Modeling and Simulation of Public EV Charging Station with Power Storage System

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***Abstract*—Forecasting the power supply capacity from the public grid and the power storage capacity in a public EV charging station is an important work when making a construction plan of the charging station. The power flow diagrams of charging station in different load periods and their electric quantity equations are given. The mathematical model considering the power dissipation in every subsystem of charging station is established. Through simulation calculating the Class I EV charging station which defined in the Beijing local standard about the public EV charging station the optimal allocation between the power supply capacity and the power storage capacity under the certain scale of charging station is known. The simulation example also shows that the calculating results are credible.**

Keywords-EV charging station; power storage system; power flow diagram; mathematical model; simulation example

I. INTRODUCTION

After the Quick Charge, a public EV(electric vehicle) charging program since 1996, and the EV Charge, its following program since 1999 [1], were implemented in Southern California, the experiment projects of EV charging station have been gradually carried out around the world. In August, 2010, North America's first public quick charge station for EV opened in Portland. This station, built by NEC subsidiary Takasago, was set up in a parking garage and could charge the electric vehicles with lithium-ion battery to 80% capacity in 20 to 30 minutes [2]. In January, 2010, JFE Engineering Corp announced to develop the "super-rapid charging system", which could charge the battery of an electric car to 50% capacity in 3 minutes and to 70% in 5 minutes [3].

In 2008, the demonstrative EV charging station project of Beijing Olympic Games [4] has started a nationwide upsurge of constructing EV charging station. Beijing Jiaotong University has studied the overall structure and operation process of the EV charging station without power storage system [5]. Beijing Institute of Technology has done research on forecasting and simulation of the distribution capacity of E-bus charging station [6]. Xihua University has studied the optimization distribution model of public EV charging station in city [7]. State Grid Corporation of China and other companies have built several public demonstrative EV charging stations in Tianjin and Wuhan etc. and have announced the future construction plans [8] [9].

In July, 2010, China's first local standard of EV charging station (hereinafter referred to as Beijing Standard) was introduced in Beijing which is significant for regulating and guiding the construction of public EV charging station. Its key content is that the charging station can be divided into four classes by scale [10] and it also stipulates the minimum power supply capacity and power storage capacity of each class.

However, so far there are few published reports and summaries of the research and demonstrative project about public EV charging station, especially lacking of researches on the system optimization of the charging station with power storage system. Compared to emerging construction tide of EV charging station, the technical preparation seems to be very insufficient. Consequently, a system-level mathematical model of public EV charging station with power storage system which can achieve its optimal allocation will be established and a quantitative analysis method and tool for the charging station will be provided in the paper. Hope this paper will cast a brick to attract jade.

II. MODELING OF PUBLIC EV CHARGING STATION

The purpose to increase a power storage system in the public EV charging station is to solve the problem of peak-to-valley equilibrium using electricity and reduce the demand for power supply capacity from the public grid. However, how much is the best capacity of the power storage system in a changing station? How to evaluate its effect? How does the power supply capacity match to the ability of a charging station? These problems are troubling us. Hence, it is necessary to establish a mathematical model of EV charging station to achieve the quantitative calculation and analysis of key parameters of its system design.

A. Definition of subsystem in EV charging station

The public EV charging station generally consists of four subsystems which are the charging, the power storage, the power distribution and the auxiliary power using subsystem, as shown in Fig. 1. The charging system (CS) is used to transform the electrical energy which inputs the system into the form which EV battery requires and then it is supplied to EV by

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charger. The power storage system (PSS) is used to save electrical energy to the system in low-load periods to be used in high-load periods. The power distribution system (PDS) is used to transform the high-voltage electrical energy from the public grid into the low-voltage one which EV charging station requires by transformers, and then it is distributed respectively to charging system, power storage system and auxiliary power using system. The auxiliary power using system (APUS) is used to distribute the electrical energy which inputs the system to several systems and equipments in the charging station, such as supervisory control, communication and lighting system, etc.

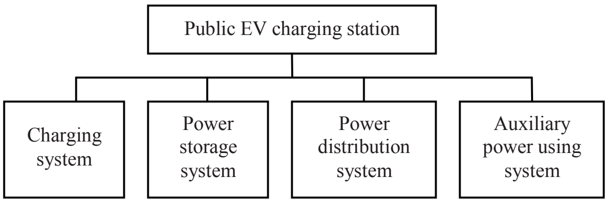

Figure 1. Structure of public EV charging station

B. Charging mode and electric quantity equation

According to people's daily schedule, the charging cycle of EV charging station can be set as 24 hours. Usually, there is the main charging demand in the daytime and rare at night. The demand in the daytime is relatively complex while it is quite busy in some period. Therefore, the charging mode of EV charging station can be indicated by three kinds of basic mode. The first is the model of high-load period whose duration is supposed as T_h. The second is the model of middle-load period whose duration is supposed as T_m. The third is the model of low-load period whose duration is supposed as T_l. Obviously, the sum of T_h, T_m and T_l is 24 hours. In order to make the best of electrical energy from the public grid in low-load period (at night), it is supposed that PSS is charged in low-load period while it discharges just in high-load period.

The power flow of EV charging station in high-load period is shown in Fig. 2. The electric quantity E can be taken as model variable and its unit is kWh. Then the basic relationship of electric quantity between each system in high-load period can be indicated as:

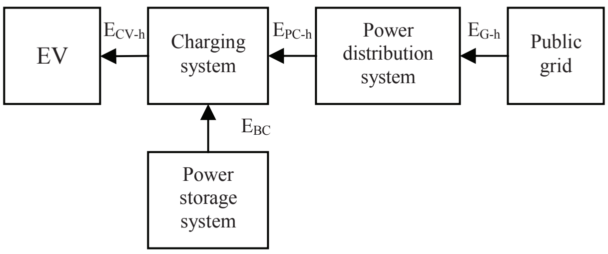

Figure 2. Power flow of EV charging station in high-load period

$$E_{CV\text{-}h} = E_{PC\text{-}h} + E_{BC} - \Delta E_{C\text{-}h} \quad (1)$$

$$E_{G\text{-}h} = E_{PC\text{-}h} + \Delta E_{P\text{-}h} \quad (2)$$

where $E_{CV\text{-}h}$ is the electric quantity which is used to charge EVs in high-load period, $E_{PC\text{-}h}$ is the electric quantity which is supplied directly by the public grid to charge EVs in high-load period, E_{BC} is the electric quantity which is supplied by PSS to charge EVs in high-load period, and it is also actual electric quantity which PSS discharges, $E_{G\text{-}h}$ is the electric quantity of the charging station which is supplied by the public grid in high-load period, $\Delta E_{C\text{-}h}$ is the electric quantity which is dissipated in CS in high-load period, $\Delta E_{P\text{-}h}$ is the electric quantity which is dissipated in PDS in high-load period.

The power flow of EV charging station in middle-load period is shown in Fig. 3. The electric quantity E can also be taken as model variable and its unit is kWh. Then the basic relationship of electric quantity between each system in middle-load period can be indicated as:

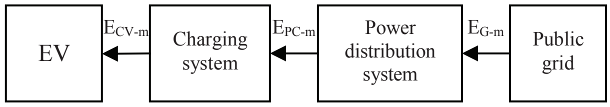

Figure 3. Power flow of EV charging station in middle-load period

$$E_{CV\text{-}m} = E_{PC\text{-}m} - \Delta E_{C\text{-}m} \quad (3)$$

$$E_{G\text{-}m} = E_{PC\text{-}m} + \Delta E_{P\text{-}m} \quad (4)$$

where $E_{CV\text{-}m}$ is the electric quantity which is used to charge EVs in middle-load period, $E_{PC\text{-}m}$ is the electric quantity which is supplied directly by the public grid to charge EVs in middle-load period, $E_{G\text{-}m}$ is the electric quantity of the charging station which is supplied by the public grid in middle-load period, $\Delta E_{C\text{-}m}$ is the electric quantity which is dissipated in CS in middle-load period, $\Delta E_{P\text{-}m}$ is the electric quantity which is dissipated in PDS in middle-load period.

The power flow of EV charging station in low-load period is shown in Fig. 4. The electric quantity E can also be taken as model variable and its unit is kWh. Then the basic relationship of electric quantity between each system in low-load period can be indicated as:

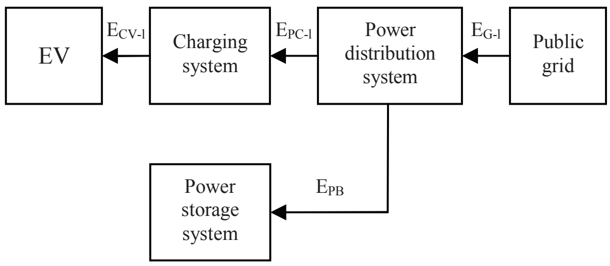

Figure 4. Power flow of EV charging station in low-load period

$$E_{CV\text{-}l} = E_{PC\text{-}l} - \Delta E_{C\text{-}l} \quad (5)$$

$$E_{G\text{-}l} = E_{PC\text{-}l} + E_{PB} + \Delta E_{P\text{-}l} \quad (6)$$

where $E_{CV\text{-}l}$ is the electric quantity which is used to charge EVs in low-load period, $E_{PC\text{-}l}$ is the electric quantity which is supplied directly by the public grid to charge EVs in low-load period, $E_{G\text{-}l}$ is the electric quantity of the charging station which is supplied by the public grid in low-load period, E_{PB} is the electric quantity which PSS is charged in low-load period,

ΔE_{C-l} is the electric quantity which is dissipated in CS in low-load period, ΔE_{P-l} is the electric quantity which is dissipated in PDS in low-load period.

C. Dissipation of charging and power distribution system

It is very complex and difficult to calculate accurately the internal electric quantity dissipation of each subsystem in the EV charging station, because the dissipation is related to the factors in each subsystem, such as device characteristic, working method and control level, etc. Consequently, the problem can be simplified appropriately when studying the charging station in the macroscopic layer. Now suppose that the electric quantity of internal dissipation in each subsystem is proportional to its input electric quantity which can be expressed by the input and output electric quantity of the charging station. Then the following equations can be got.

The electric quantity of CS's internal dissipation in each period is:

$$\Delta E_{C\text{-}t} = \zeta_C\,(1-\zeta_C)^{-1} E_{CV\text{-}t} \tag{7}$$

where ζ_C is electric quantity dissipation factor of CS, t is the period mark while t=h stands for high-load period, t=m for middle-load period and t=l for low-load period.

The electric quantity of PDS's internal dissipation in each period is:

$$\Delta E_{P\text{-}t} = \zeta_P\, E_{G\text{-}t} \tag{8}$$

where ζ_P is electric quantity dissipation factor of PDS, t is the period mark while t=h stands for high-load period, t=m for middle-load period and t=l for low-load period.

D. Power storage system and its dissipation

The operating mode of PSS is charging in low-load period and discharging in high-load period. In order to give full play to the function of PSS, generally it has been charged fully in low-load period while it has discharged fully in high-load period. So the following equation can be got.

$$E_{BC} = E_{PB} - \Delta E_B \tag{9}$$

where ΔE_B is the electric quantity of PSS's internal dissipation during each charge-discharge cycle (24 hours), and its unit is kWh.

Still suppose that the electric quantity of internal dissipation is proportional to its input electric quantity, and then the electric quantity of PSS's internal dissipation is shown in Eq. (10):

$$\Delta E_B = \zeta_B\,(1-\zeta_B)^{-1} E_{BC} \tag{10}$$

where ζ_B is electric quantity dissipation factor of PSS.

E. Mathematical model of charging processes

Transforming Eq. (1) to Eq. (10) and then rearranging them, we arrive at the power demand in the EV charging station which is supplied by the public grid as follows.

In high-load period:

$$W_{G\text{-}h} = (C_1/T_h)E_{CV\text{-}h} - (C_2/T_h)E_{BC} \tag{11}$$

In middle-load period:

$$W_{G\text{-}m} = (C_1/T_m)E_{CV\text{-}m} \tag{12}$$

In low-load period:

$$W_{G\text{-}l} = (C_1/T_l)E_{CV\text{-}l} + (C_3/T_l)E_{BC} \tag{13}$$

where the unit of $W_{G\text{-}h}$ 、 $W_{G\text{-}n}$ and $W_{G\text{-}l}$ is kWh, and

$$C_1 = (1-\zeta_C)^{-1}(1-\zeta_P)^{-1} \tag{14}$$

$$C_2 = (1-\zeta_P)^{-1} \tag{15}$$

$$C_3 = (1-\zeta_B)^{-1}(1-\zeta_P)^{-1} \tag{16}$$

III. SIMULATION EXAMPLE OF PUBLIC EV CHARGING STATION

Beijing Standard stipulates that the EV charging station which stores energy by PSS has four classes. And the power storage energy of the Class I EV charging station is not less than 6800kWh. Is this regulation reasonable? Is there an optimal allocation? With these questions, a Class I EV charging station will be taken as an example in this section. Through simulation and calculation, the optimal allocation of storage and supply capacity under certain constraints can be provided, in order to offer everybody discussion.

A. Initial condition

According to Beijing Standard, the Class I EV charging station should provide charging service for more than 200 large and medium-sized commercial vehicles or more than 500 passenger vehicles on average everyday. Calculated from the average rated capacity data of onboard battery, the Class I EV charging station need to export electricity of more than about 40000kWh to charge EVs in a day.

Based on preliminary survey data of one EV charging station, the 24 hours cycle can be divided equally into 6 periods in this example, so each period is 4 hours. The initial simulation data is shown in table I. The name and symbol of each period is that T_{h1} and T_{h2} are in high-load period, T_{m1} and T_{m2} in middle-load period, T_{l1} and T_{l2} in low-load period.

TABLE I. INITIAL DATA OF SIMULATION

	Data in concerned period					
	T_{h1}	T_{h2}	T_{m1}	T_{m2}	T_{l1}	T_{l2}
Time(h)	4	4	4	4	4	4
EVs number	166	125	98	67	34	10
$W_{G\text{-}t}$ (kWh)	13280	10000	7840	5360	2720	800

Set system parameters that electric quantity dissipation factor of CS ζ_C is 0.20, electric quantity dissipation factor of PDS ζ_P 0.03, electric quantity dissipation factor of PSS ζ_B 0.15.

B. Simulation and calculation

Substituting relevant data and system parameters in table I into Eq. (11) to Eq. (16), we arrive at the formulas of public grid supply capacity which this EV charging station requires in each period.

$$W_{G\text{-}h1} = 0.3222 \times 13280 - 0.2577E_{BC\text{-}h1} \quad (17)$$

$$W_{G\text{-}h2} = 0.3222 \times 10000 - 0.2577E_{BC\text{-}h2} \quad (18)$$

$$W_{G\text{-}m1} = 0.3222 \times 7840 \quad (19)$$

$$W_{G\text{-}m2} = 0.3222 \times 5360 \quad (20)$$

$$W_{G\text{-}l1} = 0.3222 \times 2720 + 0.3032E_{BC\text{-}l1} \quad (21)$$

$$W_{G\text{-}l2} = 0.3222 \times 800 + 0.3032E_{BC\text{-}l2} \quad (22)$$

where $E_{BC\text{-}h1}$ and $E_{BC\text{-}h2}$ are the actual electric quantity which PSS discharges in high-load period, and they are also the actual capacity of PSS. Obviously,

$$E_{BC\text{-}h1} + E_{BC\text{-}h2} = E_{BC} \quad (23)$$

where $E_{BC\text{-}l1}$ and $E_{BC\text{-}l2}$ are the actual electric quantity which PSS are charged in low-load period, and they are also the actual charging electric quantity which are indicated by the actual discharging electric quantity. Obviously,

$$E_{BC\text{-}l1} + E_{BC\text{-}l2} = E_{BC} \quad (24)$$

The simulation results are shown in table II、III and IV.

TABLE II. SIMULATION RESULTS

Input: Discharge electric quantity of PSS (kWh)				Output: Power supply capacity from the public grid (kVA)					
$E_{BC\text{-}h1}$	$E_{BC\text{-}h2}$	$E_{BC\text{-}l1}$	$E_{BC\text{-}l2}$	$W_{G\text{-}h1}$	$W_{G\text{-}h2}$	$W_{G\text{-}m1}$	$W_{G\text{-}m2}$	$W_{G\text{-}l1}$	$W_{G\text{-}l2}$
0	0	0	0	4279	3222	2526	1727	876	258
3400	3400	3400	3400	3403	2346	2526	1727	1907	1289
5400	1400	2350	4450	2887	2861	2526	1727	1589	1607

TABLE III. SIMULATION OPTIMIZED RESULTS I

Input: Discharge electric quantity of PSS (kWh)				Output: Power supply capacity from the public grid (kVA)					
$E_{BC\text{-}h1}$	$E_{BC\text{-}h2}$	$E_{BC\text{-}l1}$	$E_{BC\text{-}l2}$	$W_{G\text{-}h1}$	$W_{G\text{-}h2}$	$W_{G\text{-}m1}$	$W_{G\text{-}m2}$	$W_{G\text{-}l1}$	$W_{G\text{-}l2}$
6800	2700	3750	5750	2526	2526	2526	1727	2013	2001

TABLE IV. SIMULATION OPTIMIZED RESULTS II

Input: Discharge electric quantity of PSS (kWh)					Output: Power supply capacity from the public grid (kVA)					
$E_{BC\text{-}h1}$	$E_{BC\text{-}h2}$	$E_{BC\text{-}h3}$	$E_{BC\text{-}l1}$	$E_{BC\text{-}l2}$	$W_{G\text{-}h1}$	$W_{G\text{-}h2}$	$W_{G\text{-}h3}$	$W_{G\text{-}m1}$	$W_{G\text{-}l1}$	$W_{G\text{-}l2}$
7500	3500	750	4850	6900	2346	2320	2333	1727	2347	2350

C. Interpretation of simulation results

a. The first line of simulation input data in table II is zero, which indicates that the PSS in the EV charging station does not work. Reflected from the first line of simulation output data, without PSS, the supply capacity demand from the public grid which this EV station requires fluctuates wildly, and the ratio of peak to valley is up to 16.6. If an EV charging station is built based on the above data, its supply capacity must be greater than 4279kVA which is the capacity only to charge EVs. It is basically consistent with the regulation of Beijing Standard which the grid single-path supply capacity in the Class I EV charging station is not less than 5000kVA. But the grid capacity is basically idle in low-load period in the case.

b. The 6800kWh in PSS is halved to charge EVs in two high-load period T_{h1} and T_{h2}, and the half capacity of PSS is charged respectively in two low-load periods T_{l1} and T_{l2}. As shown in the simulation output results of the second line data in table II, the power supply capacity from the public grid which the EV charging station requires in each period keeps certain equilibrium and the ratio of peak to valley drops to 2.6. Meanwhile, the supply capacity which is required in construction of the EV charging station is only more than 3403kVA and lowers to 80% compared with the capacity without PSS.

c. In the case of the same 6800kWh of PSS, though reasonable arrangement by means of the EV charging station control system, the 5400kWh and the 1400kWh charge EVs respectively in two high-load period T_{h1} and T_{h2}, and the 2350kWh and the 4450kWh are charged respectively in two low-load periods T_{l1} and T_{l2}. As shown in the simulation results of the third line data in table II, the power supply capacity from the public grid keeps a better equilibrium while the supply capacity in two high-load periods are generally equal and the ratio of peak to valley drops to 1.8. Now, the supply capacity lowers to 67% compared with the capacity without PSS.

d. The power storage capacity of the EV charging station increases to 9500kWh. Then it is divided into 6800kWh and 2700kWh which charge EVs respectively in two high-load period T_{h1} and T_{h2}, and the 3750kWh and the 5750kWh are charged respectively in two low-load period T_{l1} and T_{l2}. As shown in the simulation results in table III, the supply capacity from the public grid in each period is optimized. The supply capacity in two high-load periods lower as the same as one in middle-load period T_{m1}, and the power consumption in low-load period would upgrade greatly which is what we want. The ratio of daily peak to valley drops to 1.5. Now the supply capacity lowers to 59% compared with the capacity without PSS.

e. The storage capacity of the EV charging station increases to 11750kWh, the daily high-load periods are changed to three periods T_{h1}, T_{h2} and T_{h3} which are covered by the discharge periods of PSS and the middle-load period is changed to a period T_{m1}. Then the 11750kWh is divided into 7500kWh, 3500kWh and 750kWh which charge EVs respectively in three high-load periods and the 4850kWh and the 6900kWh are charged respectively in two low-load periods T_{l1} and T_{l2}. The simulation results are shown in table IV and their simulation formulas are not given in the paper. In the case the supply capacity in each period is further optimized. The capacity in three high-load periods and two low-load periods tend to become the same and can be fully utilized. Now the supply capacity lowers to 55% compared with the capacity without PSS.

IV. SUMMARY AND DISCUSSION

a. Through the simulation calculation and analysis of the above large-scale public EV charging station, the proposed mathematical model of the charging station can calculate and get the optimal allocation data of supply and storage capacity. The method of calculation is simple and the calculating results are credible. However, the calculating results must have some errors, because when modeling each subsystem of EV charging station will be linearized, especially PSS. Therefore, after determining the type of each subsystem, the structure and parameters of the relevant subsystem should be corrected according to the character of the system, thus more exact calculating results will be obtained.

b. As indicated in the calculation results of the proposed simulation example, though reasonable arrangement by means of EV charging station control system, a Class I EV charging station with PSS whose storage capacity is 6800kWh can keep better peak-to-valley equilibrium using electricity of charging station and reduce obviously the demand for power supply capacity from the public grid. It is thus clear that the stipulation of Beijing Standard is reasonable and it is also very necessary to configure PSS of certain capacity in large-scale public EV charging station.

c. As still indicated in the calculation results of the simulation example, for a public EV charging station whose charging scale has been determined, there is an optimal allocation between the power supply capacity and the power storage capacity by which the power supply capacity from the public grid can be fully utilized, especially in valley period (at night). It should be pointed out that the storage capacity which is required in the optimal allocation will be much more than 6800kWh and correspondingly the PSS investment will increase. Hence, in order to achieve the goal of the global optimization, while determining the optimal power storage and supply capacity in EV charging station, the technological and economic analysis should be done about the construction and operation of EV charging station.

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