Charging Load Management of Electric Cruise Ships Based on Price Incentive

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Abstract. The disorderly charging of electric cruise ships will widen the peak-to-valley difference of the power grid. Reasonable adjustment of the charging behaviour of electric cruise ships can effectively smooth the peak-valley difference and achieve peak clipping and valley filling. Based on the forecast value of the number of electric cruise ships in the Baiyangdian area in 2022, a price incentive demand-side management model was constructed and Monte Carlo simulation was used for model calculation. The results show that under the price incentive model, the electric cruise ship users are charging at the valley of electricity consumption, and the load peak-to-valley difference and load smoothness coefficient will be reduced. While electric cruise ship service providers obtain additional benefits, charging costs for electric cruise ship users are decreased.

Keywords: Electric Cruise Ship, Disordered Charging, Price Incentive, Monte Carlo Simulation

1. Introduction
With the extensive use of fossil fuels, environmental pollution problems have become increasingly prominent. Electric energy substitution is one of the best ways to solve this problem [1]. Electric vehicles and electric cruise ships have the advantages of low energy consumption and low pollution compared with traditional fuel cars and fuel ships. With the help of V2G technology, the power grid can obtain auxiliary services such as peak shaving and frequency adjustment through electric vehicles [2]. Large-scale electric vehicles and electric cruise ships are linked to the grid for charging without being controlled and guided, which will inevitably affect the safe and stable operation of the grid.

In recent years, domestic and foreign researchers have devoted themselves to the research of electric vehicle charging management. Various charging strategies have been proposed to realize the orderly charging of electric vehicles. Zhang Lei and Li yaoyu proposed a two-stage approximate dynamic programming framework to optimize electric vehicle charging management [3]. Tong jingjing et al. established a multiple target optimal scheduling model for centralized charging of EVs on the basis of time-of-use electricity prices [4]. Chen mingqiang et al. proposed an orderly charging
method for micro-grid EVs, which effectively avoids the problem of peak load caused by a great deal of EVs linked to the grid [5]. Hu dequan et al. established an electric vehicle charging double-layer optimization model based on electricity price guidance, which realized the optimal scheduling of the upper layer system and the autonomous response of the lower layer EV users [6]. Chen lixing and Huang xueliang considered the operating status of charging stations and the charging behavior of EV users, and an orderly charging strategy based on the new electricity price mechanism to encourage users to resize the charging time is proposed [7]. The research on charging management of EVs can bring many benefits. On the one hand, peak load reduction can be realized. On the other hand, significant economic benefits can be brought. Wang Xin et al. proposed a strategy of orderly charge and discharge control for EVs considering user factors. Under this strategy, operators obtain additional benefits, and user charging costs are reduced, achieving a win-win situation for operators and electric vehicle users [8]. Ye Tao and others optimized the charging strategy of EVs to significantly reduce the peak-to-valley difference and equivalent load fluctuation of the power grid. The safety and economy of the power grid are significantly improved. [9]. Wang xiaolei et al. analyzed the potential economic benefits of the orderly charging of EVs from two aspects of investment and operation. With the help of the comprehensive benefit evaluation model of electric vehicles charging management, the comprehensive benefit calculation of orderly charging management of EVs has been completed [10].

Due to environmental and technical constraints, electric cruise ships can only be charged at shore terminals and waterway terminals. The disorderly charging of electric cruise ships increases the load sharply, leading to an increase in the load peak-valley difference, which seriously affects the safety and stability of the power grid. The above problems can be effectively solved by orderly management of electric cruise ship's charging load with price incentive model. Meanwhile, electric cruise ship service providers obtain additional revenue and reduce user charging costs.

2. Price Incentive Model

After the electric cruise ship is docked at the dock, the user of the electric cruise ship reserves the charging time with the smallest charging cost according to the existing charging electricity price, and the staff of the electric cruise service provider is responsible for charging the electric cruise ship. Electric cruise ship service providers aim to maximize their own profits (shown as formula 1).

$$\max \sum_{t \in T} (c_{i,t} - c_{t'}) p_{i,t_0}$$

Where $t$ represents time $t$; $T$ is the time period divided for demand side management; $c_{i,t}$ refers to the i-th electric cruise ship user charging unit price at time $t$; $c_{t'}$ represents the power purchase unit price of the electric cruise ship service provider at time $t$; $p_{i,t}$ refers to the charging power of the i-th electric cruise ship user; $t_0$ represents the duration of each period.

Keeping the grid load running smoothly is the goal of demand-side management, considering the load during the period of time when the electric cruise ship is charging. (shown as formula 2).

$$\min \omega = \left( \frac{\sum_{t \in T} (L_{t} + O_{t})}{T} - \left( \frac{\sum_{t \in T} (L_{t} + O_{t})^2}{T} \right) \right)^2$$

Where $L_{t}$ represents the charging load of the electric cruise ship at time $t$; $O_{t}$ refers to the basic load at time $t$, the residential electricity load and commercial electricity consumption of a certain area are included; $\omega$ represents load smoothness coefficient.

Use the dynamically changing charging load of electric cruise ships to price different charging users, and guide users to choose a reasonable charging time when their own interests are maximized. The specific implementation plan is as follows:

The initial charging electricity price $v_{t}$ at time $t$ is generated using the base load $O_{t}$ predicted one day in advance (shown as formula 3).

$$v_{t} = \frac{T O_{t}}{\sum_{t \in T} O_{t}} \times p$$
Where \( v_t \) refers to the initial charging price at time \( t \); \( p \) represents the basic charging price.

After electric cruise ship users arrive at the charging dock, they will book the charging time with the least charging cost based on the existing charging price. By considering the user's charging time and charging power, a new charging price is dynamically formed (shown as formula 4).

\[
v'_t = \frac{T(O_t + L'_t)}{\sum_{t \in T} (O_t + L'_t)} \times p
\]  

(4)

Where \( L'_t \) is the charging load of the electric cruise ship that has been reserved at time \( t \); \( v'_t \) represents the new charging price.

The number of electric cruise ship users is \( N \). Electric cruise ship users reserve the charging time one by one according to the order of returning to the terminal and maximize their own interests. The electric cruise ship service provider continuously updates the charging price at each moment until the last electric cruise ship charging user.

3. Case Analysis

The number of electric cruise ships in Baiyangdian area is expected to be 1118 in 2022. Monte Carlo simulation random sampling was used to establish statistical results reflecting the use and travel habits of electric cruise ships. The starting charging time of electric cruise ships approximately follows the truncated normal distribution of 18:00-24:00 (19:45, 5.412).

\[
f(t_{\text{start}}, \mu, \delta, 18, 24) = \frac{\Phi(t_{\text{start}} - \mu)}{\delta \Phi(24 - \mu) - \Phi(18 - \mu)}
\]  

(5)

Where \( t_{\text{start}} \) represents the start charging time.

The statistical results reflecting the daily mileage of electric cruise ships are obtained by random sampling through Monte Carlo simulation. The daily travel distance of electric cruise ships roughly follows the normal distribution of (40km, 8.232). With the help of Monte Carlo simulation, the starting charging time and mileage of each electric cruise ship to the dock are generated. Considering only the load in Baiyangdian area from 18:00 that night to 6:00 the next morning, the charging time of electric cruise ships is divided into 48 time periods, each of which lasts 15 minutes. The electric load of Baiyangdian area under the condition of disorderly charging of electric cruise ship is shown in Figure 1 (The abscissa 1 represents 18:00 in the evening and 48 represents 6:00 in the morning). As can be seen from Figure 1, the charging load of the electric cruise ship overlaps with the evening peak of the base load. The load peak-valley difference increased from 28.03% to 29.41%, an increase of 1.38%, and the load smoothness coefficient was \( 2.2685 \times 10^4 \text{MW}^2 \). The disorderly charging of electric cruise ships makes the peak-valley difference larger, but demand-side management can keep the grid load stable.

Figure 2 shows the total electricity load in Baiyangdian area under the price incentive model. In the case of price incentives, the electric cruise ship load is transferred to the night trough, which plays a role in suppressing peaks and filling valleys. Compared with the disorderly charging of electric cruise ships, the peak and valley difference decreased from 29.41% to 23.40%, a decrease of 6.01%, and the load stability coefficient was reduced from \( 2.2685 \times 10^4 \text{MW}^2 \) to \( 2.2439 \times 10^4 \text{MW}^2 \). The orderly charging of electric cruise ships under the price incentive model lessens the peak and valley load difference and effectively stabilizes the grid load.
Figure 1. All electric load of Baiyangdian area under the disorderly charging of electric cruise ship

Figure 2. All electricity load in Baiyangdian area under price incentive

Considering that the charging time for electric cruise ships is from 18:00 in the evening to 6:00 the next morning, on the basis of the peak and valley time-of-use price announced by Hebei Province: peak period 18:00-21:00, the charging price is 0.7805 yuan/kWh; stationary period 21:00-22:00, the charging price is 0.5644 yuan/kWh; valley period 22:00-6:00, the charging price is 0.3483 yuan/kWh. The results of economic benefit calculation based on this are shown in Table 1.
Table 1. Calculation of economic benefits (yuan)

| Name                  | Electricity cruise service providers purchase electricity cost | Electric cruise ship service providers sell electricity income | Profits of electric cruise ship service providers |
|-----------------------|-------------------------------------------------------------|----------------------------------------------------------|-------------------------------------------------|
| Disorder charging     | 25510.97                                                    | 52541.56                                                | 27030.59                                        |
| Price incentive       | 14376.00                                                    | 44738.52                                                | 30362.52                                        |
| Economic benefit      | 11134.97                                                    | 7803.04                                                 | 3331.93                                         |

4. Conclusion

When electric cruise ships are unordered charging, the peak and valley load difference in Baiyangdian area increased from 28.03% to 29.41%, an increase of 1.38%, and the load stability coefficient was $2.2685 \times 10^4$ MW². Under price incentives, the load peak-valley difference in the Baiyangdian area decreased from 29.41% to 23.40%, a decrease of 6.01%, and the load stability coefficient was $2.2439 \times 10^4$ MW². Orderly charging of electric cruise ships compared to disorderly charging, the charging cost of electric cruise users is decreased by 7803.04 yuan, and the electric cruise service provider has gained an additional economic benefit of 3331.93 yuan. The results of the example show that under the price incentive, the charging load of electric cruise ships shifts from peak to valley, which not only achieves peak clipping and valley filling, but also ensures the stability of power grid operation. Meanwhile, user charging costs are reduced, and electric cruise ship service providers obtain additional benefits.

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References

[1] Chen Xingying, Yu Qingyun, Xie Jun, et al. Benefit allocation method for electric energy substitution based on cooperative game theory[J]. Electric Power Automation Equipment, 2019,39(03):30-35+44. (in Chinese)
[2] Chen Kaiyan, Niu Yugang. Real-time scheduling strategy of electric vehicle based on vehicle-to-grid application[J]. Power System Protection and Control, 2019,47(14):1-9. (in Chinese)
[3] Zhang Lei, Li Yaoju. Optimal management for parking-lot electric vehicle charging by two-stage approximate dynamic programming[J]. IEEE Transactions on Smart Grid, 2017,8(4):1722-1730.
[4] Tong Jingjing, Wen Junqiang, Wang Dan, et al. Multi-objective optimization charging strategy for plug-in electric vehicles based on time-of-use price[J]. Power System Protection and Control, 2016,44(01):17-23. (in Chinese)
[5] Chen Mingqiang, Gao Jianfei, Chang Guogang, et al. Research on orderly charging strategy of micro-grid electric vehicles in V2G model[J]. Power System Protection and Control, 2020,48(08):141-148. (in Chinese)
[6] Hu Dequan, Guo Chunlin, Yu Qinbo, et al. Bi-level optimization strategy of electric vehicle charging based on electricity price guide[J]. Electric Power Construction, 2018,39(01):48-53. (in Chinese)
[7] Chen Lixing, Huang Xueliang. Ordered charging strategy of electric vehicles at charging station
on highway[J]. Electric Power Automation Equipment, 2019, 39(01): 112-117+126. (in Chinese)

[8] Wang Xin, Zhou Buxiang, Tang Hao. A coordinated charging/discharging strategy for electric vehicles considering customers’ factors[J]. Power System Protection and Control, 2018, 46(04): 129-137. (in Chinese)

[9] Tao Ye, Huang Miaohua, Chen Yupu, Yang Lan. Orderly charging strategy of battery electric vehicle driven by real-world driving data[J]. Energy, 2020, 193: 877-885.

[10] Wang Xiaolei, Yao Weifeng, Wen Fushuan, et al. Comprehensive benefit analysis of coordinated charging management of electric vehicles[J]. Electric Power Construction, 2015, 36(07): 194-201. (in Chinese)