Analysis of the Influence of Electric Vehicle Access on the Power Flow and Voltage of Distribution Network

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Abstract. Due to the load characteristics of electric vehicles (EVs), a large number of charging and replacing power stations connecting to the power grid will have certain influence on the power grid. Therefore, it is necessary to study the impact of EV access on the distribution network power flow and voltage. This paper analyzes the charging and discharging behavior characteristics of electric private cars and the influence factors of vehicle charging load, and proposes a charging method modeling method for EVs considering different charging and discharging behaviors. This method can simulate the charging behavior habits of EV users. According to the data of private car travel in a city in 2018, taking the IEEE33 node system as an example, the distribution network model of EV access was established by using MATLAB software. This paper analyzes the influence of EV access on the distribution network under two charging modes, including transformer load, line current and node voltage, which provides references for the development planning of EV and the coping strategy of the power grid.

Introduction

In recent years, with the popularization of EVs, the problems of distribution network power flow and voltage quality caused by large-scale EVs accessing residential areas have gradually attracted people's attention. In order to give full play to the advantages of EVs in the distribution network and try to avoid the negative impacts on the distribution network, it is necessary to analyze the main impacts on the distribution network after the access, so as to provide references for EV planning and response strategies of the grid.

The prediction and modeling of EV charging load is the basis for studying its impact on the distribution network. Literature [1] studied the charging and discharging probability distribution characteristics of EVs by abstract fitting the measured data based on the measured data. Literature [2] studied on the probability of charging and discharging behavior of EVs based on Monte Carlo algorithm, and a model is established to analyze the random characteristics of EVs charging and discharging. Literature [3] established mathematical models such as charging power and daily mileage of EVs, and studied the cluster characteristics of a large number of electric vehicles based on Monte Carlo algorithm. The literature [4-7] deeply analyzed the electric vehicle scheduling strategy, and the modeling method considering the behavior of electric vehicles is proposed. At the same time, the uncertainty caused by the changes in the demand of EV users is analyzed. Literature [8] analyzed the impact of EV charging and discharging behavior on the grid load. Literature [9-11] established the charging and discharging modes of EVs and analyzes their impact on the distribution network. Literature [12] introduced the development prospects of the impact technology of electric vehicles from the aspects of electricity companies and power grid operations.

In this paper, the factors affecting the charging and discharging behavior of electric private cars and the charging load are analyzed. Based on the data of private cars in a city in 2018, the corresponding
charging modes and charging periods are studied, an EV charging load modeling method considering different charging and discharging behaviors is proposed. Taking the IEEE33 node system as an example, the distribution network model of EV access is established by using MATLAB software. The effects of EV access on transformer load, line current and node voltage of distribution network are simulated and analyzed.

Analysis of Charging and Discharging Behavior Characteristics of EVs

Electric vehicles are subject to user behavioral habits and exhibit different charging and discharging behaviors. Large-scale EV access will also influence the operation of the distribution network, and these effects are closely related to the charging behavior of electric vehicles [4-7]. The main characteristics of electric vehicle charging behavior include:

Electric Vehicle State of Charge

The state of charge (SOC) is the percentage of the battery's current state divided by the maximum amount of power the battery can store. According to the SOC of the vehicle power battery pack, it is possible to predict the cruising range of the EV and control the maximum discharge current of the battery. The start charging SOC of the EV indicates the percentage of remaining battery power when the EV starts charging, and is recorded as $SOC_{st}$; The EV end charging SOC indicates the percentage of remaining battery power when the EV ends charging, and is recorded as $SOC_{en}$.

Daily Average Mileage of Battery Vehicles

The general EV power consumption is positively related to the average driving mileage, which is expressed by the formula:

$$Q_{exp, day} = S_{avr, day} \cdot W_h$$

$Q_{exp, day}$ daily power consumption; $S_{avr, day}$ average daily mileage (km), $W_h$ electricity consumption per kilometer of EVs.

EV Cruising Range

d$_{max}$. The cruising range indicates the maximum achievable mileage of an EV when it is healthy and fully charged.

Time to Start Charging EV

$T_{st}$. It indicates the time when the EV starts charging.

Time to End Charging of EV

It indicates the time when the EV ends charging. Electric private cars are limited by the cruising range, and are rarely used for long-distance travel. Most of them are used for daily work, short-distance travel, leisure, etc., and the charging locations are mainly residential areas or unit parking lots. According to the data of a city's 2018 annual traffic development report, Departure time of private car workday is mainly concentrated in 06:00-09:00 p.m. and 4:00-7:00 a.m.; Arrival time of private car workday is mainly concentrated in the morning 07:00-10:00 and afternoon 16: 00-19:00. As shown in Figure 1.
In terms of mileage, according to the statistics of the city's Transportation Development Research Institute in 2018, the average annual mileage of private cars is 11968 kilometers, of which the annual average mileage is less than 10,000 kilometers, accounting for 51.9%. The average daily travel distance on the working day of private cars is 31.3 kilometers, of which the average daily travel distance is 28.3 kilometers, and the average daily travel distance on the holiday is 37.8 kilometers. The months with higher average daily mileage on the working day are February, July, August, and September; the months with lower average daily mileage are January, March, November, and December. The daily travel distance distribution on each working day is shown in Figure 2.

Modeling Method for Charging Load of EVs Considering Different Charging and Discharging Behaviors

Analysis of Factors Affecting EVs Charging Load

The number of EVs, as well as the daily mileage and the start of charging time, are important factors impacting the charging load of EVs. Among them, the daily mileage of the EV determines its start charging SOC and assuming that the battery is fully charged after the last period of charging, the start charging SOC of the EV is:

$$SOC = \left(1 - \frac{d}{d_m}\right) \times 100\%$$  \hspace{1cm} (2)

Among them, SOC is the initial charging SOC of the EV; d is the daily driving mileage of the EV; and $d_m$ is the cruising range of the EV in the fully charged state.

According to the US Department of Transportation's family vehicle driving survey data, the daily mileage of private cars is approximately obeying a lognormal distribution, and the probability density function is:
\[ f(d) = \frac{1}{d \sigma^d \sqrt{2\pi}} \exp \left( -\frac{(\ln d - \mu_d)^2}{2\sigma_d^2} \right) \]  

(3)

Among them, \( \mu_d \) and \( \sigma_d \) represent the logarithmic mean and logarithmic standard deviation of the daily mileage of the electric private car.

For the start charging time of electric private cars, there is a large amount of literature using normal or even distribution, but there is a certain gap with the real situation. Under normal circumstances, electric private car users will return home as soon as possible after work in the evening, or a small number of users will replenish EV power after arriving at home during the lunch break. It is assumed that the car owner will charge the electric car immediately after returning home, then the start charging time of the electric private car is similar to the lognormal distribution, whose probability density function is:

\[ f(t) = \frac{1}{t \sigma_t \sqrt{2\pi}} \exp \left( -\frac{(\ln t - \mu_t)^2}{2\sigma_t^2} \right) \]  

(4)

Among them, \( \mu_t \) and \( \sigma_t \) are the logarithmic mean and logarithmic standard deviation of the start charging time distribution of the electric private car.

**EV Load Calculation**

In this paper, Monte Carlo algorithm is used to simulate the charging load of EV. Firstly, the electric private car arrives at home time and mileage, and then calculates the starting charging time and charging time duration, obtains the charging load of the car, and finally superimposes all charging loads to obtain the total charging load. The calculation process of EV charging load is shown in Figure 3.

The specific calculation process of the EV charging load is as follows:

**Take the Electric Private Car to Start Charging Time.** Assume that the owner of the EV is charged immediately after returning home. According to formula (4), the Monte Carlo algorithm can be used to obtain the starting charging time of the electric private car.

**Extract the Daily Mileage.** The daily mileage of the electric private car can be obtained by the Monte Carlo method by the formula (3).
Calculate the Charging Time According to the Driving Mileage. Assuming that the EV performs constant power charging, the charging power and charging time period of the EV can be calculated.

**Charging Power.** The EV is charged with a constant power $P$ during the charging period, and a total charging load curve is obtained by all EV charging load superimposed. The charge load calculation interval is 1 minute, a total of 1440 minutes a day. Total charging load at the $i$-th minute is the sum of the charging loads of all vehicles at the moment, and the total charging power is:

$$P_{Li} = \sum_{n=1}^{N} P_{ni}$$

Among them, $P_{Li}$ is the total charging power for the $i$th minute, $i = 1, 2, ..., 1440$; $N$ is the total number of EVs; $P_{ni}$ is the charging power of the $n$th car at the $i$-th minute.

**Simulation Analysis**

**Simulation Model Construction**

This paper constructs a residential community network model based on the IEEE33 node system. The residential community network structure is usually radiative. It is powered by one or several 10kV feeders. Considering a medium-to-high-end residential area of 1,800 households, the load will generally not exceed 10MW. The structure is shown in Figure 4.

![IEEE33 node power distribution system wiring diagram.](image1)

The load difference of residential areas in different time periods is large, and the full-day load curve is shown in Figure 5.

![residential area load curve.](image2)

There are 1,800 residents, assuming that each household owns one car, and the penetration rate of EVs considers 10%, 30% and 50%. Suppose that there is a charging post on the low voltage side of the 10kV transformer of the m nodes of nodes b1, b2, ... bm. The number of EVs served per charging pile is calculated by equation (6):

$$n = \frac{1800 \cdot p}{m}$$

Among them, $p$ is the permeability, $m$ is the number of nodes connected to the charging post.
In this paper, two scenarios of electric steam user behavior are discussed:

**Extreme Situation.** Assume that all EVs in the community are charged at the same time. Investigate the ability of 10kV feeders to meet the changing needs of EVs in extreme situations.

**General Situation.** Assume that the electric car user charges immediately after returning home from work until it is full. The time distribution and driving distance of EV users arriving from work refer to the data given by a city's 2018 traffic development annual report, including the distribution of departure and arrival time of private car work, and the daily travel distance of each month, as shown in Figure 1 and Figure 2. As shown, the charging load of the EV is calculated. In this mode, the influence of EV charging in residential areas on the steady-state characteristics of the distribution network can be examined.

**Access Impact Simulation Analysis**

Taking the IEEE33 node system shown in Figure 4 as an example, the influence of EV access on the power flow and voltage of the distribution network is analyzed. The load distribution of each node in the residential area is shown in Figure 6.

![Figure 6. Load of each node in residential area.](image)

In the simulation, the EV penetration rate is set to 30%, the EV has a total of 540 vehicles, the single charging power is 3.3kW, and the charging load is 1782kW. The total load of the IEEE 33-node power distribution system when not connected to the EV is 5084.26 kW. Four EV charging stations are provided, which are respectively connected to the nodes 10, 12, 20, and 28.

Set two charging modes:

**Mode 1.** Start charging immediately after getting home from work;

**Mode 2.** Charging when arriving at work and arriving after work.

**Analysis of the Influence of EV Accessing Distribution Network on Power Flow**

At 30% penetration, the load change of the residential 10kV substation is shown in Figure 7.

![Figure 7. Node 28 Transformer load.](image)

Comparing Figure 6 with the cell load curve before the EV is connected, it can be seen from Fig. 8 that the charging mode 1 and mode 2 of the EV will have a great influence on the distribution network, especially the peak load. In Figure 8, the maximum load of one day is above 900 kW, and the
transformer on this node may have an overload problem. In charging mode 2, the user behavior of the EV causes two load peaks to occur. In the future, when the penetration rate of EVs in the residential area is higher, if there is not enough charging power station, the peak on the node where the charging power station is installed will be too high, which may cause overload of the transformer and cause great harm to the power grid. The charging station should be reasonably constructed according to the penetration rate of the EV.

Under the same permeability, the influence of EVs on the line load of the distribution network at 20:00 at the peak load of the day is analyzed. The node load waveform with the charging station is shown in Figure 8.

![Figure 8. Load of the node with the charging station.](image)

It can be seen from the figure that the node load of the EV is increased much more than before the access, and a total of 1782 kW is added.

The current waveform of each line before and after the EV is connected is shown in Fig. 9.

![Figure 9. Current waveform of each line.](image)

It can be seen from Fig. 9 that after the EV is connected, due to the sharp increase of the load of the charging station node, the current of most nodes in the distribution network is increased. There are also some node currents that have not changed, or have little change. This is because the nodes on which these nodes are located do not have charging stations, are not affected by the access of EVs, or have less impact. It can also be seen from the figure that although there is access to the EV, the current at the node at the end of the distribution network is not greatly affected, and the current is basically unchanged, while the node at the front end of the distribution network is affected by the EV, and the impact is greater and the current is increased a lot.

**Analysis of the Influence of EV on Node Voltage of the Distribution Network**

The distribution voltage load data at 18:00 is used to analyze the node voltage after the EV is connected to the distribution network. The simulation results are shown in Figure 10.
It can be seen from Fig. 10 that compared with the EV not connected, the voltage of the distribution network node of the EV is decreased, and the voltage of some nodes is excessively dropped, which is caused by the overload of the distribution network. In order to maintain the stability of the voltage, a certain reactive power compensation can be performed.

Summary

This paper analyzes the charging and discharging behavior characteristics of electric private car and the impacting factors of charging load, and proposes a charging method modeling method for EVs considering different charging and discharging behaviors. On this basis, based on the data of private car travel in a city in 2018, taking the IEEE33 node system as an example, the model of EV access distribution network was established, and the influence of EV access on power flow and node voltage of distribution network was simulated. Simulation results show:

(1) The EVs will have a great impact on the distribution network, especially the impact of load peaks. The node load of the substation is increased sharply after the EV is connected, and the transformer of the node where the charging station is located may be overloaded with the increase of the permeability. The current of most nodes in the distribution network increases, and the load on the front node of the distribution network increases more. The current at the node at the end of the distribution network is not affected much. The charging station should be reasonably constructed according to the penetration rate of the EV.

(2) After the EV is connected, due to the overload problem of the distribution network, the voltage of the distribution network node has decreased, and the voltage of some nodes has dropped greatly. In order to maintain the stability of the distribution network voltage, reactive power compensation can be performed.

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