EV Charging and Its Applications in Active Distribution Systems

Qiushuo Li, *Student Member, IEEE*, Xiangning Xiao

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources
North China Electric Power University
Beijing, China

***Abstract*—With the development and popularization of electric vehicle (EV), impacts of large-scale of EV charging to the power system have emerged, especially to the distribution systems. In the framework of smart grid, wide integration of renewable energy and distributed generators has posed new challenges to construction and operation of power system. How to integrate EVs into active distribution systems has become a problem which needs more focus and attention. In this paper, firstly, load model of single EV charging is derived and harmonic currents are presented upon actual measurement data. Based on operation data of an EV charging station, effect of EV charging on the total load curve is analyzed secondly. Considering human behavior, the features of EV charging compared with conventional loads are summarized. In the end, combining features of EV charging and active distribution systems, applications of EVs in active distribution systems are explored. It can be expected that integration of EVs will play an important role in active distribution systems in improving the shock resisting ability of power system, increasing operation efficiency and renewable energy penetration, as well as reducing construction cost.**

***Index Terms*—electric vehicle, active distribution systems, controllable load, power balance**

I. INTRODUCTION

With the development of human society, the need for energy is soaring, while fossil fuel such as coal, oil and natual gas is exhausting. Also, the emission of CO_2 and other greenhouse gas and global warming comes into our view. According to a survey, approximately 1540 barrels of oil is consumed everyday in U.S., of which 2/3 is for vehicles [1]. In 2009, 94% of U.S. transportation energy came from fossil oil [2]. Soaring oil price caused by the reduction of oil reserve, fast development of technologies on electric driving system, energy supply as well as the smart grid, provides powerful impetus for the rapid popularization of EVs [3]-[4]. To achieve the environmental protection goals, EVs are expected to account for 10 percent of the total amount of vehicles in Scotland in 2020 [5]. In the United States, the sales volume of battery electric vehicle (BEV) is expected to account for 12 percent of that of all registered vehicles in 2025 [6]. As an energy-efficient, low-carbon and environmental friendly traffic tool, EV is expected to be more and more popular in the future.

When population of EV reaches a certain scale, charging load will bring impacts on the construction, operation and economy of distribution systems. In China, distribution capacity designed for urban residents is $60W/m^2$, which means that a $100m^2$ urban household will possess up to 6kW of distribution capacity. If a resident owns an EV, it needs 5kW extra electric power supply. Suppose one household in three owns an EV, it requires 25% additional capacity in the distribution network. Besides, compared with conventional loads such as induction motors, heating loads and electronic equipments, EV charging load has many different features. Therefore, effects of EV charging load on the power system should be paid enough attention.

On the 21st Conference International Repartition et Distribution (CIRED), active distribution systems excited attention of the conferees. In active distribution systems, wide application of intelligent devices makes distribution networks intelligent and informational; adoption of distributed generators shortens distances from generators to load centers, which fundamentally reduces power losses; integration of renewable sources provides cleaner energy; structure of distribution systems evolves from a radial one to a mesh so that the grid structure is strengthened and reliability of power supply is also increased [7]. EV charging load has some special features. Based on these features, large-scale of EV charging provides new perspectives.

Research on the effects of EV charging has started as early as 1980s'. Heydt found out that the peak of charging load was likely to overlap the peak of grid load, and there was a need for load management to avoid overload [8]. Heider expanded the Heydt's finding and showed that if there were not enough

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charging infrastructures, peak load would increase further [9]. Kristien Clement-Nyns holds that in case of disordered charging, charging of EVs may aggravate fluctuations of power load, thus leading to power losses and economic deterioration [10]. S. W. Hadley and P. Denholm did some research and analyses on the development of the electronic vehicles and its influence on the distribution network [11]-[12]. While Kejun Qian predicted the effects of a large-scale of EVs on the grid load by establishing load model of EV battery on condition of disordered as well as peak-shift charging [13]. Since 2011, the research of EV charging has no longer been limited within its effect on the power system, but also expanded to the methods of ordered charging. Eric Sortomme introduced optimization methods to obtain an optimal charging plan. Three objective functions were given and calculation result was analyzed in his paper [14]. Di Wu and Dionysios C. Aliprantis proposed the method of making charging plans by using ladder electricity price, which furthered the research into single charging load [15]. However, as the electricity price cannot alter smoothly, it probably causes higher load peak since users may start charging at the same moment. In addition, [16]-[19] discussed the influence of the users' charging demand on the load. In Japan, Toshihisa Funabashi and Tomonobu Senjyu did some research on controllable loads and their effects on the distribution network [20].

In the above-mentioned research, the features of EV charging load, human behaviors and the characteristics of active distribution systems and renewable energy are isolated. As there are few EVs that has been put into use, EV charging data is scarce, therefore research on this field depends mainly on theory analysis and simulation. In this paper, based on actual measurements of single EV charging and operation data of a charging station, static model of EV charging is derived, harmonic currents are presented, and impacts of EV charging to system load are also explained. By summarizing features of EV charging, and combining them with human behavior and characteristics of active distribution systems, conjunction point between EVs and active distribution systems is analyzed. Applications of EVs in active distribution systems are explored in the end.

II. CHARACTERISTICS OF SINGLE EV CHARGING LOAD

A.Static Mathematical Model of Single EV Charging Load

Charging power of an EV can be influenced by the following factors: battery characteristics, charging control mode, and efficiency of the charger.

First consider battery characteristics. From the perspective of circuit theory, battery can be regarded as a branch consisting of a potential in series with a resistance. Ignoring the influence of temperature, internal resistance r will be a constant. And internal potential E is determined by state of charge (SOC). Thus the $V-I$ relationship at the port of battery can be described as

$$V_O = E(SOC) + Ir \tag{1}$$

Where V_O is the port voltage, and I is the current injected into battery.

Fig.1 shows the relation curve between the potential E and SOC of a battery. The relationship can be described in function form by function fitting. Applying the fitted function and Eq.1, we can obtain the $V-I$ relation of charging and discharging.

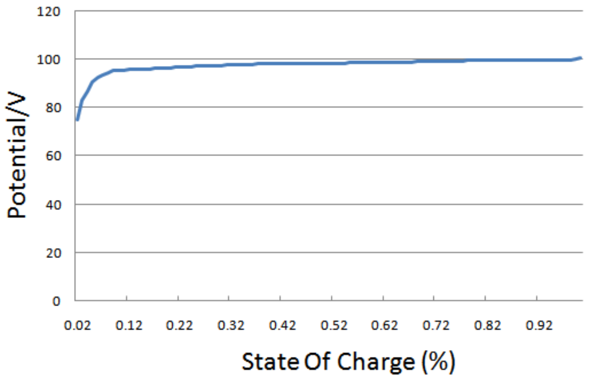


Fig.1 $E-SOC$ Relation Curve

In the earlier period of charging, the SOC is low, constant-current (CC) mode is adopted so that charging current will not be very large. When the SOC goes higher, charging mode changes into constant voltage (CV) to avoid high voltage.

In the CC mode, the relationship between SOC and time t can be describe as

$$SOC(t) = SOC_0 + \frac{It}{Q_N} \tag{2}$$

Where SOC_0 is initial state of the battery, I is the constant charging current, Q_N is the rated capacity of battery. The power injected into the battery is

$$P_{B-CC}(t) = V_O(t) \cdot I = [E(SOC_0 + \frac{It}{Q_N}) + Ir] \cdot I \tag{3}$$

In the CV mode, the $SOC-t$ relationship can be describe as

$$SOC(t) = SOC_0 + \frac{\int_0^t \frac{V - E(SOC(t'))}{r} dt'}{Q_N} \tag{4}$$

Where V denotes the constant charging voltage. By solving Eq.4 we get $SOC(t)$. Thus, the power injected into the battery is

$$P_{B-CV}(t) = V \cdot I(t) = V \cdot \frac{V - E[SOC(t)]}{r} \tag{5}$$

It can be seen that when r and the charging mode is determined, the power injected into the battery at each point wholly depends upon SOC. Static power is not influenced by the system voltage as long as the system voltage can meet the charger's requirements.

The active power loss during charging cycle includes fixed loss and the one proportional to the charging power. So active power flowing into charger is

$$P_{Ch\arg} = P_B + \eta \cdot P_B + P_{fL} \tag{6}$$

Where η is a ratio, P_{fL} is the fixed power loss, P_B is the power injected into the battery. In the CC period P_B equals P_{B-CC}, and in the CV period P_B equals P_{B-CV}.

Reactive power consuming depends on the charger's state, topological structure and control method. It differs among chargers. Experiment result shows that chargers using pulse-width modulation (PWM) rectifier can keep their power factor above 0.99 during the charging cycle, while power factor of the ones using diode rectifier and power factor correction (PFC) decreases because of active power reduction during the CV period.

Using the mathematical model above, simulation program calculated a load power curve of EV charging. Comparing it with experimental data, the result is presented in Fig.2. The $E-SOC$ relationship of the battery is shown in Fig.1. Adopting CC-CV charging mode, the current in CC period is 60A, and the voltage in CV period is 101.6V. Fixed loss of charger P_{fL} is 0.3kW, and ratio η is 0.047.

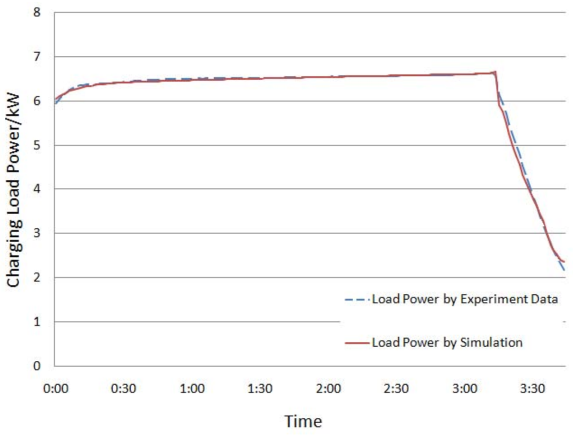


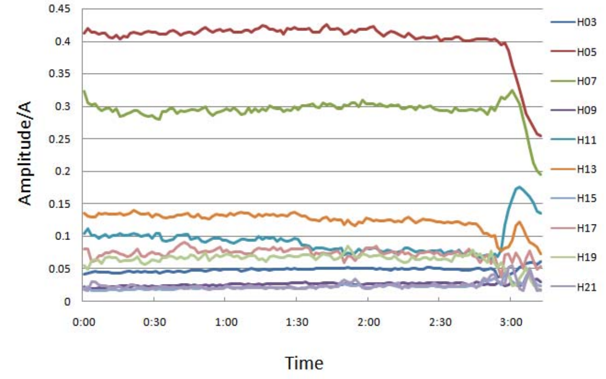
Fig.2 Comparison of Load Power Between

Model Simulation and Measured Data

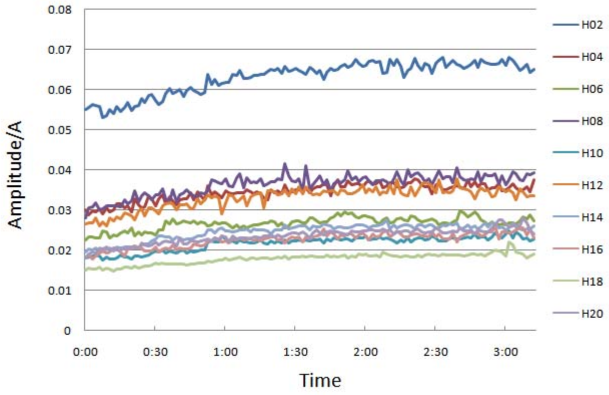
Obviously, in Fig.2 it can be seen that the simulation result almost coincides with the experimental data. The accuracy of the static mathematical model is proved.

B.Harmonics of Single EV Charging Load

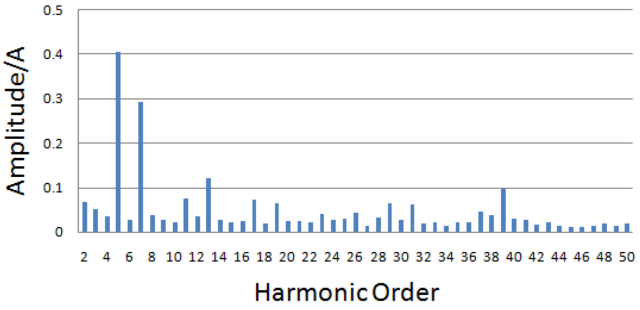
As a power electronic converter, chargers cannot get rid of harmonics. The system voltage is determined by distribution network, and it is supposed to be constant. Thus harmonic characteristics of a charger depends on its power. For the charger whose maximum charging power is 7kW, the total harmonic current is about 0.58A per phase, and it does not change in the whole charging cycle. Root-Mean-Square (RMS) values of each harmonic current in phase A during the charging period are shown in Fig.3(a) and (b), and its frequency spectrum at the time of maximum power moment is shown in Fig3(c).



(a) Odd Harmonics



(b) Even Harmonics



(c)Frequency Specturm at t=3:15

Fig.3 Harmonic Currents of Single EV Charging

From Fig3, we can see 5th and 7th harmonics are the most serious components, and odd harmonics are higher than even ones. In general, amplitudes decrease with the incerase of harmonic order, and components on 3k (k=1,2,3...) orders are relatively less than the other odd orders. This phenomenon is caused by the topological structure of the charger as shown in Fig4. The charger has three converting modules in it, and each module is supplied with a line-to-line voltage. Angel connection sheme is applied and neutual line is not connected. So the harmonics which has zero-sequence characteristics are restrained.

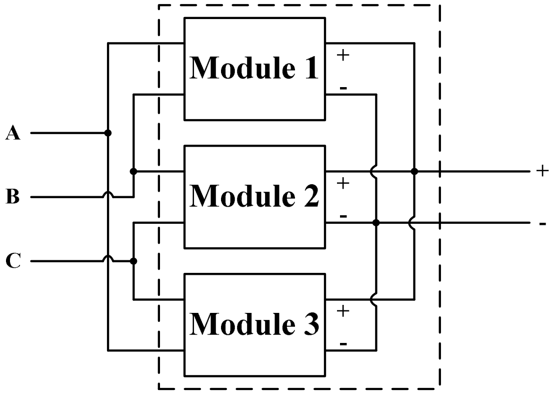


Fig.4 Structure of the EV Charging

Besides, amplification on some high order harmonics appeared in the experiment. This phenomenon can be observed in the whole charging cycle. As shown in Fig.5, harmonic components at 7500Hz and nearby is much larger. High order harmonics can be easily filtered. But if not given enough attention, they may cause serious accident such as damages to other equipments.

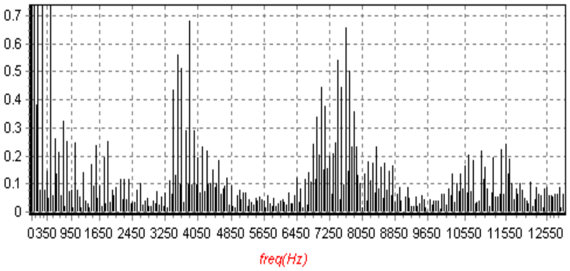


Fig.5 Frequency Spectrum of High Order Harmonics

III. Impacts of EV Charging to the Power System

Operation data of one EV charging station in China is collected. The charging station serves for 80 electric taxies and each charger has a maximum charging power of 6kW. According to statistics, a representative daily charging load power curve of the charging station is shown in Fig.6.

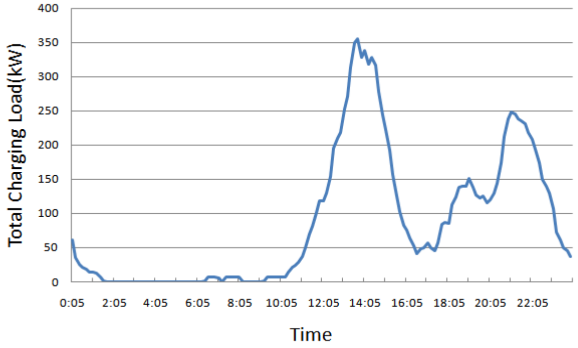


Fig.6 Representative Daily Charging Load Power Curve of Charging Station

At present, charging time is decided by users. Charging service begins when an EV is integrated. It can be seen in Fig.6 that there are two major peaks on the load power curve every day. One is from 12:00 to 15:00 in the afternoon, and the other is from 20:30 to 22:30 in the evening. The peak load in the day time is higher than that in the evening. This is caused by human behaviors. Drivers will park their electric taxies in the charging station overnight and charge to prepare for the next day. Usually an EV can run 80-100km on average after fully charged, which means electric taxies require energy supply in the daytime. Most of the drivers would like to charge their taxies in the lunch break. So charging time in the daytime is more concentrated compared with that in the evening. This results in the higher peak load in the daytime.

Comparison of load power curve with and without EV charging is presented in Fig.7. Before EVs are integrated, peak power is 1730kW, difference between peak and valley power is 1232.2kW, load factor is 0.688. When EVs are integrated, the peak load rises to 1968kW, the difference between peak and valley power rises to 1470.2kW, and the load factor decreases to 0.651. EV charging worsens operation of the distribution network, and the power in the valley period is not made full use of. In this case, total charging power is not quite large comparing with the power of conventional load. If there are more EVs, the condition will be even more serious.

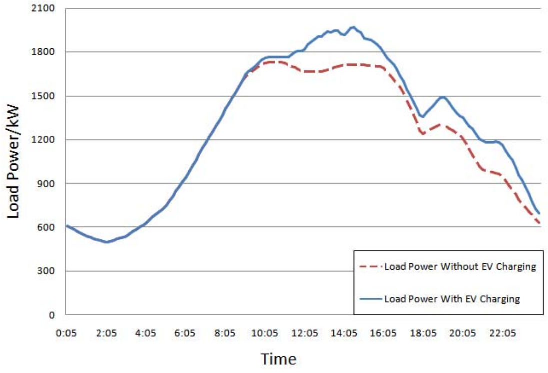


Fig.7 Comparison of Load Power Curve Between

with and without EV Charging

IV. FEATURES OF THE EV CHARGING LOAD

As a special kind of electric load, comparing with conventional loads, EV charging load has many features.

- First, users focus on different aspects. For most conventional loads, such as lighting, motors, and electronic devices, users are sensitive to load power at every moment. But for EV charging load, users care about the energy provided by power system over a period of time.
- Second, when adopting trickle charging, it will take several hours. Users will leave and do some other things or charge in the night. That means the time EVs connected in the distribution network is much longer than that required for charging.
- Third, chargers are power electronic converters. So its active and reactive power can be adjusted rapidly.
- Finally, as an energy storage device, with appropriate regulation, batteries in EVs can feedback energy to the power system when necessary.

The first and second features allow EV chargers to be regulated by power system, so that they can give positive effects to the system. The third feature gives EV chargers ability of stabilize power fluctuations in the power system by rapid alteration of their own power. And the final feature makes EV batteries be treated as distributed generators or emergency sources. Summing on the four features above, integration of EVs brings new ideas and development space to operation and construction of distribution systems.

V. APPLICATIONS OF EV IN ACTIVE DISTRIBUTION SYSTEMS - ORDERLY CONSUMPTION OF ELECTRIC ENERGY

In distribution systems, power of load is determined by users. When there are no EVs integrated, active power balance can be achieved only by generators and energy storage devices, and reactive power compensation depends on additional compensation devices. With EVs integration, their abilities of energy feedback, active power adjustment and reactive power compensation provide new power balance methods.

In conventional distribution networks, as the ability of monitoring and regulation is limited, real-time control can be hardly achieved. Thus, a time-shift method is adopted. Based on load forecast, charging is shifted in the permitted period to make best use of power in the valley duration so that higher peak load can be avoided. Since charging is under schedule, if load forecast deviates far from actually, or there are unexpected power fluctuations, this regulation method cannot perform a satisfactory response.

In active distribution systems, integration of renewable energy causes fluctuations to active distribution networks. How to deal with these fluctuations and make the best use of renewable energy is an important issue. Meanwhile, installation of intelligent meters and control devices makes achievement of real-time regulation possible.

On the perspective of economic operation, in the real-time regulation situation, rapid load power alteration of EV charging is used to stabilize the total load of each distribution node in a period of time. Hence the distribution network operates in several steady and economical states. By altering the operation condition at some set intervals according to actual operation situation, energy demand of EVs can be met. With this regulation, in the adjustable range of EVs, load power at each nodes and power flow in each transmission lines remains in ideal states. Meanwhile, this regulation does not rely on accurate load forecast, and it can easily copy with unexpected power disturbance. EVs perform like many decentralized storage devices at different nodes and make up a large energy storage capacity in the distribution network. This also means construction of expensive storage devices can be greatly reduced.

On the perspective of system security, without EVs integration, active power balance is completed by storage and sources. Power fluctuations spread in the distribution network to these nodes even the point of common connection (PCC) with the main grid, which might influence the operation of the main grid and the generators connected nearby. If a disturbance occurs at the node far away from sources, storage and the PCC, it will transmit a long distance, and affect the other nodes. In this situation, defense of the distribution network is point-to-point, which is inelastic and short of depth. After integration of large-scale of EVs, benefitting from their dispersibility, every node has the ability of power balance. As a result, power fluctuations can be balanced locally or in a small range with the help of the nodes nearby. Even though there is no source or storage, the disturbance will not affect the nodes far away. The distributed power balance ability achieves better performance than centralized storage in large capacity. In this case, defense against power fluctuations is solid, elastic and with depth. In addition, improvement on the ability of withstanding power fluctuations will increase penetration of renewable energy in active distribution systems.

However, there are still many problems to be solved on cooperation between EV charging and power systems. For instance, a conventional energy storage device has a certain capacity, while adjustable range of EVs is variational because the power is not constant during charging cycles and state of battery in each EV is various. In real-time regulation mode, how to distribute power among chargers? Further research is required to deal with these problems.

VI. CONCLUSIONS

In this paper, a static mathematics model of EV charging is derived, and comparison is made to prove its accuracy. Harmonic currents are shown and high order harmonic phenomenon is discovered. According to operation data from charging station, negative effects to the power system by disordered EV charging are presented. Then through comparing with conventional electric load, four features of EV charging load are summarized. Combining the four features and characteristics of active distribution systems, taking the adjustable ability of EV charging as conjunction point, applications of EVs in active distribution systems and ordered consumption of electric energy are analyzed. With rational regulation, EVs will play an important role in increasing stability, economy and penetration of renewable in active distribution systems.

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