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A probability load modeling method for the charging demand of large-scale PEVs accounting users' charging willingness

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ABSTRACT

This paper presents a new strategy in order to model the charging power demand due to large-scale plug-in electric vehicles (PEVs) as realistic a fashion as possible and analyze their impact on the residential power distribution system. The strategy takes the charging willingness of PEV users into consideration, and accounts for the difference in charging frequencies among users. A detailed classification, derived from the historical data on users' driving patterns, on PEV users is conducted in order to ensure that users in the same user set have the same charging properties. Seven probability load models for PEV charging are established for these user sets, and each model accounts the inherent randomness in the usages and recharges of PEVs. After the consideration of charging willingness, the charging demand differs among weekdays. The aggregated charging demand from a user set on each weekday is calculated based on the Law of Large Numbers, and the total charging demand from all PEVs on each weekday can be obtained by accumulating the aggregated charging demand of the user sets with charging willingness. The strategy can ensure a high utilization of the battery capacity, and the aggregated charging demand resulted is more rational and credible. The proposed charging load modeling strategy is finally applied on the electric load profile on a winter day in Manitoba.

Introduction

The plug-in electric vehicle (PEV), utilizing electricity instead of diesel and gasoline completely as a propulsive engine element, is a kind of clean-energy transport with such advantages as high energy conversion efficiency, low noise, zero tailpipe emissions, independence on fossil fuels, and so forth. The large-scaled application of PEVs will effectively ameliorate current global concerns over environmental issues and petroleum paucity [1–3], and thus many automotive manufacturers all over the world have begun to lay increased emphasis on the development of PEVs [4]. However, as a kind of potential high-power common household electricity load, the high penetration of PEVs will challenge the power margin of current residential distribution network with high probability, and would cause some grid stability and security issues in consequence. Therefore it is necessary and important to study the load demand due to considerable PEV charging behaviors and their influence over the load characteristics of power distribution system.

Several important strides have been performed in recent years on this topic field. Gómez et al. [5] qualitatively analyzed the effect of battery chargers on the system load, and pointed out that the charging load won't make major problems to the system loads, and there is no need for any special system changes. However, the paper only estimated the penetration of PEVs as less than 10%. In fact, given a PEV penetration of more than 35%, the required network reinforcements can reach values up to 19% of total actual network costs in a situation without PEVs [6]. Staats et al. [7] developed a probability load modeling methodology, which is also adopted by [8–10], and calculated the aggregated charging demand yielded by a concentration of PEV chargers. The paper modeled both the charging start time and the initial state of charge of PEVs at the charging start time as random variables, and thus dealt with the inherent randomness in PEV charging behaviors precisely. However, the paper assumed that each PEV must get recharged once every day, and would cause some irrationality since the state of charge of most PEVs is still very high after one day's travel from a full battery capacity. Fig. 1, plotted according

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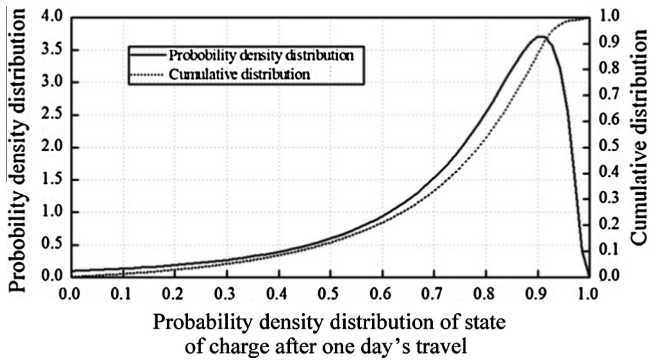

Fig. 1. Probability distribution of state of charge after one day's travel.

to the national household travel survey (NHTS) in 2009 [11], displays the probability density distribution versus state of charge of PEVs after one day's travel. The figure shows that the majority of PEVs get recharged from a state of charge of more than 0.5, and a half of PEVs even have a state of charge of more than 0.7 just before recharging. Moreover the state of charge after one day's travel with the highest probability almost reaches 0.9. Then concluding remarks can be resulted from Fig. 1 that under the condition of charging every day, a big waste exists in the utilization of battery electricity capacity of a large number of PEVs, and most users has the capability and probability to take multi-day spaced charging mode. With the development of battery technology and EV market, driving range of EVs would increase, and the arch within Fig. 1 will turn up to be higher and right shift, which means the battery utilization of EVs would further worsen under the condition of charging once every day.

Actually, the electromobile users, from the district where the authors live, barely charge their electromobiles every day. Most of them take a recharge when the state of charge of their electromobiles is too low to afford the supposed travel in the next day. Therefore the assumption of charging every day does not follow the charging willingness of PEV users to closely. Qian et al. [8] utilized the same load modeling method with [7] to analyze the impact of PEV charging on distribution systems under various scenarios. The difference is that Qian et al. accounts for the effect of the time span in number of days between recharges. Nevertheless the paper made the simplification that the same charging frequency, i.e. once every day or once every two days, was set to all PEVs. In fact, the daily travel distance differs among PEV users in a broad value range [8], and so does charging frequencies in most cases. And thus the consideration on charging scenarios in [8] is not enough and accurate to depict the actual situation of charging behaviors. Besides, charging scenarios other than charging every day has not been concerned yet in published literature except [8].

This paper puts forward a new strategy for modeling the charging power demand due to large-scale PEVs on a residential distribution network. The difference of the charging frequency, along with the inherent randomness of PEV charging behaviors, is elaborately and thoroughly considered in the strategy. Charging willingness of PEV users is another important factor considered, and has a decisive effect on the charging frequency. After the account of charging willingness, a different amount of charging demand due to PEVs will take place from weekday to weekday. The charging load models resulted can help to reveal the hourly charging power demand due to PEVs on each weekday, which is essential and important for utility companies to analyze the impact of PEV charging demand on the power system load, to reinforce the network duly and felicitously, and to arrange power reserves in response to PEV charging load to maintain the frequency and voltage of the power system.

This paper is organized into five sections. A detailed classification on PEV users derived from the historical data on users' driving patterns is conducted in Section "A detained classification on PEV users". The classification is a foundational preparation for establishing the PEV charging load model and calculating the number of PEVs getting recharged on each weekday. Section "Charging demand on each weekday" illustrates the charging power demand modeling method, and figures out the charging loads on each weekday. Case studies and simulated results based on the load profile on a winter day in Manitoba Hydro, Canada is presented in Section "Example system and simulation". The final section provides the conclusions on the proposed charging load modeling strategy and the impact of PEV battery chargers on the distribution network.

A detained classification on PEV users

As mentioned in Section "Introduction", charging frequencies differ among PEV users generally. The PEV user classification in this section is aimed to aggregate PEV users with the same charging frequency into a set and achieve the convenience that the charging load of PEV users in the same user set can be calculated by the same probability model. According to the NHTS in 2009, the daily travel distance of 91.4% household vehicles is less than 80 miles, and 14% household vehicles won't be used at all within a day. 80 miles is a currently typical value of PEV driving range [7,12], and is adopted in this paper too. Since a long-time normal charge at night can charge an empty PEV to a full capacity [8–10,13], then 91.4% PEV users can meet their daily charging requirement through the outlets at residential buildings. Moreover with the future development of the battery technology, the PEV driving range and charging power will probably grow gradually, and consequently more and more users can choose the outlets at residential buildings as the charging infrastructures. In general, there exist three kinds of charging infrastructures for PEVs, namely public built charging stations, scattered charging piles, and the common outlets in residential and workplace buildings. The optimum one for PEVs to recharge are the outlets in residential buildings for the sake of convenience for performing charging, sufficiently long parking time for uninterruptedly charging, and less impact on power distribution system by adopting the normal charging mode with comparatively small charging power [14]. This paper only studies the characteristic of PEV charging load on residential areas, and charging at residential buildings is the only charging mode concerned.

Commuting and business travels accounts for the majority of users' daily vehicle travel miles [15]. It is assumed that the daily travel distance of each individual PEV user is fixed on weekdays based on the fact that the commuting and business travels of each weekday are almost the same. In the meantime, the usage of PEVs on weekends is more arbitrary and unexpected, and thus the charging demand on weekdays and weekends should be calculated according to different probability load model. This paper only accounts the charging demand on weekdays, and the charging demand on weekends will be studied in authors' future work.

After the usage of several non-recharging weekdays, PEVs may fall into a dilemma that the battery remainders can't afford the routine travel in a following day, and have to get recharged. This dilemma, along with the ending of the working period within a week, is the only two conditions that can arouse charging willingness in this paper, and PEV users won't charge their vehicles until they have charging willingness. In this way, PEV users with a small daily travel distance won't perform charging every day any more. For the sake of convenience, the authors define the dilemma that the battery remainders can't afford the routine travel in a following