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Stochastic Modeling of Plug-in Electric Vehicle Distribution in Power Systems

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Abstract – This paper proposes a stochastic modeling of plug-in electric vehicles (PEVs) distribution in power systems, and analyzes the corresponding clustering characteristic. It is essential for power utilities to estimate the PEV charging demand as the penetration level of PEV is expected to increase rapidly in the near future. Although the distribution of PEVs in power systems is the primary factor for estimating the PEV charging demand, the data currently available are statistics related to fuel-driven vehicles and to existing electric demands in power systems. In this paper, we calculate the number of households using electricity at individual ending buses of a power system based on the electric demands. Then, we estimate the number of PEVs per household using the probability density function of PEVs derived from the given statistics about fuel-driven vehicles. Finally, we present the clustering characteristic of the PEV distribution via case studies employing the test systems.

Keywords: Plug-in electric vehicle (PEV), Probability density function (PDF), Cumulative distribution function (CDF)

1. Introduction

Due to the rising price of fossil fuels and the increasing pressure to reduce greenhouse gas emissions in the transportation sector, the penetration level of electric vehicles (EVs) is expected to increase rapidly in the near future. Moreover, since the EV industry is considered a national growth engine in many countries, including the US and South Korea, each government aggressively supports EV-related technology development and its sale through various policies [1]. Even though popularizing EVs involves many challenges, including overcoming the short driving range, slow charge time, high cost and battery heaviness, battery technologies have improved and their costs have decreased, making these obstacles more surmountable.

Although there are various types of EVs, the most promising form is the plug-in EV (PEV) which directly charged from the power grid via a charger including ordinary home outlet. Since the rating of a PEV charger in a home or commercial charging station is expected to easily reach 7.7kW level, which is much higher than the levels of other conventional electric appliances such as refrigerators, or air conditioners, the charging demands of PEVs may require the expansion or reinforcement of power systems if its penetration level becomes sufficiently high. Moreover, since the charging demands of PEVs are very different than typical electricity demands and their demand patterns are not familiar to power system engineers, new methods for considering the charging demand of PEVs in power system planning would be required.

In order to assess the impact of PEV charging demands on a power system, the number of PEVs and the characteristics of their charging demands such as the charging start time, the initial state-of-charge (SOC), the charging location and the power rating of the charger are required considering the driver's behavior and the characteristics of the PEV charging infrastructure[2]. However, since there is no experience of the PEV modeling and historical data for PEV operations [3], and since all of the given data are statistics related to fuel-driven vehicles and existing electric demands in power systems, a stochastic approach is required to estimate the charging demands of PEVs and to assess the impact of overall PEV charging demand.

As a first step for this approach, this paper proposes a stochastic methodology to estimate where PEVs are located and how many PEVs are connected to power systems. In the proposed method, the number of PEVs per household is derived using a stochastic method based on statistics related to fuel-driven vehicles and existing electricity demands in power systems. This method can be easily adopted by power system engineers because it utilizes typical data from power system planning. This paper verifies the usefulness of the proposed method by applying it to test systems. In addition, the clustering characteristics of PEV distribution could be found through case studies where the portion of PEVs is much higher than the overall penetration level. These clustering

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characteristic simply that power system facilities could become overloaded in a local area even though the overall penetration level of PEVs is not considerably high.

This paper is organized as follows. Section 2 describes the characteristics of the charging load of PEVs. In section3, the stochastic modeling of the PEV distribution in power systems is presented. In section 4, case studies are conducted using the proposed method and the simulation results are analyzed. Conclusions are drawn in section 5.

2. Charging Loads of PEVs

The transportation sector is considered one of the key industries to decrease greenhouse gas emissions, and consequently, interest in PEVs which are the most promising alternatives to fuel-driven vehicles has increased over time. Furthermore, according to the technology roadmap for electric and plug-in hybrid electric vehicles from the International Energy Agency (IEA), the total number of PEVs is expected to reach approximately 100 million units by 2050. Thus growth is depicted in Fig. 1 [5].

Since PEVs are charged directly from a power system through chargers, the charging load of PEVs must be considered in power system planning and operations [3, 4] For reference, Figs. 2, 3 present the estimated annual energy use and charging load of PEVs for South Korea. The impact of the PEV charging load in the power system is insignificant with respect to the annual charging energy, as shown in Fig. 2. In Fig. 2, the annual energy uses of electricity customers are referred to the 5th basic plan of long-term electricity supply and demand published by Korean government [6], and the annual energy uses of the electric vehicles are calculated by applying the historical data of vehicle uses in Korea. It is assumed that the annual mileage per PEV is 20,000km and the fuel efficiency of PEV is 5km/kWh with given number of PEVs [7]. On the other hand, with respect to instantaneous power, the

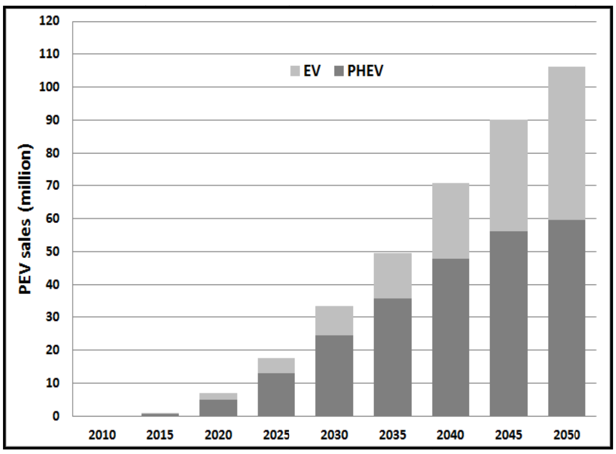

Fig. 1. Annual global EV and PHEV sales in BLUE Map scenario

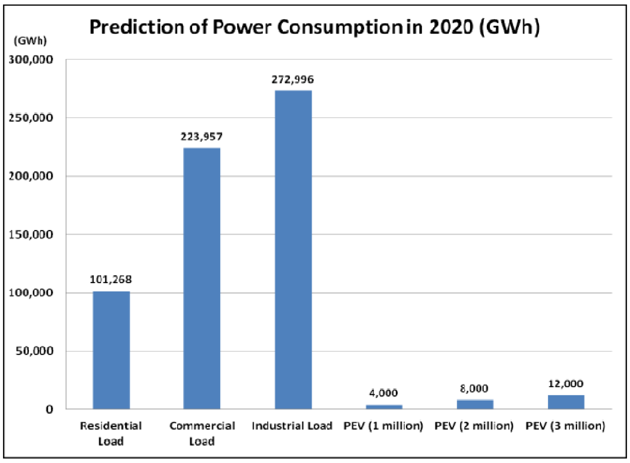

Fig. 2. Estimated annual energy used by PEVs in Korea [2020]

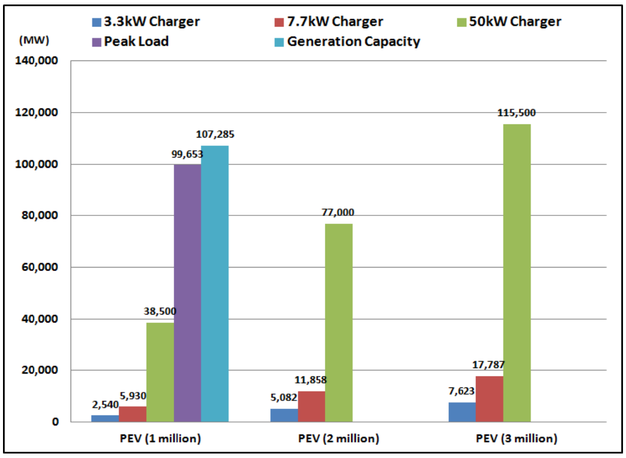

Fig. 3. Estimated charging load of PEVs in Korea [2020] (Coincidence factor: 77%)

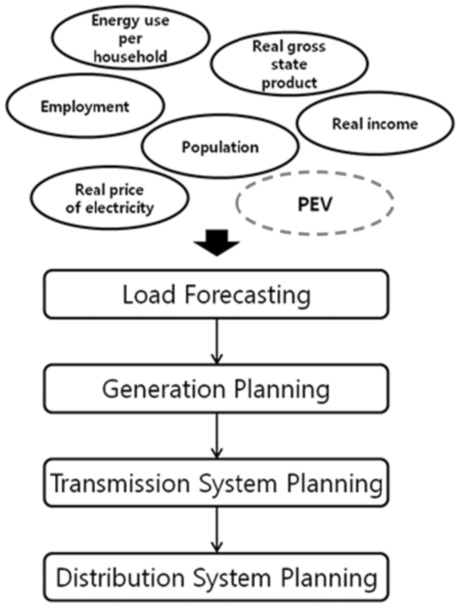

Fig. 4. Power system planning process with PEVs

charging load of PEV can be significant depending on the power rating of the charger, the penetration level of PEV and the coincidence factor of the PEV charging as shown in Fig. 3 [8].

Accordingly, the charging load of PEVs should be taken into account in the power system planning process, which is illustrated in Fig. 4 [9].

However, since there is no experience in the PEV modeling and operation, and the given data are statistics related to fuel-driven vehicles and existing electric demands in power systems, the stochastic approach is required to represent the PEV charging demand.

Hence, as the part of the process for planning a power system with PEVs, this paper proposes a stochastic modeling of a PEV distribution in a power system, and analyzes its clustering characteristic.

3. Stochastic Modeling of PEV Distribution

Since it will take time to develop a sufficient number of charging stations along streets, PEVs would be charged mainly at drivers' homes in the early stages of their development. Therefore, in this paper, PEVs are assumed to be connected into power systems at homes, and the charging loads of the PEVs are modeled for individual households. To achieve accurate results, we first estimated the number of households using the existing electricity demands at residential customers which are easily available from power utilities.

3.1 The number of households based on electricity use

In this section, the number of households is derived from the electric load data provided by power utilities. Since the residential electricity load is roughly proportional to the number of households at a bus, the number of households can be calculated from the electric load data, which is readily available per different types of customers from power system data considering the typical coincidence factor [10]. If the electric load data is provided as a total load at a bus, the residential load could be calculated by using a typical ratio between different types of customers which is usually known. The coincidence factor is defined as the ratio of the maximum load of a system to the sum of the individual maximum loads, as given in Eq. (1).

$$CF = \frac{\text{The maximum system load}}{\text{The sum of individual maximum loads}} \tag{1}$$

This factor represents the degree of coincident occurrence of individual maximum loads.

Since power system data usually consist of the electric load at buses collected at peak time basis, the number of households at each bus can be calculated using Eq. (2).

$$N_k = \frac{S_k \times pf}{CF \times P_{Contract} \times 1.1} \tag{2}$$

where N_k is the number of households at bus k, S_k [VA] is the maximum apparent power of the residential load at bus k, pf is the power factor, and $P_{Contract}$ [W] is the typical contracted power of a household. The denominator is multiplied by 1.1 to account for the fact that the effective available power is 10% greater than the contract power as usually assumed in a similar analysis [10].

Since power utilities usually have a typical coincidence factor for their standard loads that is based on operation experience, the number of households at each bus can be derived by applying the specific coincidence factor to the specific system.

3.2 Probability of the number of PEV in a household

In this section, the number of PEVs per household is derived based on statistics related to fuel-driven vehicles for a given penetration level of PEVs. The penetration level of PEVs is defined as the ratio of the number of PEVs to the number of total registered vehicles as shown in Eq. (3).

$$p = \frac{\text{The number of PEVs}}{\text{The number of total registered vehicles}} \tag{3}$$

However, since the number of registered vehicles varies for different households, the number of PEVs should be derived using the probability of PEVs among the total registered vehicles in each household. The probability that the number of PEVs is n among N registered vehicles in any household is defined in Eq. (4) for a given penetration level of PEVs.

$$P_{PEV}(n/N) = {}_N C_n \times p^n \times (1-p)^{N-n} \tag{4}$$

where N is the number of registered vehicles in a household and n is the number of PEVs which varies from 0 to N. Thus, if n is larger than N, $P_{PEV}(n/N)$ is zero. As the maximum number of registered vehicles per household is assumed to be three here, the number of PEVs must be

Table 1. The probability of n PEVs among the N registered vehicles in a household

#EV \ #V	0	1	2	3
0	1	$1-p$	${}_2C_0 \times (1-p)^2$	${}_3C_0 \times (1-p)^3$
1	0	p	${}_2C_1 \times p \times (1-p)$	${}_3C_1 \times p \times (1-p)^2$
2	0	0	${}_2C_2 \times p^2$	${}_3C_2 \times p^2 \times (1-p)$
3	0	0	0	${}_3C_3 \times p^3$
Total	1	1	1	1

less than or equal to three. Therefore, Eq. (4) can be calculated as shown in Table 1. Here, #V and #EV represent the number of vehicles and the number of PEVs respectively.

Additionally, since the number of registered vehicles per household in Eq. (4) varies, the probability that a household has *n* PEVs can be calculated using Eq. (5).

$$P_{PEV}(n) = \sum_{i=0}^{N} \left\{ P_{veh}(i) \times P_{PEV}(n/i) \right\} \tag{5}$$

where $P_{veh}(i)$ is the probability that the number of registered vehicles in a household is *i*. Therefore, $P_{veh}(i)$ can be defined for *i* registered vehicles as shown in Table 2.

As described above, once the penetration level of PEVs has been determined, the probability that a household has *n* PEVs can be calculated by using Eqs. (3, 4) and (5).

Table 2. The probability of the number of registered vehicles per household

The number of vehicles	Probability
0	$P_{veh}(0)$
1	$P_{veh}(1)$
2	$P_{veh}(2)$
3	$P_{veh}(3)$
Total	1.0

3.3 Distribution of PEVs

In this section, the distribution of PEVs is derived from the probability of the number of PEVs in a household. Since the only information available is the statistical data and the probability distribution for the PEVs, a stochastic procedure should be used in order to find the distribution of PEVs.

To determine the distribution, the probability distribution function (PDF) and the cumulative density function (CDF) are first composed from the probability calculated in Eq. (5). Then, a random variable (Rand), indicating a household is generated between 0 and 1. Finally, the number of PEVs in a household is determined by comparing the Rand and the CDF, as demonstrated in Fig. 5. These processes can then be applied to all of the households. Fig. 6 shows the overall procedure for the stochastic modeling of the PEV distribution.

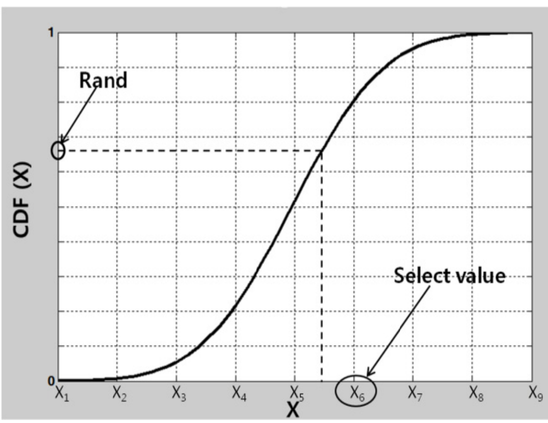

Fig. 5. Method to find X in CDF(X) corresponding to Rand

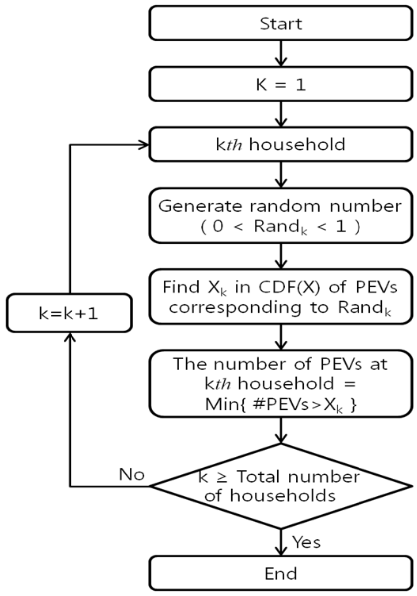

Fig. 6. Stochastic modeling procedure for distribution of PEVs

Since PEVs are assumed to be charged at drivers' homes in the early stage of the development, the calculated PEVs for each household are likely charged from power systems interconnected with each household.

4. Case Study

In this section, the proposed method is applied to a test system in order to model the number of PEVs per household. The employed test system is shown in Fig. 7 [11]. The test system is assumed to supply various types of customers

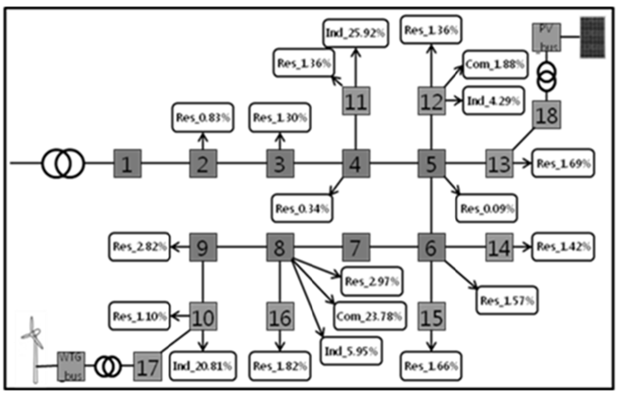

Fig. 7. Test system

through one substation, and its peak demand is about 5550kW at the substation as shown in Fig. 7.

In order to determine the number of PEVs in a household, the number of households at each bus must be calculated first. The number of households at each bus can be calculated using Eq. (2), making some assumptions on the power factor (0.98), the coincidence factor (0.77) and the contract power of the residential load (3kW). In addition, the maximum residential load at each bus is provided in Table 3. The results are also shown in Table 3.

The second step is to compose the probability distribution for the number of PEVs in a household. In this paper, it is assumed that the penetration levels of PEV are 5%, 10% and 20%. The probability of the number of PEVs in a household is calculated using Eqs. (4) and (5) based on the assumed penetration level of the PEV. Note that, the probability of the number of registered vehicles in a household — a value that is necessary for Eq. (5) — is found from the Korean statistics given in Table 4 [12].

Table 3. Residential loads of test system

Bus #	Maximum residential load at buses(kVA)	Percentage with respect to total load (%)	Number of households
2	50.816	4.11	20
3	75.592	6.11	29
4	20.816	1.68	8
5	5.510	0.45	2
6	96.122	7.77	37
8	181.469	14.66	70
9	172.041	13.90	66
10	66.857	5.40	26
11	83.265	6.73	32
12	82.763	6.69	32
13	102.857	8.31	40
14	86.939	7.03	34
15	101.633	8.21	39
16	110.816	8.95	43
Total	1237.496	100	478

Table 4. The probability of the number of vehicles in a household in Korea

Number of vehicles	Probability (%)
0	36.43
1	48.12
2	13.83
Over 3	1.62
Total	100

Table 5. The probability of the number of PEVs at a household based on the penetration level of PEVs

P.L. / #EV	5%	10%	20%
0	0.9601425	0.9212074	0.8460563
1	0.0393943	0.0769557	0.1467256
2	0.0004612	0.0018207	0.0070886
3	0.0000020	0.0000162	0.0001295
Total	1	1	1

※P.L.: Penetration level of PEV, #EV: The number of PEVs

Accordingly, the probabilities of the number of PEVs in a household are given in Table 5 for the various penetration levels of PEV.

Then, the CDF of the number of PEVs in a household can be represented using data given in Table 5, as shown in Fig. 8.

Finally, the number of PEVs in each household is calculated through the procedure shown in Fig. 6. The procedure is repeated 100 times to thoroughly examine the modeling results.

Figs. 9, 10 and 11 show the statistics of the proposed model. Fig. 9 shows the range of the PEV portion with respect to the substation. It can be seen that the PEV portion at total area exists predominantly near the assumed penetration levels. Fig. 10 shows the range of the PEV portion with respect to the each load bus. It can be observed from Fig. 10 that the range of the PEV portion can have large variation based on the location of the bus. Moreover, the range of the PEV portion in a local area can be larger than that in a total area.

These two figures substantiate the proposed method because the stochastic method has the desired characteristics — i.e., it produces results that are distributed based on the

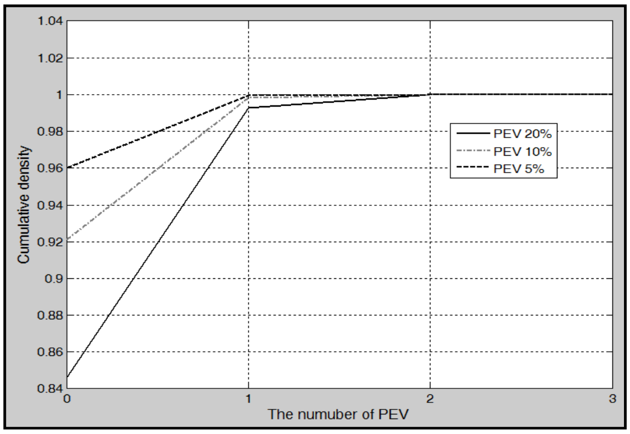

Fig. 8. Cumulative distribution of the number of PEVs in a household

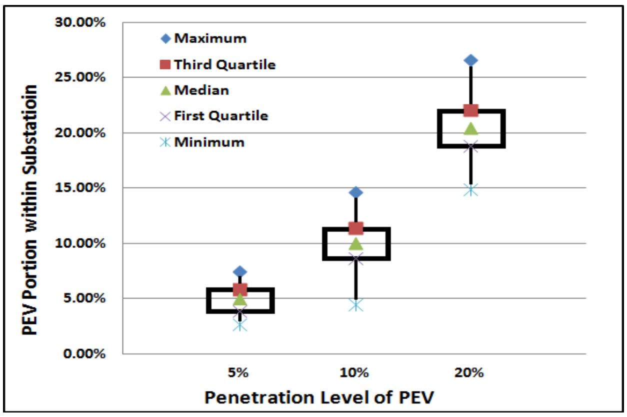

Fig. 9. Box plot analysis for PEV portion within substation

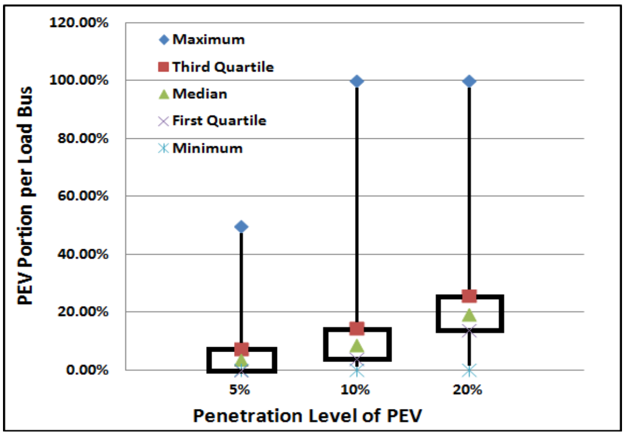

Fig. 10. Box plot analysis for PEV portion per each load bus

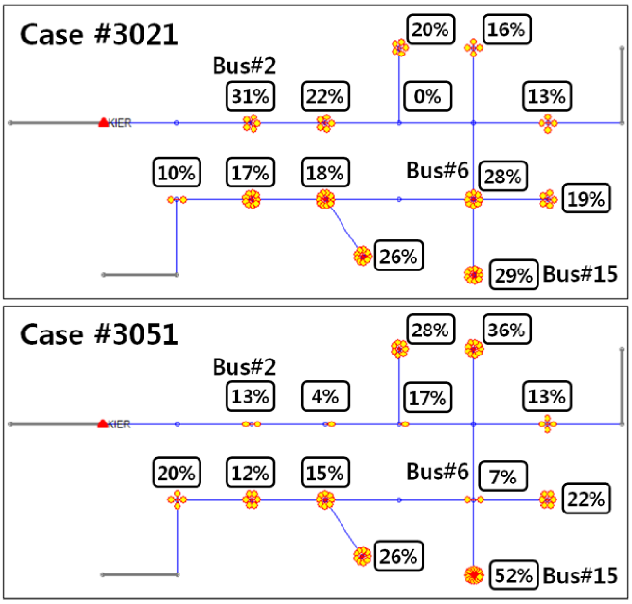

Fig. 11. Scheme for PEV clustering in the test system at 20% penetration level

average of the given statistics, and it verifies that smaller observation scope sizes correspond to larger ranges of variation in the results.

Fig. 11 shows the selected two cases (Case #3021 and #3051) among 100cases created in the stochastic modeling for showing the clustering pattern of PEVs distribution when the penetration level of PEV is 20%.Each PEV is represented by a yellow circle. For example, the figure shows that the PEV portion is notably different at bus #2 (13% to 31%), at bus #6 (7% to 28%), and at bus #15 (29% to 52%). The PEV portion of each bus could be much higher than the penetration level of the PEV in the total area. Therefore, it implies that the power supply facility could be overloaded in a local area even with a low penetration level of PEV.

5. Conclusion

This paper proposed a stochastic modeling method of the PEV distribution in power systems, and analyzed its clustering characteristics. The proposed modeling method accounted for the stochastic nature in the number of PEVs per household and the distribution of the charging demand of PEVs. In addition, the clustering characteristics of the PEV distribution were verified in the case studies. The results indicated that even if the penetration level of PEV is low, overloading and congestion are likely to occur depending on the location of bus because the PEV charging loads will not increase equally across the whole power system. Consequently, these case studies should be considered when planning a power system. The result of this paper is expected to provide good guidance to future power system planning and operations.

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