The Charge and Discharge Integrated Management Mode of EVs with Financial Incentive Mechanism

Suwei Zhai[1], Yonghui Sun*[1], Denis Sidorov[2], Daniil Panasetsky[2]

***Abstract*—High penetration renewable energies (REs) and large numbers of electric vehicles (EVs) integrated into the grid have brought a great challenges for the grid. The charge and discharge management of EVs to support the grid is the main target of this paper. First, the AC/DC converter, the bidirectional DC/DC converter, the wireless power transfer system and corresponding controller are taken to realize the charge and discharge control of EVs. Second, due to the different service customers, EVs are mainly divided into different categories, their operation rules are analyzed and classified, respectively. Then, a charge and discharge integrated management mode is proposed, the corresponding financial incentive mechanism is proposed to promote the participation of EVs into the grid support activities. Finally, the simulation results are given to illustrate the effectiveness of the proposed method.**

***Index Terms*—Electric vehicles, financial incentive mechanism, charge and discharge management, renewable energy generation**

I. Introduction

To realize the future target of energy conversation and environment protection, renewable energies (REs) have been widely applied, and electric vehicles (EVs), as clean and environmentally friendly transports against the traditional fuel automobiles, have also received more and more consideration [1]. Due to the special characteristic as distributed loads or electric sources, EVs have a positive potential ability in the grid support, such as the grid peak shaving and valley filling, fluctuations suppressing and frequency control, etc [2-4].

The utilization of EVs for grid support has been considered to be valuable and practical [5]. However, it is still a great challenge to make a great quantity EVs participate in the grid support activities. With the substantial increase in the quantity of EVs, the stochastic connection between EVs and the grid may cause the negative impact on the grid [6-7].

To solve these issues, some studies on EVs have been carried out. In [8], a dynamic control of EVs charging stations was proposed to maximize the profit based on linear programming, while the stochastic distributions of EVs were ignored. In [9], considering the stochastic behaviors of EVs, a spatial-temporal model of EVs was proposed to analyze the charging demands, where the corresponding management strategy was not given. In [10], a fuzzy logic controller was designed for EVs to support the grid, however, the dynamic change of the EVs batteries stored energy was ignored. In [11], a hierarchical control method was presented, however, the EVs were treated as loads, and the roles of EVs as power sources were not considered. In [12], considering the capacity constraints, a cooperative dispatch method of wind generation and EVs was proposed. In [13], a cloud-based energy management service for the EVs was presented. In [14] a real-time decentralized demand-side management was proposed for EVs, energy storage systems and REs in balancing the planned generation.

The aforementioned results have solved some issues on EVs management, planning and cooperating with REs from a macro perspective. However, what have to be mentioned are that EVs participate in the grid support activities will affect the normal utilization of EVs and bring inconvenience to the owners. In fact, the charge and discharge of each EV in reality needs the corresponding device and controller, these are not described in the above literatures.

The charge devices are the basis of EVs to interacting with the grid. At present, the EV charging device is divided into wired and wireless two categories [15-16]. The wired charging devices are widely used due to the relatively simple and mature technology. A typical wired charging device was made up of the bidirectional DC/DC converter [17], and it is suitable for the plug-in EVs. By designing the corresponding controller, it can switch the charge and discharge mode and adjust the power of charge and discharge. The other one is the wireless charging device, which was developed on the basis of the wireless power transfer system [18]. Recently, the wireless power transfer devices have received more and more attention because of

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Suwei Zhai and Yonghui Sun are with the College of Energy and Electrical Engineering, Hohai University, Nanjing 210098, China (e-mail: suwei_zhai@163.com; sunyonghui168@gmail.com).

Denis Sidorov and Danill Panasetsky are with the Melentiev Energy System Institute, Russian Academy of Sciences, Irkutsk, 664033, Russia (e-mail: contact_dns@gmail.com; panasetsky@gmail.com).

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safety and convenience. Additionally, it is reported in [19] that compared with the wired charge devices, adopting the wireless charge devices can leads to more successful interaction with the grid. Hence, the research of the wireless power transfer system for EVs participating in the grid activities is very necessary.

When EVs participate in the grid support activities, the EVs should not disconnect to the grid. During this period, the EVs cannot be used as vehicles for travels, which may sacrifice the interests of the owners. Therefore, the EV owners will lack enthusiasm to participate in these activities [20]. To avoid these situations and promote the participation degree of EVs in the grid activates, a financial incentive mechanism is proposed.

The rest of this paper is organized as follows: In section II, the charge and discharge devices are described in detail, and the corresponding controllers are designed for the management. In section III, considering the different operation characteristics of different EV categories, a financial incentive mechanism is proposed, and a charge and discharge integrated management mode for EVs is given. In section IV, a case study is committed to illustrate the effectiveness of the proposed management mode. Finally, some conclusions are drawn.

II. THE CHARGE AND DISCHARGE OF EVS

To realize the effective management of EVs, the analysis of the charge and discharge device for EVs and design of the controller is very significant. At present, the charge and discharge device for EVs can be divided into two kinds according to wired connection or wireless connection.

A. *The Connection between the Grid and EVs*

Normally, the AC of the grid is translated into DC through the AC/DC converter, and then it connects to the DC bus. The charge and discharge device connects the DC bus and the EV battery, and the diagram block is shown in Fig. 1.

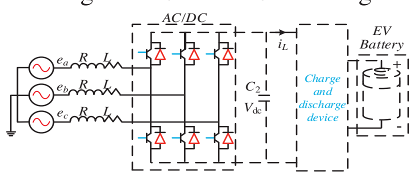

Fig. 1. The diagram block of an EV battery connected to the grid

The state equation of a three-phase voltage source AC/DC converter after the Clarke's transformation is given [21]

$$\begin{bmatrix} C\dot{u}_{dc} \\ L\dot{i}_d \\ L\dot{i}_q \end{bmatrix} = \begin{bmatrix} 0 & 1.5S_q & 1.5S_d \\ -S_d & -R & -\omega L \\ -S_q & -\omega L & -R \end{bmatrix} \begin{bmatrix} u_{dc} \\ i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & 0 & -1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} e_d \\ e_q \\ i_L \end{bmatrix} \tag{1}$$

where e_d and e_q, i_d and i_q are the voltages and currents in dq axis. u_{dc} and i_L are the DC voltage and current. S_d and S_q are the equivalent switch signal in dq axis.

The controller of a three-phase voltage source AC/DC converter is designed as

$$\begin{cases} i_{d\_ref} = (k_{pi} + \frac{k_{ii}}{s})(V_{dc\_ref} - V_{dc}) \\ V_{d\_ref} = (k_{pd} + \frac{k_{id}}{s})(i_{d\_ref} - i_d) \\ V_{p\_ref} = (k_{pp} + \frac{k_{ip}}{s})(i_{q\_ref} - i_q) \end{cases} \tag{2}$$

where V_{dc_ref}, V_{d_ref}, V_{q_ref}, i_{d_ref} are the reference voltage and current, and k_{pi}, k_{ii}, k_{pd}, k_{id}, k_{pp} and k_{ip} parameters of the PI controller, respectively.

The block diagram of a three-phased voltage source AC/DC converter with controller is shown in Fig. 2.

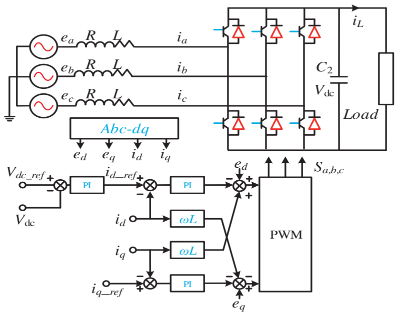

Fig. 2. The block diagram of a three-phase voltage source AC/DC converter

B. *The Bidirectional DC/DC Converter for EVs*

The bidirectional DC/DC converter is a typical wired connection device, it connects the DC power and the EV battery, it contains two switches S_1 and S_2 [22], and it is shown in Fig. 3.

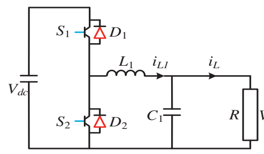

Fig. 3. The diagram block of a typical bi-directional DC/DC converter for EVs

When S_1 is in the working state and S_2 is in the off state, the bidirectional DC/DC converter is in the buck circuit mode, and the expression can be described as follows [23]

$$\begin{bmatrix} \dot{i}_{L_1} \\ \dot{V}_{bat} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_1} \\ \frac{1}{C_1} & -\frac{1}{RC_1} \end{bmatrix} \begin{bmatrix} i_{L_1} \\ V_{bat} \end{bmatrix} + \begin{bmatrix} \frac{d(t)_1}{L_1} \\ 0 \end{bmatrix} V_{dc} \tag{3}$$

When S_2 is in the working state and S_1 is in the off state, it is in the boost circuit mode, and the expression can be described as follows [24]

$$\begin{bmatrix} \dot{i}_{L_1} \\ \dot{V}_{bat} \end{bmatrix} = \begin{bmatrix} 0 & \frac{(1-d(t)_2)}{L_1} \\ \frac{(1-d(t)_2)}{C_1} & -\frac{1}{RC_1} \end{bmatrix} \begin{bmatrix} i_{L_1} \\ V_{bat} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \end{bmatrix} V_{dc} \tag{4}$$

where C_1 is the capacitor, L_1 is the inductor, R is the equivalent resistance, and $d(t)_1$ is the duty ratio of the switch S_1. $d(t)_2$ is the duty ratio of the switch S_2.

To realize the charge and discharge control of the EV, the block diagram of the designed controller is shown in Fig. 4.

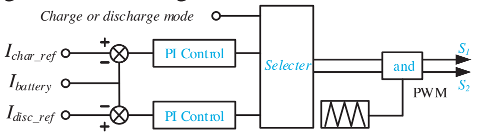

Fig. 4. The block diagram of current controller

C. The Wireless Power Transfer System for EVs

Compared with the wired connection device that requires to manual insert and pull out the plug, the wireless power transfer system is more convenient and safe for the EVs [25]. A wireless power transfer system contains two inverters and a LC-series compensation circuit ($L_{pc}, R_p, L_{sc}, R_s, C_p, C_s$) [26]. V_{dc}, V_{bat} are the voltage of the DC bus and EV battery. V_{pi}, V_{si} are the AC voltage of two inverters, and two side are working at the resonant frequency to realize the wireless power transmission.

The voltage of the two inverters can be described by [27]

$$\begin{cases} V_{pi} = \dfrac{4}{\pi} V_{dc} \cos(\omega_r t) \sin(\dfrac{\alpha}{2}) \\ V_{si} = \dfrac{4}{\pi} V_{bat} \cos(\omega_r t + \delta) \sin(\dfrac{\beta}{2}) \end{cases} \tag{5}$$

where α and β are the control signal phase difference between the upper arm and the lower arm of the two inverters, respectively. $\omega_r = 1/\sqrt{L_{pc} C_P}$ is the resonant frequency. δ is the phase difference between V_{pi} and V_{si}, respectively.

In most cases, $R_p, R_s \ll \omega_r M$, and according the Kirchhoff laws, the simplified expression is given by

$$\begin{cases} I_{pi} = \dfrac{R_s V_{pi} - j\omega_r M V_{si}}{R_p R_s + (\omega_r M)^2} \\ I_{si} = \dfrac{R_p V_{si} - j\omega_r M V_{pi}}{R_p R_s + (\omega_r M)^2} \\ P_{pi} = \dfrac{8}{\pi^2 \omega_r M} V_{dc} V_b \sin(\dfrac{\alpha}{2}) \sin(\dfrac{\beta}{2}) \sin(\delta) \\ P_{si} = -\dfrac{8}{\pi^2 \omega_r M} V_{dc} V_b \sin(\dfrac{\alpha}{2}) \sin(\dfrac{\beta}{2}) \sin(\delta) \end{cases} \tag{6}$$

where I_{pi} and I_{si} are the currents of left inverter and right inverter, respectively. M is the mutual inductance, p_{pi} and p_{si} are the power of the two inverters.

If $\delta = \pi/2$, the EV is in the charge mode, and if $\delta = -\pi/2$, the EV is in the discharge mode. The corresponding controller is given as follows

$$\begin{cases} \sin(\dfrac{\alpha}{2}) = (k_1 + \dfrac{k_2}{s})(I_{ref} - I_{pi}) \\ \sin(\dfrac{\beta}{2}) = (k_3 + \dfrac{k_4}{s})(P_{ref} - P_{pi}) \end{cases} \tag{7}$$

where k_1, k_2, k_3 and k_4 are the coefficients of the controller, I_{ref} and P_{ref} are the reference current and power.

III. Integrated Management Mode of EVs with Financial Incentive Mechanism

Due to the different service customers, EVs are mainly divided into electric bus, electric taxi and private EVs three classes, their operation rules are totally different. Hence, the research of the EVs operation characteristics is necessary [28].

A. The operation characteristics of different kinds of EVs

Electric buses run according to the bus scheduling timetable of each line in every day, which has strong regularity. As long as the bus scheduling plan is unchanged, the time, interval and route of the bus are fixed. The equation can be described

$$\begin{cases} t_{di} = 2d_i / v_i \\ n_i = \lceil t_{di} / t_m \rceil \\ Soc_i^{k+1} = Soc_i^k - 2d_i \eta / E \end{cases} \tag{8}$$

where d_i is the distance from the starting station to the terminal station of line i, t_{di} is the time of a round-trip, and v_i is the average driving speed. t_m is the time interval between two buses, n_i is the number of buses of the same route, η is the energy consumption per unit distance, E is the battery capacity, is the percentage of residual capacity of battery.

The electric bus will replace the battery at the departure station, then the battery will be sent to the centralized charging station for charging, which means the battery charge of the electric bus can be arranged according to the operation state of the grid, if there are enough spare batteries. The total charging demands of electric buses in each route within one day can be calculated as follows

$$E_{db} = c_i n_i 2 d_i \eta \tag{9}$$

where E_{db} is the charging demands of electric buses in each route within one day, c_i is the average round-trip number of one electric bus.

Unlike the electric buses, the batteries of electric taxies and private EVs are not normally replaced. When they are charging, they stop at the place. Although the running time of electric taxi and private EVs are different, the running distance of electric taxies and private EVs in a day can be approximately lognormal distribution [29], the probability density function is given

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} \tag{10}$$

where σ and μ are the standard deviation and expectation, respectively.

The total charging demands of electric taxis and private EVs can be expressed as

$$E_{dt} = \eta n_t \int x f(x) dx \tag{11}$$

where $f(x)$ is the probability density function, n_t is the total number of taxis or private EVs, η is the energy consumption per unit distance.

B. *Charge and Discharge Integrated Management*

Stochastic and considerable EVs integrated to the grid will bring potential overloads, and affect the stable operation of the grid. Hence, the management of EVs charge is very necessary.

To facilitate the management of charging and discharging of EVs, one day is divided into 24 time intervals. Considering the changes of the conventional loads consumption and the REs power generation at each time interval, the changes trend of power supply and demand e_i can be obtained

$$e_i = P_{c,i} + P_{r,i} - P_{l,i} \tag{12}$$

where $P_{c,i}$ is the conventional power generation, $P_{r,i}$ represents the REs power generation, P_{load} is the traditional loads consumption.

When e_i is less than zero, it is not suitable for EVs to connect to the grid for charging, however, it is encouraged for EVs discharging to support the grid. When e_i is greater than zero, EVs are arranged to charge, and the suggestion number of EVs to charge from the grid can be calculated

$$N_i = \frac{P_{c,i} + P_{r,i} - P_{l,i}}{P_{EV}} \tag{13}$$

where N_i is the suggestion number of EVs to charge from the grid at time interval i , P_{EV} is the average charging power of EV.

To avoid numerous EVs integrated to the grid at the same time, the related information about the suggestion number for EVs charging and discharging decision is published in a specific platform and pushed to the owner. Then the owners will decide to make an appointment or not. The charge and discharge management diagram of EVs is shown in Fig. 5.

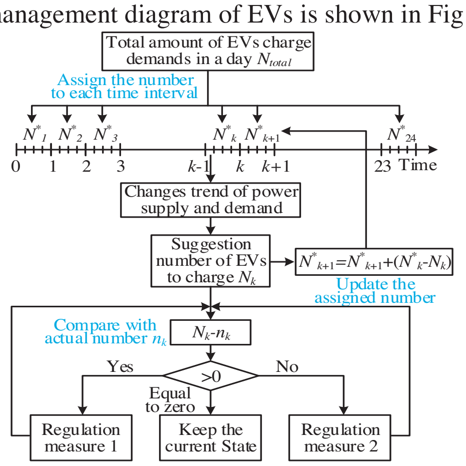

Fig. 5. The diagram of charge and discharge integrated management

The assigned number of EVs to charge or discharge in each time interval will be allocated in advance. Due to the changes of power supply and demand, the suggestion number N_k of EVs to charge from the grid in time interval $(k-1,k)$ can be calculated in formula (13), however, the suggestion number N_k may be different from the previous assigned number N_k^* , therefore, the assigned number N_{k+1}^* in the next time interval will be updated, meanwhile, the actual number of EVs charging from the grid is regulated to equal the suggestion number. When the actual number of EVs that connect to the grid for charge is less than the suggestion number, the regulation measure 1 is taken—a proper reduction in the price is committed to attract the EVs to charge. When the actual number of EVs for charge is more than the suggestion number, the regulation measure 2 is taken—on one hand more EVs are banned in charge, and on the other hand a proper price mechanism is committed to promote the EVs to discharge or exit charge. The corresponding financial incentive mechanism is described in detail.

C. *The Financial Incentive Mechanism*

When the EVs obey the grid scheduling plan to participate in the charge or discharge process, which will affect the normal utilization and bring inconvenience to the owners. Especially, the frequent charge and discharge will reduce the life of EVs battery more or less. Therefore, the owners of EVs will lack enthusiasm to participate in these grid activities [30]. It is necessary to propose a financial incentive mechanism to promote the EVs to involve in the grid activities. When the grid bans EVs to charge, and EVs still need to charge for some reasons, the price that grid get from the EVs is calculated by

$$s_{cha,k} = s_g + s_c \tag{14}$$

where s_g is the current electric price of the grid, and s_c is the additional costs for the violation of the guidance.

When the grid needs EVs to participate in the discharge process, the price that grid offered to the EVs is calculated

$$s_{dis} = s_g + s_{EV} + \sigma \times s_c \tag{15}$$

where s_{EV} is the average depreciation expense of EV, σ is a coefficient between 0 and 1.

When the grid needs EVs to participate in the charge process, the price that grid get from the EVs is calculated

$$s_{cha,s} = s_g \text{-} (1\text{-}\sigma) \times s_c \tag{16}$$

The simulation results and corresponding parameters are exhibited in the case study.

IV. CASE STUDY

As described in section II, the parameters of the AC/DC converter, the DC/DC converter and the wireless power transfer system is shown in TABLE. I.

TABLE I
The parameters of the converters

R	0.4(Ω)	L	3.5(mH)
L_1	0.005(H)	C_1, C_2	470, 940(μF)
Lpc, Lsc	101(μH)	C_p, C_s	36(μF)

f	26.5(KHz)	R_p, R_s	0.03(Ω)

Fig. 6 is the voltage results of a three phase AC/DC converter, which connect the grid and the DC bus. The three phase AC is translated into a constant DC voltage.

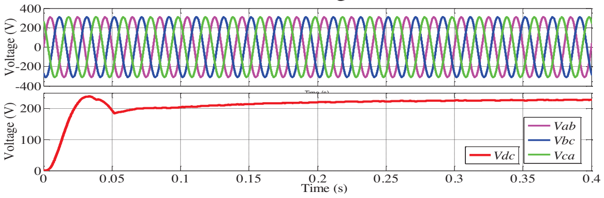

Fig. 6. Voltages of AC/DC converter under constant voltage control

The simulation results of DC/DC converter are shown in Figs. 7-8, Fig. 7 shows the voltage and current of the EV battery when it charges from the grid, and Fig. 8 exhibits the voltage and current of the EV battery when it discharges to the grid.

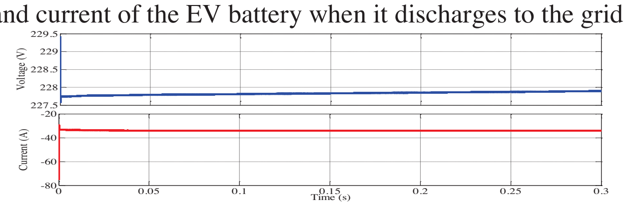

Fig. 7. Simulation results of DC/DC converter at constant charge power

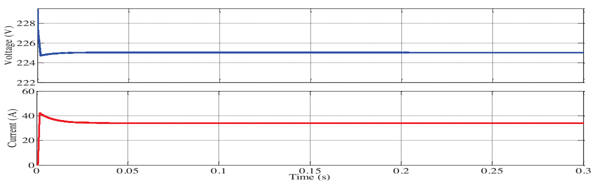

Fig. 8. Simulation results of DC/DC converter at constant discharge power

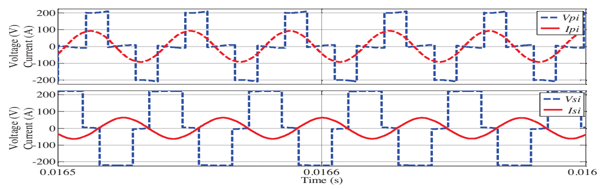

Fig. 9. Voltages and currents at constant charge power of 10kw

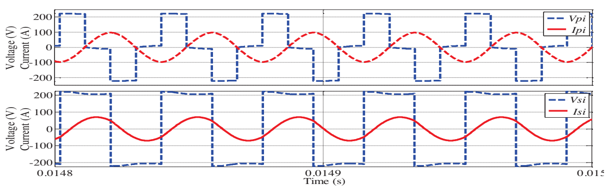

Fig. 10. Voltages and currents at constant discharge power of 10kw

Fig 9 and Fig. 10 are the voltage and current of the wireless power transfer system, it realizes the charge and discharge of EVs by wireless coupling. Fig. 9 exhibits the voltages and currents of two inverters at charge power of 10kw, and Fig. 10 shows the voltages and currents of two inverters at discharge power of 10kw.

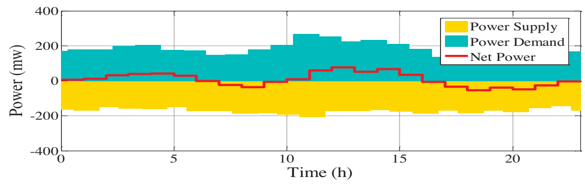

Fig. 11. The changes of power supply and demand

Suppose that the conventional power generation is constant without regulation, the REs generation and tradition loads of a day in some area is taken, the changes of power supply and demand is shown in Fig. 11, and the corresponding suggestion number of EVs to charge and discharge in each time interval is given in TABLE II.

TABLE II

The suggestion number of EVs in each time interval

Time Interval	Charge Number	Discharge Number	Time Interval	Charge Number	Discharge Number
0-1	-	-	11-12	7791	-
1-2	1089	-	12-13	5140	-
2-3	3046	-	13-14	6674	-
3-4	3987	-	14-15	3284	-
4-5	4167	-	15-16	-	-
5-6	2853	-	16-17	-	3460
6-7	-	-	17-18	-	5364
7-8	-	2356	18-19	-	3972
8-9	-	3718	19-20	-	4967
9-10	-	556	20-21	-	2525
10-11	777	-	21-22	-	-
11-12	5964	-	22-23	-	-

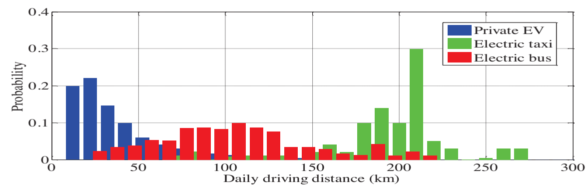

Fig. 12. The changes of power supply and demand

The daily driving distance probability of three different categories EVs is shown in Fig. 12.

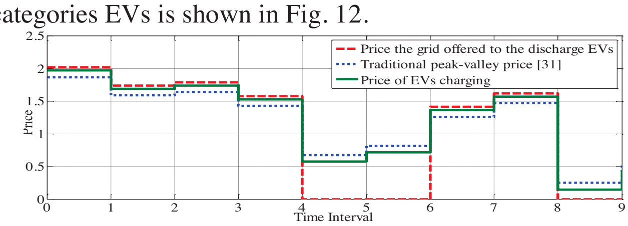

Fig. 13. The price comparison under different price mechanism

Obviously, the driving distance of electric bus is the longest and the most centralized due to the operation of all day. Therefore, the main objects to participate in the discharge process are private EVs and some electric taxis. They will obey the dispatching instructions to charge or discharge according to the grid actual demand. The traditional peak-valley price cannot stimulate the EVs to participate in discharge behavior. Compared to the peak-valley price, the different price is set. It can be seen from Fig. 13 that when the grid power supply is insufficient, the charging of EVs will increase the charging cost of EV owners, at the same time, the discharge of EVs to support the grid will get great rewards. When the grid power supply is sufficient, charging at this time will get a more favorable price.

V. Conclusion

The main contributions of this paper are as follows: First, the EV charge and discharge devices of the wired connection and the wireless connection were analyzed, and the corresponding controllers were designed to realize the charge and discharge control of EVs. Second, considering the different operation characteristics of the EVs, a charge and discharge integrated management mode with financial incentive mechanism was proposed to encourage the EV owners to participate in the power system activities. Finally, the effectiveness of the proposed charge and discharge control of EVs were verified by simulation results.

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Suwei Zhai was born in Hubei in China, on February 2, 1991. He obtained a bachelor degree from Hohai University. Now he studies for a doctorate in Hohai University.

His special fields of interest included modeling, analysis and control of the renewable energies integrated power system.