

| | PHEV30 | PHEV40 | PHEV60 |
|---|---|---|---|
| Percentage | 21% | 59% | 20% |

## Plug-in time

It is premised that PHEVs charge once a day, after their last trip arrival time [1], [12], and [13]. Thus last trip arrival time is considered here as plug-in time of PHEVs. Databases of 2009 NHTS are analyzed to determine percentage of vehicles based on their plug-in time. Fig. 1 shows the result.

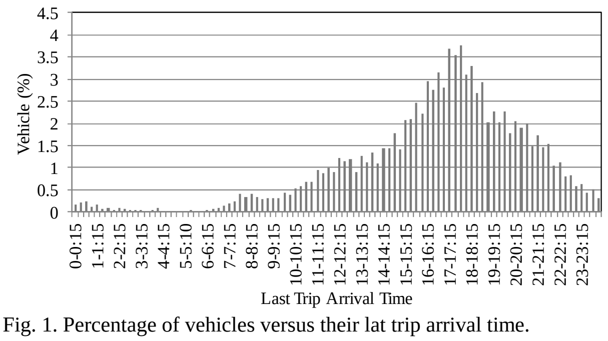


Fig. 1. Percentage of vehicles versus their lat trip arrival time.

According to Fig. 1, most of vehicles arrive home between hours 16 and 21.

## Required Energy for Charging PHEV

SOC of the battery at home arrival time determines the required energy to charge the battery. This amount of energy for a PHEV is expressed as below:

$$E_c = (1 - \frac{SOC}{100})C, \quad (1)$$

where C is the PHEV battery capacity [kWh], $E_c$ is the required energy to fully charge the battery, and SOC is the percentage of remained energy in the battery. SOC depends on the daily miles driven and can be expressed as:

$$SOC = \begin{cases} (1 - \frac{d}{AER})100 & d \le AER \\ 0 & d \ge AER \end{cases} \quad (2)$$

where d is the miles driven by the PHEV during daily trip. Here, it is assumed that PHEV runs in electric mode until the battery reaches a certain level. The distribution of vehicles in the network based on daily miles driven is drawn in Fig. 2.

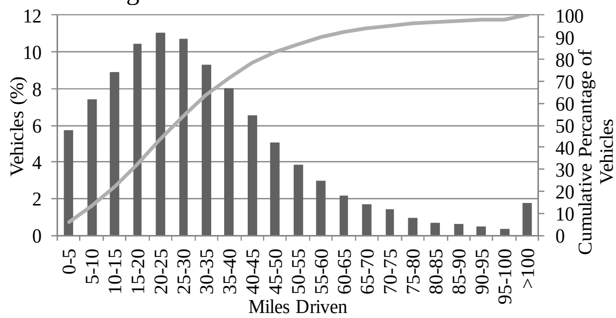


Fig. 2. Percentage of vehicles versus their daily miles driven.

This figure demonstrates that majority of driving distances are between 20 and 30 miles.

## Number of Vehicles per House

According to [2], 2.3 vehicles in average are assigned to each house. The number of PHEVs distributed in the network plays a major role in the PHEV impacts on distribution systems. The number of PHEVs depends on the PHEV penetration levels among estimated number of vehicles. The PHEV penetration levels during upcoming years are premised to be as Fig. 3 [14].

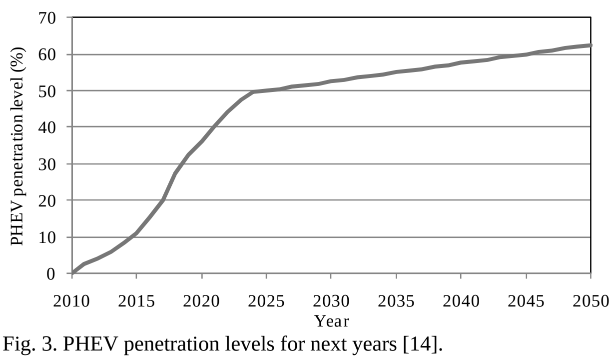


Fig. 3. PHEV penetration levels for next years [14].

## Load Growth

Load growth is the function of increasing the electricity uses in the existent households, and addition of new customers. According to [15], the annual incremental growth rate of residential electricity consumption will be 1.3%. The number of houses is assumed to increase similar to Fig. 4 [16].

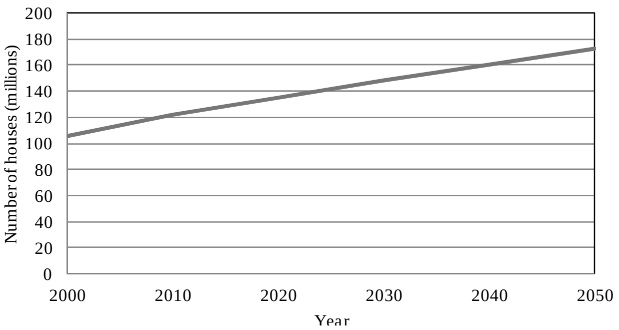

Fig. 4. Number of houses till 2050 in U.S..

## NUMERICAL RESULTS

The impacts of PHEV charging on the load demand of distribution system through different PHEV penetration levels for a single year and also for the upcoming years are investigated in this section.

### System Topology

The IEEE 34 node test feeder is shown in Fig. 5. Since there is not any specific information about the load class of each node in the system definition [17], we assigned as many as houses to each node, as the peak load of these houses reaches to the load of that node described in [17]. Fig. 6 shows an average household load profile [1]. This load profile is assigned to each house in the network.

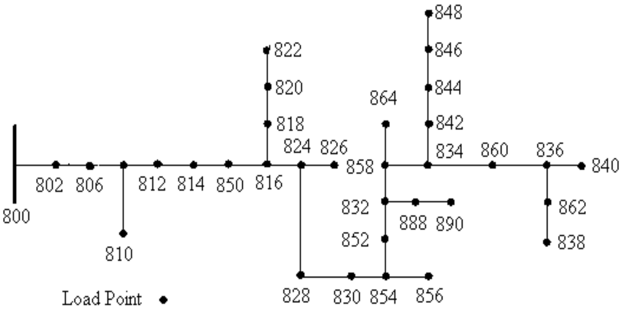

Fig. 5. IEEE 34 node test feeder [17].

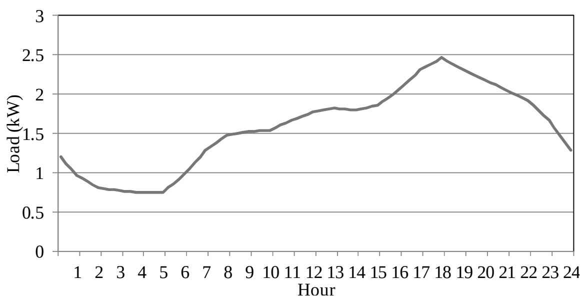

Fig. 6. An average household load curve.

The total number of vehicles is determined by the number of houses and the number of vehicles per house explained before. Then, PHEV are selected randomly among the vehicles based on PHEV penetration levels. Also, PHEV characteristics are determined based on the extracted data in the previous section. Using daily miles driven, PHEV class, and AER, the required energy to fully charge PHEVs is calculated. The charging level of the battery is premised 4 kW. The load of each node is the summation of household load and PHEV charging load.

The following case studies are conducted to investigate the impacts of charging PHEV on the distribution network:

**Case I:** impacts of PHEV charging with different penetration levels on the load profile of distribution system in a single year, 2020, are studied in this case;

**Case II:** this case investigates the impacts of PHEV on the load curve between years 2020 and 2050.

### Case I

This case shows the impact of PHEV charging on the test distribution load profile. Since some of the PHEV characteristics are randomly distributed, about 2000 samples are taken to reach an accurate average for PHEV consumption in 15-min time intervals.

11%, 35%, 45% PHEV penetration levels are, respectively, considered here as low, medium, and high PHEV penetration levels [14]. Fig. 7 depicts the total feeder load curve in 2020. Also, Table IV shows different system characteristics, i.e. system peak load, peak to average ratio (PAR), and standard deviation of the system load profile. The presented results expectedly indicate that the PHEV charging coincides with the peak of household energy consumption, since majority of people come back home between hours 17 and 21 and plug in their PHEVs. According to Fig. 7, it also can be concluded that the transformer can supply the feeder, without congestion, with 11% PHEV penetration level. However, 35% and 45% PHEV penetration levels cause transformer to be overloaded 11% and 16%, respectively. Moreover, second row of table IV shows that PAR has a significant increase in the case of PHEV presence, due to PHEV charging in the peak load periods. It is desirable to have PAR close to one. Higher PAR might result in cost increment for utilities in long-term since it needs new investment in generation and transmission capacities to serve higher peak load.

The third row of Table III shows that the standard deviation of the system load profile increases significantly by ascending PHEV penetration level. This leads to a more non-smooth load curve which is uneconomical for the grid operator.

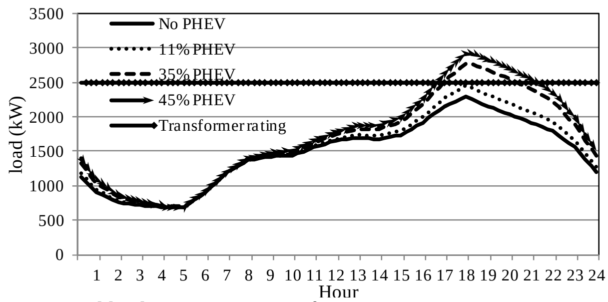

Fig. 7. Total load curve in summer of 2020.

TABLE IV
DISTRIBUTION SYSTEM SPESIFICATION UNDER DIFFERENT PHEV PENETRATION LEVELS

| | PHEV penetration level | | | |
|---|---|---|---|---|
| | 0% | 11% | 35% | 45% |
| Peak Load [kW] | 2298 | 2450 | 2777 | 2915 |
| PAR | 1.56 | 1.59 | 1.65 | 1.69 |
| Standard Deviation [% average load] | 32.8 | 34.5 | 38 | 39.6 |

**Case II**

In this case, the increment of the number of houses as well as load growth of each household should be considered based on the aforementioned data. According to Fig. 8 the peak load increases due to the PHEV penetration level increment. The presented results show that the PHEV charging coincides with the peak of household energy consumption. Also, PAR increases before year 2026, since in this period, PHEV penetration level grows highly and PHEV charging is coinciding with peak load curve. This causes the peak load increment to be more than average load increment.

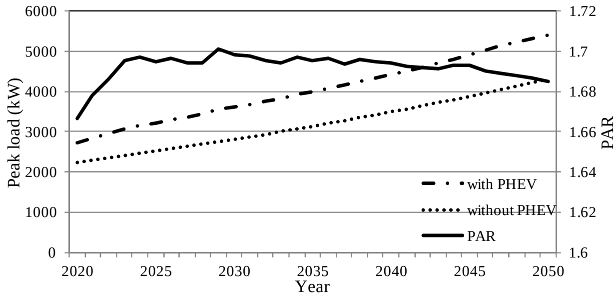


Fig.8. System peak load and PAR between year 2020 and 2050.

## CONCLUSION

In this paper, required PHEV characteristics are extracted from published data and a reasonable model is developed for PHEVs. Then, impacts of the PHEV charging in a single year and long term run are probed on the IEEE 34-node residential test feeder. The load growth is also considered in the investigation of PHEV impacts on the distribution system for upcoming years. Results verify that widespread use of PHEVs in distribution systems can cause significant congestion due to coincidence of daily peak load and charging time of PHEVs. Also, PAR and standard deviation of distribution load profile are increased due to PHEV penetration level increment. It sounds essential to control the time and level of charging PHEV to prevent distribution congestion, decrease PAR and standard deviation. This issue as an open research area is currently under our study.

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