Optimization Strategy of Electric Vehicle Charging Based on Electricity Price Demand Response

1st Ke.Xu
State Grid Jiangsu Electric Power Co.Ltd.Research Institute
Nanjing, China
15105168883@163.com

2nd ShuHui Ren
College of Electrical Engineering and Control Science
NanJing tech univesity
NanJing, China
360167160@qq.com

3rd Bing Xie
State Grid Jiangsu Electric Power Co.Ltd.Research Institute
NanJing, China
xbcquhv@163.com

4th Xun Dou
College of Electrical Engineering and Control Science
NanJing tech univesity
NanJing, China
dxnjut@njtech.edu.cn

5th Pan Zhang
College of Electrical Engineering and Control Science
NanJing tech univesity
NanJing, China
zpanjing@163.com

***Abstract*—With the rapid development of electric vehicles at home and abroad, as an electric load, electric vehicles have an increasing impact on the power grid. Therefore, it is of great significance to study the charging optimization strategies of electric vehicles. This paper proposes an electric vehicle charging optimization strategy based on electricity price demand response. First, based on the driving characteristics of electric vehicles, the load model of electric vehicles in disordered charging mode is established. Then, considering the real-time electricity price, a multi-objective charge-discharge model of electric vehicles under different weight combination modes is established. Finally, through a comparative example, the charging and discharging schemes of electric vehicles in different scenarios are analyzed and compared, and the effectiveness of the multi-objective optimal control strategy for electric vehicles proposed in this paper is verified, which is conducive to coordinating the impact of load fluctuation regulation on consumer interests, to achieve optimization of multi-objective cars.**

Keyword—electric vehicle, multi-objective optimization, disorder charging, real-time electricity price, particle swarm optimization

I. Introduction

In today's world, a large number of various types of fuel vehicles consume a large amount of oil resources, at the same time produce a huge amount of greenhouse gases, exacerbating the world energy crisis and environmental problems [1]. Electric vehicle (EVs) takes electric energy as its power source, which can reduce the consumption of oil resources in the field of transportation, and the battery can achieve zero emission, which has the characteristics of environmental protection and energy saving. Therefore, the development of electric vehicles has become the focus of attention in various countries in the world. But previous studies have shown that electric vehicles connected to the grid charging may have a significant potential impact on the grid [2]. The charging behavior of electric vehicles is generally disordered, which has the characteristics of strong timeliness and high rate, so it will bring adverse effects to the power grid. From the perspective of the power system, since the autonomous charging cycle of the electric vehicle is consistent with the peak load cycle of the residents, when a large number of electric vehicles are charged at the peak of electricity consumption, the peak-valley difference will be further increased, resulting in lower line voltage, transformer overload or other circuit failure. Moreover, when a large-scale charging vehicle is connected to the power grid, it may change the distribution of power flow in the power grid, increase the maximum voltage offset, and increase the network loss of the distribution network. If they can be effectively regulated, they will play a key role as demand-side resources for smart grid infrastructure [3]. Therefore, how to optimize its charging strategy is an urgent problem to be solved.

Relevant scholars have been working on related research on charge strategy of electric vehicles. Literature [4] studied the charging methods of electric vehicle batteries and the basic concepts of charging stations. The expected number of electric vehicles will increase significantly in the future, and the impact on the distribution network will also be more significant, so it is very necessary to use the management capabilities of charging stations. [5] proposed a multi-layer frame of Vehicle-to-Grid, which introduced an internal grid structure, cleverly use of aggregator to gather electric vehicles. Once connected to the grid for charging and discharging, it can be expanded to absorb energy and feedback energy from the grid, respectively, to achieve peak shaving during the day and valley filling at night, and cleverly control the power flow in the intranet and grid. [6] briefly describes the harmonic pollution of electric vehicles to the power grid. Various types of rectifiers used in the chargers of electric vehicle charging stations will generate higher harmonics, mainly the fifth and seventh orders, which will affect the power supply. quality and stability on the grid side. [7] summarizes the impact of electric vehicle charging on the power grid, introduces the characteristics of the charger equipment in detail, and explains various

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mainstream rectifiers. Finally, it summarizes the electric vehicle charging in power supply capacity planning, power quality, and environment. The impact of the four aspects of impact and load stability and its application in V2G connection communication, peak and valley filling, frequency adjustment of the power system, and coordinated operation with intermittent new energy. [8] mainly expressed the influence of electric vehicle charging load on the Danish distribution network. Denmark has sufficient wind resources, and wind power occupies a large proportion of power system power generation. This article describes the effect of electric vehicle charging load on the wind power output curve. The results show that both have a good promotion effect. Wind power can reduce the voltage offset and network loss caused by the electric vehicle charging to the distribution system, and electric cars can consume wind energy. [9] evaluated the impact of electric vehicles on the distribution network, and used distributed photovoltaic power generation to optimize the charging behavior of electric vehicles and reduced the impact on the distribution network. [10] evaluated the impact of electric vehicles on the distribution network impact, and use distributed photovoltaic power generation to optimize the charging behavior of electric vehicles and reduce the impact on the distribution network. [11] predicts the charging load of electric vehicles, analyzes the effect of disorderly charging of electric vehicles on the active distribution network, as the results show that no charging may cause overload and congestion in local power grids. [12] shows that large-scale penetration of electric vehicles will have a significant impact on the operation of distribution networks. [13] focuses on the analysis of the harmonic effects of electric vehicles connected to the grid, and analyzes the principle of harmonic generation from the three-phase bridge rectifier circuit of single to multiple chargers, and provides from the selection and improvement of charger a method for controlling harmonics in charging stations is provided.

There are also many researches on electric vehicle charging optimization strategies based on demand response. [14] proposes an orderly charging strategy for electric vehicles responded by users autonomously, and studies the impact of large-scale electric vehicle electric vehicle charging on the power grid. [15] considers the goal of peak-to-valley difference and minimum peak value, and optimizes the charging and discharging of electric vehicles using time-of-use electricity prices. [16-17] studied the charging and discharging strategies of electric vehicles participating in the electricity price demand side response.

The above literature has made a more in-depth discussion on the charging and discharging characteristics of electric vehicles, load prediction and the impact of access to the grid. It can also guide electric vehicles to charge and discharge based on price-based demand response, but less consideration is given to the combination of different weights based on multi-target charging and discharging behavior of electric vehicles with real-time electricity prices. Based on this, this paper first establishes a model of electric vehicle's disorderly charging load. Then based on real-time electricity prices, considering the goal of smoothing load fluctuations and maximizing the income of electric vehicle owners, a multi-objective charging and discharging model of electric vehicles under different weight coefficients is established . Finally, the effectiveness of the proposed method is verified by an example analysis. The main contributions of this article are as follows:

(1)Considering the goal of smoothing load fluctuation and maximizing the income of electric vehicle owner, the multi-objective charge-discharge model of electric vehicle under different weight coefficients is established.

(2)Based on real-time electricity price, a multi-objective optimal control strategy for orderly charging of electric vehicles under real-time electricity price is proposed., which is conducive to coordinating the influence of load fluctuation regulation on consumer interests.

The structure of this paper is as follows: second section establishes model of disordered charging load for electric vehicles. The third section establishes the optimal control model of electric vehicle charging under real-time electricity price. Section 4 verify the model of the third section by example analysis. Section 5 summarizes the main findings of this paper.

II. Model of Unordered Charging Load for Electric Vehiclesof

In this paper, the charging time of electric vehicle is divided into 96 time sections according to 15 minutes as the time step, and the charging load of each electric vehicle is accumulated in each time period, so that the daily charging load curve of 96 points of all electric vehicles is obtained. The formula is as follows:

$$L_t is \sum_{nis1}^{N} P_{n,t} \text{,} \quad 1 \leq t \leq 96 \qquad (1)$$

Where, L_t is the total charging load of the electric vehicle in the *t-th* period, unit kW. $P_{n,t}$ is the charging power of the *n-th* electric vehicle in the *t*-th period, unit kW.

Assuming that private car owners start charging electric vehicles as soon as they get home from work, the probability distribution model followed at the start of charging is as follows:

$$f_t(x) = \frac{1}{\sqrt{2\pi}\sigma_t} exp\left[-\frac{(x-\mu_t)^2}{2\sigma_t{}^2}\right], 0 \leq x < 24 \qquad (2)$$

Where, μ_t is the mean value of x in the above Gaussian distribution, here is 19.47. σ_t is the standard deviation of x in the above Gaussian distribution, here is 3.41. The probability density function of the average daily driving distance of electric vehicles is:

$$f_m(x) = \frac{1}{\sqrt{2\pi}\sigma_m} exp\left[-\frac{(ln\, x-\mu_m)^2}{2\sigma_m{}^2}\right] \text{,} \quad 0 \leq x < 100 \qquad (3)$$

Where, μ_m is the mean value of x in the above distribution, where $\mu_m = 3.70$; σ_m is the standard deviation of x in the above distribution, where σ_m is 0.024. State of charge (remaining battery capacity) at the beginning of the charging cycle:

$$SOC_{sta} = (1 - \frac{m}{M}) \times 100\% \text{,} \quad 0 \leq m \leq 100 \qquad (4)$$

Where,SOC_{sta} is the initial SOC value of the electric vehicle. *m* is the distance the electric vehicle travels per day, in km. *M* is the maximum distance the electric vehicle travels per day, *M* is100km.

We can see from the m value that the starting SOC is also a random variable from the lognormal distribution. After we get the starting SOC, if we know the charging power of the electric vehicle, we can use the following formula to calculate the charging time of each electric vehicle:

$$T_{con} = \frac{(SOC_{max}-SOC_{sta})\cdot B_c}{\eta\cdot P_{n,t}} \quad (5)$$

T_{con} is the charging time of electric vehicles, unit h. SOC_{max} is the maximum SOC of electric vehicles. SOC_{sta} is the starting SOC of electric vehicles. B_c is the battery capacity of electric vehicles, unit kWh. η is the charging efficiency of electric vehicles, between 0-1 Time; $P_{n,t}$ is the charging power of electric vehicles in kW.

III. Real Time Optimal Control Model of Electric Vehicle Orderly Charging under Electricity Price

A. objective function

This section combines the minimization of the variance of the power load curve with the maximization of the profit of consumers participating in the electric vehicle on the basis of the real-time electricity price of the power market, so as to realize the multi-objective control strategy of the electric vehicle.

Mean variance's objective function of minimizing load curve is as follows:

$$\min F_1 = \sum_{t=1}^{T}\left(P_{l,t} - \sum_{t=1}^{T} P_{l,t}/T - \sum_{n=1}^{N} P_{n,t}\right)^2 \quad (6)$$

Where, T is the time period, that is, 24 hours a day. $P_{n,t}$ is the exchange power between the nth electric vehicle and the grid in the t-th segment (assuming that the charging power is negative and the discharging power is positive). N is the number of electric vehicles. $P_{l,t}$ is the original load in the period t.

The objective function that makes the owner obtain the highest profit is:

$$max\ F_2\ is \sum_{nis1}^{N}\sum_{tis1}^{T}(C_{n,t}+D_{n,t}) \quad (7)$$

$$C_{n,t}\text{isp}(t)\cdot P_{n,t}\cdot\eta\cdot t \quad (8)$$

$$D_{n,t}\text{isp}(t)\cdot\frac{P_{n,t}}{\eta}\cdot t \quad (9)$$

Where, T is the time period, that is, 24 hours a day. N is the number of electric vehicles. η is the charge and discharge efficiency. $C_{n,t}$ is the cost of charging the n-th electric vehicle in the period t. $p(t)$ is the real-time price in the t-th period. $D_{l,t}$ is the profit of the discharge of the n-th electric vehicle in the period t. $P_{n,t}$ is the exchange power of the n-th electric vehicle and the grid in the period t.

The objective function that minimizes the mean square error of the power load curve and maximizes the profit of users with different weight coefficients is as follows:

$$\min F = \omega_1\cdot F_1/F_{1\max} - \omega_2\cdot F_2/F_{2\max} \quad (10)$$

Where, F_{1max} and F_{2max} is the maximum value of F_1 and F_2 . ω_1,ω_2 is the weight coefficient,. $\omega_1+\omega_2=1, 0\le\omega_1,\omega_2\le 1$.

B. Constraints

(1) Power constraints

Maximum charge/discharge power per EV

$$P_{n,t\min}\le P_{n,t}\le P_{n,t\max} \quad (11)$$

(2) Capacity constraints

Excessive charging and discharging of electric vehicle batteries will affect life, so the capacity constraints are as follows:

$$0.2\le SOC\le 1 \quad (12)$$

(3) Charging Demand Constraint

Before the user takes the car, the battery charge must reach the user's preset value and be less than equal to the total capacity of the battery.

$$SOC_{pre}\cdot B_c\le SOC_{sta}\cdot B_c+\sum_{t}^{t+T_{con}}(P_n\cdot\eta\cdot\theta_{n,t}\cdot\Delta t) \quad (13)$$

$$SOC_{sta}\cdot B_c+\sum_{t}^{t+T_{con}}(P_n\cdot\eta\cdot\theta_{n,t}\cdot\Delta t)\le B_c \quad (14)$$

Where, Δt is the charging time step size. SOC_{pre} is the SOC desired by the user at the end of charging.

(4) Total charge constant

The total charge quantity of electric vehicle in this optimization model should be the same as the integral value of the disorderly charge load curve of electric vehicle.

$$\sum_{t=1}^{T}\sum_{n=1}^{N}P_{n,t}\cdot\eta\cdot\theta_{n,t}\cdot\Delta t=\int_0^{24}P(t)dt \quad (15)$$

(5) Charging Time Limit

The charging time must be less than the time from the start time of charging to the time of taking the car.

$$T_{con} < T_{end} - T_{sta} \quad (16)$$

T_{end} is pick up time for users.

IV. Example Analysis

In this paper, according to the basic load value of a substation in 96 time periods, the load curve of the substation is drawn 24 hours a day. The disordered charging load of the electric vehicle obtained by the above method is increased to each time period of the original load, and the daily load curve diagram of the substation including the disordered charging of the electric vehicle is obtained based on the disordered charging load model of the electric vehicle. The black curve represents the original load of the substation, the blue curve represents the EVs charging load, and the red curve represents the total load including EVs charging.

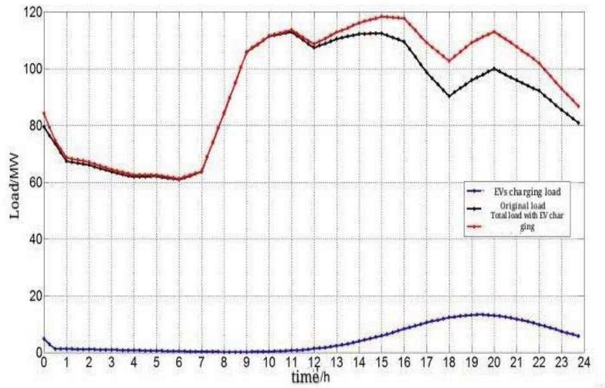

Fig. 1. Daily load curve of substation

A. Analysis on the Influence of Unordered Charging Behavior of Electric Vehicles

From the above analysis and Figure 1, it can be seen that most of the electric vehicle's charging load is distributed between 16:00 and 23:00, and it is most concentrated around 20:00, which will cause a "peak" during the peak period of the original load. The "upper peak" situation has increased the operating pressure of the power grid, and has also increased the loss of electrical equipment in the power grid. In the future, the number of electric vehicles will increase rapidly, and the penetration rate of electric vehicles into the grid will further increase. If electric vehicles are still charged in this disordered and random manner, it will have a serious impact on the grid. For electric car owners, the peak electricity consumption period is from 19:00 to 21:00, and the electricity price is higher. Charging within this time will make the charging cost very high, reducing the enthusiasm of users to use electric vehicles, which is not conducive to the development of electric vehicles.

B. *Real-time electricityAimed at smoothing power load fluctuations as far as possibleOptimal Control Strategy for Electric Vehicle Orderly Charging*

Only to smooth the fluctuation of power load for the orderly charging of electric vehicles, the switching power of electric vehicle and power grid in each period is shown in the following figure2.

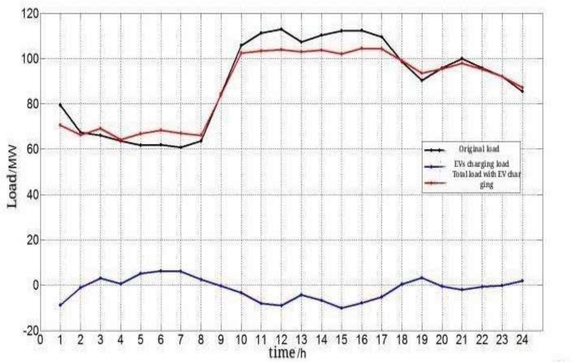

Fig. 2. Daily load curves of electric vehicle orderly charging substation

As can be seen from figure 2, after the electric vehicle is connected to the grid, the load power curve becomes smooth. However, due to power and capacity limitations, the curve cannot be a straight line.

C. *Optimized control strategy for orderly charging of electric vehicles with the goal of maximizing consumer benefits under real-time electricity prices*

The equations are an exception to the prescribed only for the purpose of maximizing consumers' interests, the electric vehicles are charged in an orderly manner. The exchange power between the electric vehicles and the grid in each period is shown in the table below.

TABLE I SWITCHING POWER OVER TIME PERIODS

Duration/ h	Power/ MW	Duration/ h	Power/ MW	Duration/ h	Power/ MW
1	-6.5677	9	14.9882	17	-6.9528
2	-1.5399	10	12.7917	18	-4.2325
3	-0.5697	11	11.3087	19	0.5768
4	-5.0418	12	14.7916	20	14.9162
5	1.4583	13	-6.9679	21	14.2652
6	4.7999	14	2.7512	22	-0.7520
7	-6.2527	15	-6.9970	23	0.7707
8	0.6540	16	-6.9188	24	14.9866

It can be seen from table 1 that electric vehicles respond to real-time electricity price changes, find the optimal charging and discharging plan, and obtain a maximum power trading spread profit of 70218.26 yuan. At 9:00-12:00, 20:00-21:00, the electric vehicle is in a discharged state, and the price is high during the maximum discharge power is turned on. At 1, 7, 15h, etc, the electric vehicle is in a charged state when charging the maximum power, the price is lower, so you can get the most profit. This method is consistent with the strategy that electric vehicles discharge when the price is higher and charge when the price is lower, so the correctness of the PSO algorithm is verified.

D. *Multi-objective optimal control strategy for orderly charging of electric vehicles under real-time electricity price*

The particle swarm optimization algorithm [18] is used to solve the optimal control model for the orderly charging of electric vehicles under the real-time electricity price in section 3. The parameter settings are shown in table 2.

TABLEII MAIN PARAMETERS OF PARTICLE SWARM OPTIMIZATION ALGORITHM

V_{min}	V_{max}	c_1	c_2	ω	Particle swarm size	Evolutionary times
-4	4	1.495	1.495	0.6	30	3000

Among them, V_{min} is the particle speed limit, V_{max} is the particle speed limit, c_1 is the acceleration constant, c_2 is the acceleration constant, and ω is the inertia factor.

When the weight coefficients are different, the results are also different. Therefore, under three different combinations of weight coefficients, the results are shown in figure 3.

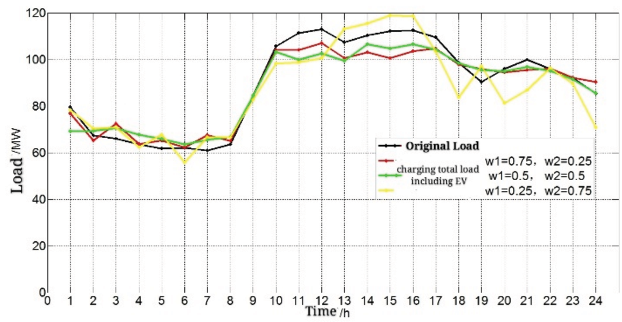

Fig. 3. Daily load curves under different weight coefficients

TABLE III PROFITS BY WEIGHT

Serial number	Weight coefficientω_1	Weight coefficientω_2	Income/yuan
1	0	0	39873.5
2	0.75	0.25	42303.6
3	0.5	0.5	43164.9
4	0.25	0.75	68362.5
5	0	1	70218.3

Consumers' benefits in multi-objective optimal control strategy and single-objective optimal control strategy are shown in table 3. It can be seen from figure 3 that as the weight coefficient is biased toward load fluctuation adjustment, the load power curve becomes flatter, but the impact is less than the single target adjustment. As can be seen from table 3, as the weighting coefficient is biased towards profit, the profit of the car owner is increasing. Although the profits of consumers have dropped significantly, the peak shaving effect has improved significantly after changing the weighting factor. Therefore, we can use different combinations of weighting coefficients as different needs, and coordinate the impact of load fluctuation regulation on consumer interests, so as to achieve multi-objective optimization.

V. Conclusion

This article first discusses the factors that affect the charging behavior of electric vehicles, establishes a model of electric vehicle random charging load, and analyzes the goal of smoothing load fluctuations and maximizing the benefits of electric vehicle owners based on real-time electricity prices. Multi-objective charge-discharge model of electric vehicles under different weight coefficients. In the MATLAB environment, the particle swarm optimization algorithm is used to solve. Finally, the multi-objective control optimization strategy for electric vehicle charging and discharging under real-time electricity prices is obtained, and the following conclusions are drawn:

- As the weight coefficient is biased toward the adjustment of load fluctuations, the load power curve becomes flatter, but the impact is less than that of a single target adjustment.
- As the weighting coefficient is biased towards profit, the profit of car owners is increasing. Although the profits of consumers have dropped significantly, the peak shaving effect has improved significantly after changing the weighting factor.
- Through the combination of different weight coefficients, it is conducive to coordinate the impact of load fluctuation regulation on consumer interests, so as to achieve multi-objective optimization.

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