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Dynamic operation model of the battery swapping station for EV (electric vehicle) in electricity market

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ABSTRACT

The BSS (battery swapping station) is a newly proposed mode of supplying power to the EV (electric vehicle). Different from the BCS (battery charging station), the BSS prepares the batteries for EVs in advance and could complete the battery swapping in a short time. The operations designed for the BCS are not appropriate for BSS anymore and the researches about BSS are at the early stage. In this paper, we propose a dynamic operation model of BSS in electricity market. The new model is based on the short-term battery management and includes the mathematical formulation and market strategy. We have tested the model in a 24-hour simulation. The result shows clearly that the BSS makes decisions in market environment through tracing the number of batteries in different kinds of states and acquires additional revenue by responding actively to the price fluctuation in electricity market. The feasibility and the practicability of the model are confirmed.

1. Introduction

Electricity market has undergone liberalization since the 90s. Competition is introduced to enhance the efficiency and reduce the cost. Wholesale markets have been built up in many countries, like the United States, Australia, European countries, etc. The success of these markets has brought great enthusiasm to the public and the reformers all around the world. The planning of a larger market is prepared to integrate new participants including demand customers, distributed energy sources, electric vehicles, and so on, which will be well supported by the development of smart grid and some new market tools.

As the oil price remains high and environmental problem is getting serious around the world, the EV (electric vehicle) is favored by plenty of customers and investors. It is estimated that the market share of EVs could reach 25% by 2020 [1], while the total mechanic capacity vehicles can be several times greater than that of the entire power generation system, such as the situation in the US [2]. It is predictable that EVs with the increasing number will have significant impact on the electric grid. Not merely as the flexible load with controllable charging features [3], but also it can serve the system as temporary energy sources through strategic charging and discharging. The ability of EVs to provide storage for electric system has been studied since several years ago [4]. Nowadays, widely known as the V2G (vehicle-to-grid) technology, the BCS (battery charging station) has been proposed to be available for kinds of auxiliary services through the bi-directional power flow, like the frequency regulation, the system reserve and the support for the renewable energy [5,6], etc. These services are usually sold through contracts in secondary auxiliary market. With the deregulation of the retail market, the BCS can take part in the electricity market for energy trading as a market participant [7,8]. However, the BCS is always pressured to create bidding capacity from forecasting EVs' demand according to historic data since it has no solid storage capacity itself [9]. Comparing with the traditional petrol station, the BCS also has the shortage of much longer charging time which is up to tens of minutes or several hours. The development of BCS has been heavily relied on the charging and discharging abilities with electronic technology.

In recent years, battery swapping initially proposed by the companies of Renault and Better Place is considered as a new mode to develop EV. The battery types for EV have been widely discussed [10]. It can be concluded that a kind of EV has its corresponding suitable battery type. With the uniform technology standard of the same kind of the battery, the BSS (battery swapping station) will prepare plenty of batteries ahead of time and swaps batteries for EV with an industrial robot. The driver could repower his EV in less than 5 min. Unlike the BCS's significant consideration on the

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coordination between the driver and grid in the operation, the BSS has its own storage of batteries which give it extra ability to sell or buy energy even when there is no vehicle in the station. An EV can also bring a full battery with itself to extend the range limitation. All of these advantages make it more attractive when competing with the BCS, and BSS is obtaining more and more support for the further development. There has been serious consideration of the EV development in China. The two national electricity companies, the State Grid and the Southern Grid, has changed its proposed mode to BSS since 2010 even though the BCS has been studied by them for years [11]. The EU Commission has supported the battery swapping of EV in the EASYBAT project. Some other new development about BSS has been achieved in Australia, Israel, etc. In this paper, we formulate the dynamic operation model of the BSS from the perspective of battery management in electricity market. We hope our work will inspire other researchers.

The rest of this paper is organized as follows. Section 2 gives the theoretic basis of the model. The dynamic operation model of the BSS is introduced in Section 3. The simulation of the model for testing is provided in Section 4. And Section 5 is devoted to the conclusions.

2. Theoretic basis

2.1. Mechanisms for the BSS integration

With the penetration of the BSS or the aggregations of wind turbine and solar cells, the adverse direction power flow performs a considerable role in the energy balance. The interactions between these distributed devices and the operators have been a critical issue. There have been trials to integrate these customers' devices with direct control mechanisms, such as 'Economy 7' and 'White Meter' in the UK. However, they are more or less arbitrary and may neglect the local conditions, the mechanisms based on the price signal are proved to be much more efficient, economic and environmental [12,13]. The rational pricing of charging has also been considered as the key factor to promote the development of EV [14].

From the electricity market point of view, the BSS charges batteries on behalf of the EVs, and it plays the role of the trader or the agent since it doesn't generate or consume electricity itself. There could be two kinds of price mechanisms to guide the market behaviors of the BSS. In the first one, the BSS may submit the bidding which indicates the quality to sell or buy after the system operators publish the price. In the second one, the system operators may accept the biddings from the BSS, and then publish the price after clearing the market. However, like the gasoline station, there could be dozens of BSSs in a medium-scale city, or even several hundred in a province. Considering the large number of BSSs, the first kind of price mechanism is generally more operable and is adopted here though it requires the grid operators to be sophisticated.

2.2. Key features of the batteries

The rechargeable battery has been the bottleneck of the EV development for years. Especially, the EV battery needs to have much larger capacity than the electronic one to support a substantial driving range. It has been estimated that the battery EV with the capacity between 15 kWh and 72 kWh could support a range between 100 km and 500 km [15]. At present, the batteries have exhibited their ability to serve for the EV, like Audi A1 with 12 kW, Volvo C40 with 25 kW, etc. Not long ago, the Tesla company introduced its new EV called Model S which has reached an extraordinary 85 kWh. The capacity would have a predictable breakout in the near future.

Meanwhile, the standardization of the batteries' connection interface has attracted much attention. The famous international organizations have proposed the standards like IEC 62196 and ISO 6469 recently, and many countries' governments have also worked on their own ones. However, the J1772 standard proposed by SAE (Society of Automotive Engineers) has intimately track the technologies since 2001, and has been widely known and referred by the others. Its previous version J1772-2010 has indicated two kinds of AC charging levels, Level 1 and Level 2. Level 1 is known as "overnight charging". It charges the battery with 120 Vac single phase and 12 A maximum current, taking up 8 $\sim$ 30 h. Level 2 charges the battery with 208–240 Vac single phase and 80 A maximum current, taking up 4 $\sim$ 8 h. However, another "fast charging" level frequently referred as Level 3 doesn't appear in J1772-2010. It's the DC charging with 300 $\sim$ 400 Vdc and is supposed to complete the charging in less than half an hour. However, its cost remains high, and charging the battery too quickly may cause a false full and reduce the battery's lifetime. Its detailed realization is expected to be given in the next version of J1772. On the other hand, the discharging of the battery is also required to be even stronger to support the sudden acceleration of the EV, and the SOC (state of charge) of the discharging battery is usually protected from being less than 20% in case the battery suffers permanent damage and won't be charged again.

2.3. Assumptions of the model

The proposed model in this paper is based on the management of the battery. However, the operation also has to satisfy the basic physical constraint and market environment. Before the building of the model, the following assumptions are given at first:

(1) The auxiliary services like reserve and regulation indicated by the traditional V2G are not taken into considerations here. However, they could be well integrated with the proposed model.
(2) The SOC (state of charge) is defined as the percentage of its available capacity. The swapped batteries for EV are referred as 0% and 100% respectively. Actually they could be 20% and 80% or some other values to prevent the battery from permanent damage. They will be adjusted according to the actual case.
(3) The retail market is open for energy trading. The real-time price is usually published by the grid operator for every half or an hour which can also be adjusted according to different markets and is considered as a basic period for the dynamic operation of the BSS.
(4) The structure of the EVs' power supply through the BSS is shown as Fig. 1.

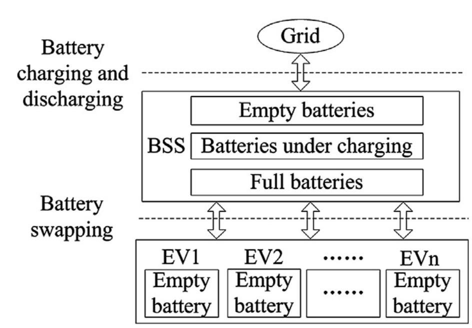

Fig. 1. The structure of EVs' power supply through BSS.