International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0985

RESEARCH ON ORDERED CHARGING OF ELECTRIC VEHICLES BASED ON DIFFERENTIATED CHARGING PRICE

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ABSTRACT

With the rapid growth of electric vehicle (EV), EV charging load has a significant impact on the safe operation of the power grid. An ordered charging control strategy is proposed in the paper based on differentiated charging price. In the strategy, different charging prices, which are aimed at mobilizing the participation of ordered charging behavior, are accessible for EV users. In nature, relatively lower charging price is for the EV user's license of the translation of EV charging load, i.e., the EV charging load is permitted to be moved to expected period during which the grid is with valley electricity load. The effectiveness of the proposed method is verified by the analysis of the benefits of various stakeholders.

Keywords: differentiated electricity price, ordered charging, departure time, minimum charging time, benefit

1. INTRODUCTION

As electric vehicle (EV) has many advantages, e.g. it is friendly to environment, EV are vigorously developed all over the world[1-3]. With the rapid growth of EV, an increasing charging load is overlapped onto the traditional load of power grid, which may lead to deterioration of the power grid operation. Therefore, it is necessary to properly control the charging behavior of EVs. In addition, EV users[4], EV charging stations[5] and power grids[6,7]are all stakeholders related to EVs. When necessary measures are taken, the benefits of different stakeholders should all considering[8].

In nature, an ordered charging control of EVs is to realize the translation of the EV charging load on time scale. In fact, to complete an EV charging business the EV user only needs to provide two information to the charging station: the departure time and the target charging amount. The former reflects the urgency of the charging demand, and the latter represents the value of charging demand. In general, there are two kinds of methods to realize ordered charging of EVs: direct charging load control and time-of-use (TOU) electricity price guiding[9]. In [9], oriented to the electric vehicle charging station, a method of TOU charging price is proposed based on the comprehensive consideration of the user's charging demand and the changing of grid load. Peak shaving and valley filling are realized by demand response. In [10], the user's charging behavior is guided by formulating the peak-to-valley electricity price in different periods. A response model of the user's charging time selection to the peak-valley electricity price period is constructed, and the best peak-to-valley electricity price period is the one which could minimize the peak-to-valley difference. In [11], by establishing a two-layer electricity price optimization model involving system scheduling mechanism and electric vehicle charging station, the optimal scheduling of the upper system and the autonomous response of the lower electric vehicle users is achieved.

Noticeably, when taking ordered charging intervention, followings are necessary. On one hand, the fair participation status of EV users. They should not be directly controlled. On the other hand, the enthusiasm and effectiveness of electric vehicle users' participation. However, the above two aspects have not yet been

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

considered in existing research effectively at the same time. An ordered charging strategy based on differentiated charging price is proposed in the paper. Its biggest feature is to provide EV users different charging schemes. Generally, the scheme with higher charging price can complete the charging task in short time and the scheme with lower charging price will meet the charging task with long stay period. With this handle, both fairness, enthusiasm and effectiveness are taken into consideration.

It should be noted that the essence of the strategy proposed in the paper is to provide relatively lower charging price for the license of the translation of EV charging load, which makes sense in places where the EV charging pile is enough. In actual system, places, liking residential community and companies, can or will meet above requirements. A charging simulation case in company scene is studied. From the perspective of the changes of different stakeholders, the results show that the ordered charging control strategy is effective.

2. THE SHORTCOMINGS OF CONDUCTING ORDERED CHARGING CONTROL ONLY WITH TIME-OF-USE ELECTRICITY PRICE STRATEGY

TOU electricity price is an effective guiding mechanism. Period is divided into several kinds: period with peak electricity price, period with valley electricity price. Electricity price difference is aimed at motivate users to charge their cars at different times to realize peak shaving and valley filling. By cutting down the peak load, the distribution network can realize safe and stable operation. With the guidance of TOU electricity price, many EVs choose to charge at the beginning of valley electricity price. Fig 1 gives the charging diagram, and it is likely new load peak appears.

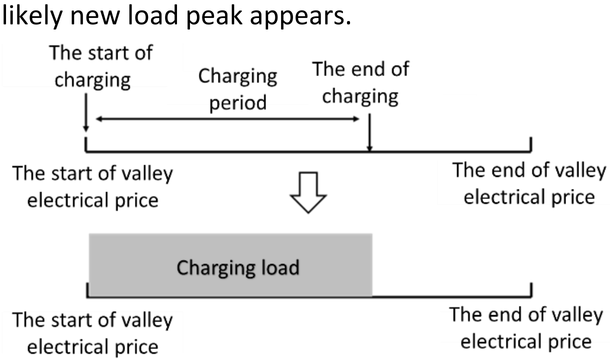

Fig.1 Charging diagram under TOU price guiding

Now we assume that a certain region has implemented TOU tariff policy, and valley electricity price begins at 22:00. The maximum daily load of the original load is 1000kW. The garage of the village can charge all the electric vehicles at the same time. The number of electric vehicle considers 80, 100, and 120 respectively to compare the changes in the load curve caused by EVs. The load curve with EV charging load is shown in Fig 2. It can be found that under the guidance of TOU electricity price information, there is a new obvious peak load. What's more, a valley load is tightly followed the peak load.

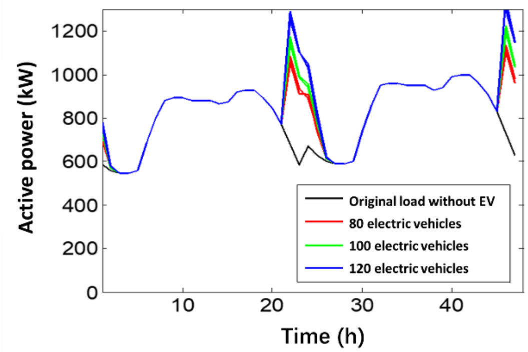

Fig.2 Total active power with EV charging load

3. ORDERED CHARGING CONTROL THEORY

Lithium-ion batteries have been widely used in EV field. Lithium-ion EV is studied with slow charging mode.

3.1 Resources for ordered charging control

The state of charge (SOC) of the battery is denoted as SOC, which indicates the ratio of the remaining electricity in battery to its rated capacity. In a charging station, an EV enters with initial SOC_{begin} at T_{begin}. The expected departure time is denoted as T_{end}, and the expected charging state when leaving charging station is SOC_{end}. The rated capacity of the battery is E, and the rated charging power is P. So, the minimum charging period, denoted as ΔT, of the car is:

$$\Delta T=(SOC_{\mathrm{end}}-SOC_{\mathrm{begin}})*E/P \qquad (1)$$

The EV stay period, denoted as δT, is:

$$\delta T=T_{\mathrm{begin}}-T_{\mathrm{end}} \qquad (2)$$

The prerequisite for ordered charging control is $\Delta T<\delta T$. T_{end} and SOC_{end} are the most important information inputed by EV user.

In EV slow charging mode, the bigger of the difference between the EV stay period and the minimum charging period is, the higher of the flexibility that the charging station conduct ordered charging control will be. That is, the resource that the charging station owns to conduct ordered charging control is the difference between δT and ΔT. If the period, δT-ΔT, can be mastered by the charging station through optimization measures, higher profit and other goals can be achieved. However, in existing researches, a user's departure time T_{end} is randomly inputted by the user. Even if the difference δT-

ΔT allowed by the user is very big, there is no corresponding economic compensation. It is very unreasonable. In actual, we cannot stand in the perspective of "God" to try to maximize the benefits of various stakeholders only through complex control strategies. Differentiated electricity price is suggested to longer available δT-ΔT.

3.2 The impact of differentiated electricity price on the available charging period

At first, establish the relationship between δT and differentiated charging price.

$$\delta T=\beta*\Delta T \tag{3}$$

$$p_{cha}=\alpha*p_{sta}=f(\beta)*p_{sta} \tag{4}$$

Here, β is the proportional relationship of δT to ΔT; p_{sta} is the current charging price of the power station, e.g., 1 ￥/kWh; α is the proportional relationship of p_{cha} to p_{sta}, and α is a function of β.

Then, the ratio of users responding to the differential charging price to total EV users is denoted as η. The relationship, $\alpha=f(\beta)$, directly impacts the enthusiasm η, which in turn affects the charging resources available to the charging station and ultimately affects the revenue of the charging station. By studying the relationship between formula $\alpha=f(\beta)$ and η, it is possible to analyze the sensitivity of the charging station revenue based on the differentiated charging price, and finally obtain the charging price that maximizes the revenue of all related stakeholders. The more intense $f(\beta)$ changes, the larger the value of η is.

Finally, under the premise of meeting the EV charging demands, the ordered charging control of electric vehicles is carried out with the goal of smoothing the load curve of the power grid.

4. BENEFIT FUNCTION OF DIFFERENT PARTICIPANTS

Ordered charging strategies can benefit various participants, including power grid, electric vehicle charging stations, electric vehicle users, *etc*. The difference in benefits between ordered and out-of-order charging is the benefit of the ordered charging strategy.

To grid enterprises, its control goal is to minimize the annual peak load and the network loss, and the benefit is the reducing money in investment cost corresponding to the reduction of grid capacity and reduction in network loss:

$$C_1=\sum_{d=1}^{365}\sum_{t=1}^{t_{to}}p_{d,t}^2*\Delta t \tag{5}$$

$$C_2=C_{net}\times\max(p_{d,t}) \tag{6}$$

Among which, $P_{d,t}$ indicates the total load, with EV charging load, at the tth interval in dth day; t_{to} represents the total number of time intervals Δt in each day, where Δt can be 15 minutes, or 1 hour or other values; C_{net} represents the unit capacity investment of power grid; and denote the grid loss cost and system investment cost.

As a profit-oriented enterprise, the EV charging station is regarded as a profit- target body. Its cost is the electricity purchasing cost from power grid and the direct benefit is the charge fee of EV users:

$$C_3=\sum_{d=1}^{365}\sum_{t=1}^{t_{to}}\sum_{j\in\Omega_{st}}(S(d,t,j)*\Delta P*\Delta t*C) \tag{7}$$

Among which, $S(d, t, j)$ represent the charging state of the jth electric vehicle at the tth time interval in dth day, charging state is 1, and static state is 0. ΔP indicates active charging power.

To EV user, it wants the charging cost to be minimized under the premise of meeting charging requirements. The calculation formula of charging cost is:

$$C_4=\sum_{d=1}^{365}\sum_{t=1}^{t_{to}}S(d,t)*\Delta P*\Delta t*C \tag{8}$$

Among which, $S(d, t)$ represents the charging state of the EV at the tth time interval in dth day, and C represents the charging price. The target of ordered charging control is to get a maximum total benefit of EV users, EV charging station and power grid corporation.

5. CASE STUDY

The charging station of parking lot in company/enterprise is selected, where adequate charging piles are available. As the EV stay period δT is long enough relative to the time required for charging, only slow charging mode is used to extend the life of EV battery.

5.1 Case parameters

The referenced charging price in the charging station is 1.5 yuan/kWh, and the relationship between β and $f(\beta)$ is shown as Table 1.

Table.1 The relationship between β and $f(\beta)$

β	$f(\beta)=1/\beta$	$f(\beta)=1/\beta^2$	$f(\beta)=1/\sqrt{\beta}$
1	1	1	1
1.5	0.667	0.444	0.816
2	0.5	0.25	0.707

Generally speaking, the more the deduction in charging price is, the more EV users respond to the incentive policy. The assumed participation ratio of user responding the differentiated charging price is shown in Table 2. For company, the users' entry time is subject to a standard normal distribution with an average of 8:00 and a standard deviation of 0.5 hour. The user's departure time is subject to a standard normal distribution with an average of 18:00 and a standard deviation of 0.5 hour. When the user enters the community, the SOC of the electric vehicle conforms to the uniform distribution of [0.2 0.4]; When the user leaves the company, the required SOC of the EV conforms to a uniform distribution of [0.6 0.8].

Table.2 Positive relationship between η and $f(\beta)$

	$f(\beta)=1/\beta$	$f(\beta)=1/\beta^2$	$f(\beta)=1/\sqrt{\beta}$
η	0.75	0.9	0.6

When calculating grid loss cost, the electricity price is suggested to be 0.7 yuan/kWh, and the resistance is 1Ω. For 1 kW saved system capacity, the system investment cost that can be saved is 8,000 yuan/kW. The TOU price information of the power grid is shown in Table 3. The original load of the system takes the recommended parameters of the IEEE-RTS system.

5.2 *Evaluation results*

The maximum power load of a company is 3000 kW. Now, 200 EVs are added. The EV charging results are shown in Table 4 and Table 5 with the no-ordered and ordered charging control strategy. When the no-orderly charging strategy is adopted, the increase investment in system capacity cost exceeds other costs obviously, reaching a number of 6.75 million ￥, which correspondingly an increase of 844 kW. Fig 3 shows the time-series load curve for the annual peak load day in this case. It shows that EV charging load is superimposed to the peak load from 9:00 to 11:00 in the morning.

Table. 3 TOU price information of power grid

	Valley 1:00~9:00	Peak 10:00~21:00	Valley 22:00~24:00
Electricity ￥/kWh	0.3	1.2	0.3

Table. 4 Annual evaluations with no-ordered charging

Annual charging electricity /MWh	C_4 /10^3￥	C_3 /10^3￥	$\triangle C_1$ /10^3￥	$\triangle C_2$ /10^3￥
874.5	1311.8	548.8	35.9	6754.2

Note: $\triangle C_1$ and $\triangle C_2$ mean the increased cost of C_1 and C_2 after the injection of EV charging load.

Table. 5 Annual evaluations with ordered charging

Charging strategy		Annual charging electricity /MWh	C_4 /10^3￥	C_3 /10^3￥	$\triangle C_1$ /10^3￥	$\triangle C_2$ /10^3￥
β=1.5	$f(\beta)=1/\beta$	87.65	882.7	694.9	26..1	2287.8
	$f(\beta)=1/\beta^2$	87.63	588.9	704.6	261	1755.2
	$f(\beta)=1/\sqrt{\beta}$	87.70	1081.1	676.3	26.2	22.0.8
β=2	$f(\beta)=1/\beta$	87.46	660.7	814.0	24.9	1155..2
	$f(\beta)=1/\beta^2$	87.58	331.3	829.7	24..9	944.8
	$f(\beta)=1/\sqrt{\beta}$	87.68	95.5	786.7	25.1	1416.0

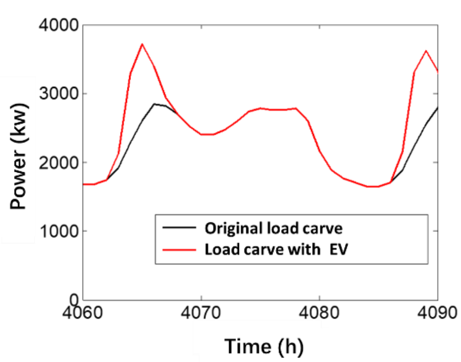

Fig.3 Time-series load curves in annual peak load day with no-ordered charging control

Under ordered charging strategy aiming at a more flattening load curve, the system capacity cost is greatly reduced, from 6.8 million to [0.94, 2.28] million yuan. Obviously, the orderly charging strategy under the differentiated charging price makes a big difference. Fig 4 shows the time-series load curve of the company's annual peak load day for β=2, $f(\beta)=1/\beta^2$. It shows that under the ordered charging strategy the peak charging load in Fig 3 has been greatly reduced.

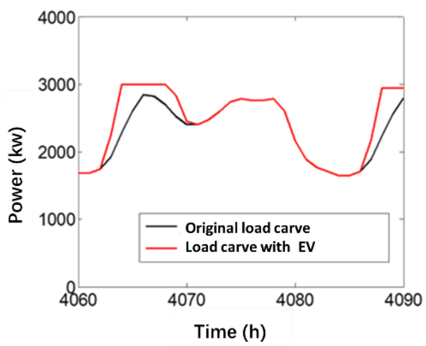

Fig.4 Time-series load curves in annual peak load day with ordered charging control

Followings can be found: (1) The increase of grid system capacity cost is the most critical cost, far exceeding other costs. (2) Above benefits are obtained under the premise of differentiated charging price, which means it is very necessary to taking differentiated charging price strategy to encourage EV users to extend the stay period δT. (3) The power grid corporation benefit is great, while the charging station earns less money. Therefore, the grid enterprises should provide certain compensation to the charging station.

6. CONCLUSIONS

Firstly, an ordered charging control strategy for electric vehicles based on differentiated charging price is proposed. The essence of the creative strategy is to exchange for a longer EV staying period with at the cost of lower charging price to EV users. Then, the available resources, the translation of EV charging load on time scale, is used to achieve an increase in benefits from EV users, EV charging station and power grid corporation. Finally, with a time-series simulation to a company with 200 EVs the effectiveness of the differentiated charging price strategy is verified. It can bring huge economic benefits by motivate users to extend the charging time of electric vehicles.

ACKNOWLEDGEMENTS

This work was supported by the fund of the 2016 Field Strategy Research Project of Chinese Academy of Engineering (2016-ZCQ-06).

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