The Interaction Research of Smart Grid and EV Based Wireless Charging

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***Abstract*—As an important part of the smart grid, Electric Vehicles (EVs) could be a good measure against energy shortages and environmental pollutions. By wireless charging technology, the interaction between EVs and the grid could be achieved without physical link. In this paper, the interaction capability of the EVs based wireless charging and the smart grid is mainly studied. The results of numerical simulations show that the EVs based wireless charging could better absorb renewable energy and reduce the impact of large-scale EVs application on the power distribution system. Finally, a four-layer framework of V2G system is designed for the EVs based wireless charging.**

***Index Terms*--Distribution System, EVs, Interaction, Smart Grid, Wireless Charging**

I. INTRODUCTION

Over the past decade, many issues such as energy shortages, serious environmental pollutions and global warming have become increasingly significant and EVs have emerged as a new traffic tool. Compared with internal combustion engine vehicles (ICEVs), which burn fossil fuels, EVs, only using electricity while running, have a great advantage in solving the energy crisis and reducing the emissions of carbon dioxide, as well as a means of drastically reducing the man-made pollutions in the environment. More and more governments, car manufacturers and energy companies are getting active in development and production of EVs. July 9, 2012, China's State Council officially promulgated the "energy-saving and new energy automotive industry development plan (2012-2020)", and clearly pointed out that pure electric drive would be the main strategic orientation of the auto industry restructuring plan and the development of the automotive industry would focus on promoting the industrialization of Pure Electric Vehicles (PEVs) and Plug-In Hybrid Electric Vehicles (PHEVs) with the cumulative production and sales reaching 500000 by 2015, and up to 5 million by 2020.

With the large-scale introduction of EVs, the power grid will face a major challenge. And then many domestic and foreign scholars have carried out the study on the impact of EVs on power distribution system [1]-[3]. As an energy storage bank, V2G technology, which uses EVs to store and supply energy back to the grid, is gaining more and more popularity and researches and makes it possible to achieve the bidirectional flow of energy between EVs and the power grid [4][5]. However, in most of the reference the impacts and interactions of EVs on the power grid are carried out based on the plug-in EVs (labeled as EVs-PI). In this paper, we mainly focus on the interaction research of the smart grid and EVs based wireless charging (labeled as EVs-WC). By analyzing the characteristics of wireless charging, the advantages of EVs-WC in the interaction with the grid are expounded with numerical simulations. Finally, a four-level V2G system based on EVs-WC is designed for practical applications in future.

II. WIRELESS CHARGING TECHNOLOGY

There are two main ways of EV charging: the wired charging mode and the wireless charging mode, corresponding to the above EV-PI and EV-WC, respectively. In this paper we focus on the wireless charging mode, i.e. EV-WC.

As an emerging research field, Wireless Power Transmission (WPT) can transfer energy without direct physical link. For EVs, inductive coupling and resonant coupling are two major means of the WPT technology. In either inductive or magnetic coupled systems, power is transferred from a primary transmitter coil to a secondary receiver coil with the aid of an alternating magnetic field, stored in EV battery by the control circuit [6][7].

The WPT technology quickly became a hot pursuing topic for research institutions in recent years [8]-[10], and some further breakthroughs have been made in electric vehicles, body implantable medical devices, small robots and portable mobile device chargers. The wireless charging diagram of EV is shown in Fig. 1.

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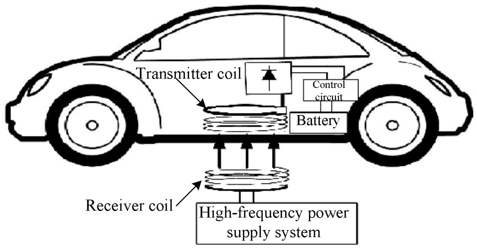

Figure 1. Diagram of EVs wireless charging system

Due to abandoning traditional plug-in cable, the WPT technology makes it easier and safer to recharge EVs. In November 2011, the first commercial test of wireless charging for EVs had launched in London by Qualcomm. It was the great progress of the EV industry and demonstrated the future direction of development of the EV charging.

III. Interactive Capability of EVs-WC

The technology of EVs switching in the smart grid is an important part of the "smart grid technology", of which the main key is that the power of EV battery could be two-way interaction with the grid in a controlled state. The greater the interactive capability, the more significant the positive role of EVs on the smart grid is. The interactive capabilities of wired and wireless charging mode with the grid are analyzed and compared as follows.

There are mainly three conditions must to be met to achieve the interaction of EVs and the power grid: 1) EV is parked at the charging station; 2) EV is successfully connected to the grid; 3) EV is set in the interaction state. Due to various reasons, each of the three conditions mentioned above is assumed to correspond to an independent variable with a percentage, respectively.

A. Parking at the Charging Station

It is necessary to park the EV at the charging station for recharging. In this paper, p_s is used to stand for the percentage of the EVs at the charging station. In the wired charging mode, we need to apply for special construction land to build the charging station. With the large-scale emergence of EVs, a large amount of land is required and this will aggravate the land squeeze in populated cities. So the number of charging station is much less than that of EVs, i.e. just a small number of EVs with the p_s of 30% at the same time could park at the charging station to participate in the interaction with the power grid. While in the wireless charging mode, it is easier to build the stations by retrofitting the existing parking space rather than applying to the government for special land. Then many EVs simultaneously could interact with the power grid and the p_s might as well set to 80%.

B. Connecting to the Power Grid

When EVs are parked at the charging station, for the interaction of EVs and the power grid, it is necessary to assure that EVs are successfully connected to the grid. The p_c represents the probability of the EVs connected to the grid at the charging station. In the wired charging mode, there is a physical link between EVs and the grid. EVs are manually connected to the grid by the plug-in cable. Taking into account the driving habits of the people and the security issues, it is reasonable for us to set p_c to 90%. In the wireless charging mode, EVs would automatically be connected to the grid once they reach to the charging stations. So the p_c is close to 100%.

C. Setting Interaction Willingness

After the EVs connected to the grid, the driver must also set the interaction willingness. The p_w stands for the possibility of driver selecting interaction, expressed as a percentage. In the wired charging mode, when parking the EVs at the charging station, the drivers must get off to plug in the socket and go back into the EVs to set the interaction willingness. This process is tedious and inconvenient, and some people maybe forget to go back for willingness setting. Meanwhile, there are at least two options for driver to choose in V2G system: charging or interacting, and it is also possible to reduce the percentage of setting interaction willingness considering the traditional concept of people and the security issues such as the exposed charging cable. So the p_w might as well set to 35% in this paper. While in the wireless charging mode, the driver could set the willingness in the EVs and it is safe to interact with the grid without the exposed cable. Compared to the wired mode, a large p_w up to 80% would be generated.

Through the above analysis, the proportion (p_A) of the EVs participating in the interaction with the grid can be derived.

$$p_A = p_s \bullet p_c \bullet p_w \tag{1}$$

Then the interactive capability can be evaluated based on the total amount of EVs and the capacity of EV battery. Full results are given in Table I.

TABLE I. Interaction Capability of Two Mode

Charging Mode	Three Conditions of Interaction			Proportion of Interactive EVs p_A (%)
	P_s (%)	p_c (%)	p_w (%)	
Wired	30	90	35	9.45
Wireless	80	100	80	64

In Table Ⅰ, it is obvious that the interaction capability of wireless charging mode is far greater than that of wired charging mode. To better illustrate the differences of two modes in the interaction capability, we predict daily interaction capability of EVs and the grid in Nanjing in 2020, given as in Table Ⅱ. It should be noted that we get the main parameters, such as the number of EVs, the battery capacity and the charging time from a SOC of 20% to full charging, from Nanjing EV Charging/ Exchanging Station Development Plan of "12th Five-Year".

TABLE II. INTERACTION CAPABILITY IN 2020, NANJING

Charging Mode	Maximum Daily Interactive Capacity (MWh)	Maximum Daily Interactive Power (MW)
Wired	1587.6	264.6
Wireless	10750	1791.7

IV. ADVANTAGES OF EVS-WC

Due to the great interaction capability, EV-WC plays a more significant role of the smart grid.

A. Better to Suppress the Fluctuations of the Output of Renewable energy

By the designed intelligent interaction system to set a reasonable strategy of EV charging, EVs-WC could use to absorb more renewable energy and suppress the fluctuations of its output.

Fig.2 shows the daily load profiles of a medium-sized city, including the dispatching power and wind energy output.

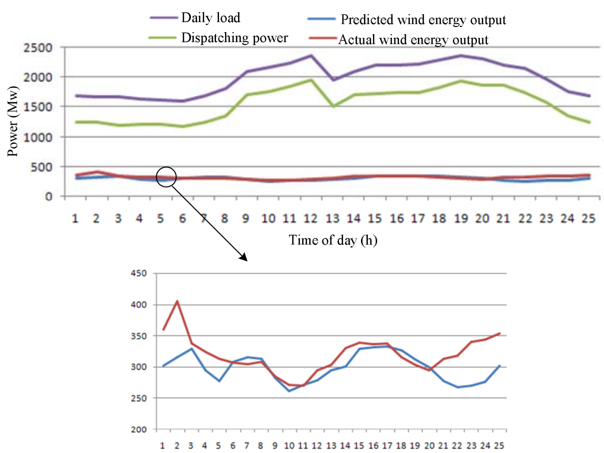

Figure 2. Profiles of the alignment load and wind energy output

Generally, the wind energy output has great randomness and it is clearly that the actual value has a large fluctuation compared with the predicted value in Fig. 2. Then the grid scheduling would become more difficulty. In order to minimize the impact on the scheduling, it is necessary to use the interaction capability of EVs.

It is assumed that there are 50,000 EVs in a medium-sized city, and the charging power of each EV is about 2.5 kW. Fig. 3 shows the abilities of EV to suppress the fluctuation of wind energy output in wired and wireless charging mode, and Fig.4 shows the number of EVs participated in the interaction.

In Fig. 3 and Fig. 4, the x axis represents the time of day with the coordinate of 25 corresponding to 1:00 of the next day. The blue and red curves in Fig. 3 stand for the predicted wind energy output and the actual wind energy of inputting into the grid after the EVs absorption, respectively. There are great differences between the two curves in Fig. 3 (a), and as a

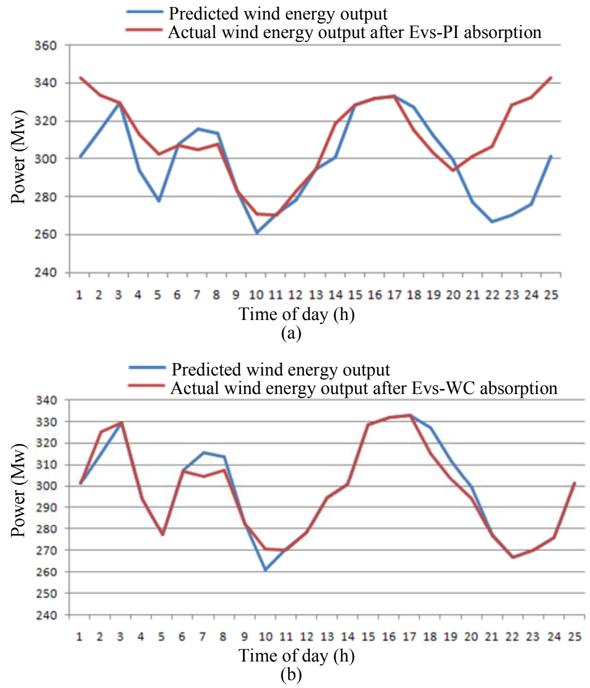

Figure 3. Comparison of two type EV suppressing the fluctuation of the wind energy output: a) EVs-PI; b) EVs-WC

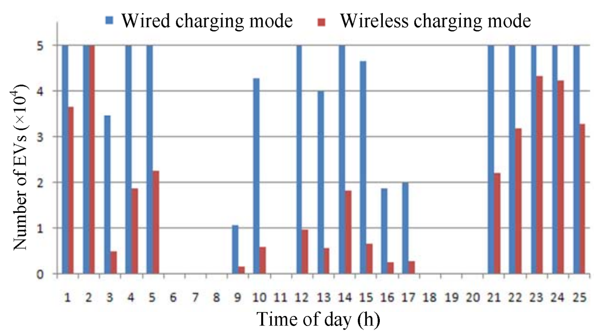

Figure 4. The number of EVs participated in the interaction

consequence it makes scheduling more difficult. And the large the difference, the more the number of EV participating in the interaction is. Clearly, in Fig. 4 almost all of EVs in the wired mode interact with the grid for a long time. A lot of operations are necessary to schedule so many EVs and the scheduling delay time would be long. While in Fig. 3 (b), the two curves are relatively consistent and the number of interactive EVs significantly reduces in Fig. 4. This indicates that in the wireless charging mode the EV is better to suppress the fluctuations of renewable energy. In addition, it should be noted that there is no related policy to allow EVs to feed energy back to the grid, and the simulation is to suppress fluctuation by charging the EV battery.

B. Better to reduce the impact on the power grid

In the wireless mode, the charging locations are more dispersed and it would make for reducing the degree of aggregation of the EV charging. Meanwhile due to no physical link to the grid, wireless charging mode is more flexible and safer by dispersing the continuous charging time and greatly reducing the possibility of the fast charging way (a way to charge EV battery from a SOC close to 0% to full-charge with a great power in a very short period of time, about 20 minutes). To illustrate that wireless charging mode could effectively reduce the impact of EVs on the grid, we predict the daily load of a province, including the generated EV power in these two different modes. In this prediction, it is assumed that there is no incentive for EV owners to avoid peak load charging.

In deriving the generated EV power, based on the above mentioned Nanjing EV Development Plan, the light EV ownership would be 280,000 by 2015, and up to 756,000 by 2020 (converting the large EV and midsize EV into the light EV by a ratio of 5:1 and 2:1, respectively), and all EVs are assumed to charge every three days on average. According to statistical data, the commuter peaks occur at 7:00-8:00 and 17:00-18:00. Generally, the fast charging operations are mainly carried out in the two periods for emergencies. The conventional charge operations (with a small power and a long charging period of about 6 hours) are expected to begin every day at 0:00. The average daily load profiles of a province in 2015 and 2020 are shown in Fig. 5.

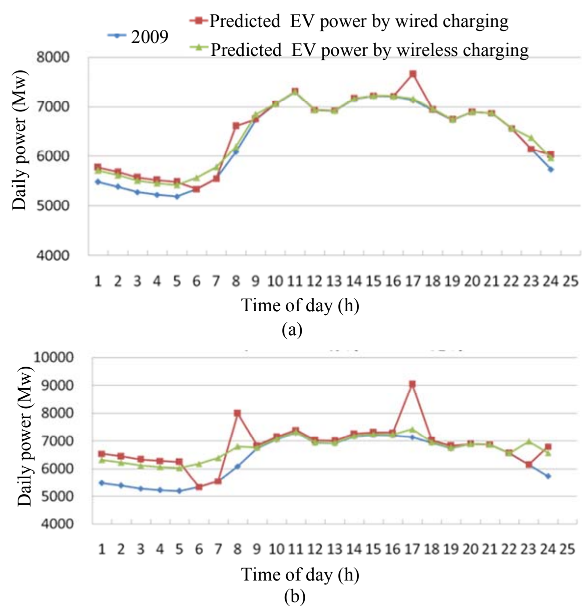

Figure 5. Profiles of the predicted daily load: a) in 2015; b) in 2020

In Fig. 5, the blue curve stands for the reference daily load of 2009. And the red and green curves represent the daily loads combining the generated EV power by wired charging and wireless charging, respectively. Clearly, there are two peaks in the red curve and the green curve is below the red excluding 22:00-24:00. In the wireless charging mode, it could lower the impact on the grid by reducing the clustering effect of EV charging and increasing the charging time of non-peak.

C. *Better to reduce peak and fill valley of the grid*

Through the EV owner willingness and grid intelligent scheduling, the wireless charging/discharging technology could make EV participate in the interaction with the grid at any time. As an energy storage bank, EVs could be used to balance load to improve the grid stability by storing the electric energy in the EV battery and feeding the power back to the grid with the effective scheduling. In the wireless charging mode, EV plays a more important role in reducing peak and filling valley.

D. *Better to reduce the requirements on the battery capacity*

At present, the EV battery is mainly charged through the cable plug. This wired mode is inconvenient and maybe a main factor to restrain the popularity of EVs. When the road haul of EV is accumulated to 150,000 km, the EV battery may be un-effective and the EV owner has to spend additional RMB 60,000 to buy a new battery. However, the wireless charging mode could relatively be used to reduce the requirements of the battery capacity.

An “Online Electric Vehicle” system, which was an environmentally friendly public transportation system based on charging load, was similar to the monorail system and firstly used in an amusement park in Seoul, South Korean on March 9, 2010. The capacity of the special EV battery is just one fifth of that of the traditional EV battery and does not require a long time to charge. In 2011, the experiments of wireless charging the commuting EV battery during its stop time in the bus stop had carried out in European. This measure could drop the battery capacity of commuting EV from 145 kWh to 45 kWh.

E. *Higher degree of informatization and intellectualization with lower cost of human resources management*

Compared with the wired charging mode, it is easier to realize the automatic interaction between the EVs and the power grid in the wireless mode. Through the joint construction of EVs and the smart grid, the SOC of every EV battery could be monitored and it is easy to guide the EV owner to reasonably charge by collecting the related information such as peak load, valley load and electricity rate. And this interaction system does no longer require many staffs to participate in the management and the costs of human resource management and maintenance would be significantly reduced.

V. V2G SYSTEM BASED ON EV-WC

In 2002, AC Propulsion, Inc. fitted a Volkswagen Beetle® as a PHEV with V2G and wireless communication technologies [4]. A general view of the V2G system is shown in Fig. 6. In this study, the V2G system had an aggregator that managed the interactions between the Independent Service Operators (ISOs) and the connected vehicles. The purpose of this system was that the ISOs would communicate with the aggregator instead of separate PHEVs [4].

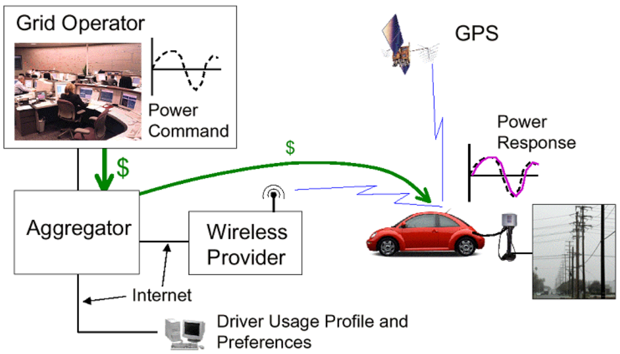

Figure 6. A General Diagram of the V2G System [7]

Because the EVs-WC could more effectively interact with the grid with a significant positive effect, it is necessary to design a V2G system based on EVs-WC. An ideal function configuration of V2G based on EVs-WC is shown in Fig. 7.

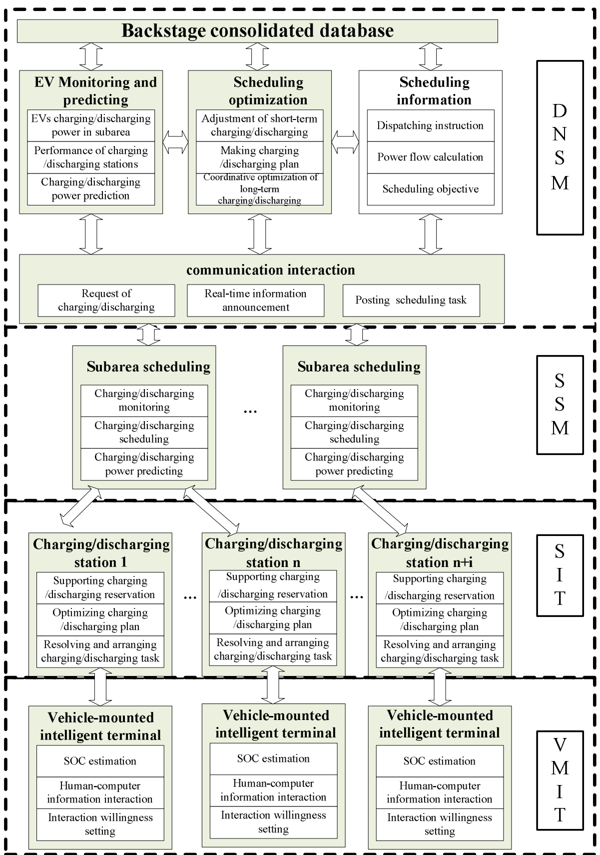

Figure 7. Function configuration of V2G based on EVs-WC

In Fig. 7, the designed V2G system consists of 4 layer structures: vehicle-mounted intelligent terminal (VMIT), stall intelligent terminal (SIT), subarea scheduling management system (SSM) and distribution network scheduling management system (DNSM). VMIT, installed inside the EV, interacts with user (including mainly setting the interaction willingness) though touch screen, on which SOC and other information are displayed; SIT resolves charging instructions ，and fulfils charging operation with optimized charging plan; SSM monitors and dispatches the total charging power in the area by predicted and real-time power data；DNSM posts the scheduling tasks，and reacts to the charging request in line with real-time grid information.

VI. CONLUSION

Wireless charging is the future development direction of EV charging. Compared with the wired charging, we have concluded that EVs-WC have a greater ability to interact with the power grid and further use numerical simulations to illustrate that EVs-WC could better absorb the renewable energy, more effectively reduce the impact of large-scale EVs application on the distribution system and play a more important role in reducing peak and filling valley. Finally, a V2G design concept based on EVs-WC is presented.

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