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Research Article

Orderly charging strategy for electric vehicles based on multi-level adjustability

Changlong Teng^{a,b}, Zhenya Ji^{a,b}*, Peng Yan^c, Zheng Wang^c, Xianglei Ye^{a,b}

^aSchool of Electrical and Automation Engineering, Nanjing Normal University, Nanjing, China

^bInternational Joint Laboratory of Integrated Energy Equipment and Integration in Jiangsu Province, Nanjing, China

^cState Grid Jiangsu Electric Vehicle Service Co., China

Abstract. The development of electric vehicles (EVs) is one of the essential ways to reduce environmental pollution. With the rapid growth in EVs, an orderly charging strategy based on multi-level adjustable charging power is proposed to address the problem of increasing peak-to-valley difference due to disorderly charging in different scenarios. Based on the information of multi-level adjustable charging power, information about staying in the residential area, and charging demands of EVs, this research designs a centralized charging mode with complete information under the centralized scenario and a decentralized charging mode with incomplete information under the decentralized scenario. This research takes the minimization of peak-to-valley difference in the residential area as the objective function and considers that the charging pile can have the function of multi-level adjustable charging power to support these two scenarios. Two charging modes of the charging pile are designed, and orderly charging model of EVs in the residential area is constructed. EVs can select charging time and charging power by using Bluetooth or code scanning in the charging pile. This research aims to design two orderly charging modes to effectively implement peak shaving and valley filling while ensuring the charging demand of EVs. This research uses the CPLEX solver in MATLAB to solve the objective. The simulation results show that EVs can reasonably select the multi-level adjustable charging power under different scenarios and provide a reference for engineering related to orderly charging. Strategy 4, proposed in this research, has the lowest peak-to-valley difference of the four strategies. The peak-to-valley difference is only 87 kW under the centralized scenario, and the peak-to-valley difference is 282 kW under the decentralized scenario.

Keywords: Electric vehicles, Orderly charging, Multi-level adjustable charging, Different scenarios, Minimization of peak-to-valley difference



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1. Introduction

Societal awareness of environmental issues associated with vehicular emissions has spurred the development of cleaner transportation solutions (Nguyen *et al.*, 2022; Qin *et al.*, 2023; Tippichai *et al.*, 2023). In this respect, electric vehicles (EVs) are emerging as the defining transportation trend. In this research, the state has vigorously promoted and supported EVs due to their clean and environmentally friendly characteristics, and the number of EVs has been increasing (Ehsani *et al.*, 2021). Making full use of the dual nature of the source and load of EVs (Naqash *et al.*, 2021; Ahsan *et al.*, 2023) and reasonably guiding EVs to carry out orderly charging can not only satisfy the charging demand for EVs but also reduce the load pressure brought by EVs when they enter the residential area. Therefore, combining the multi-level adjustable charging power of the charging pile is of great importance to carry out orderly charging in centralized and decentralized scenarios to reduce the peak load in the residential area.

Currently, charging scenarios of EVs consist of two main types (Sanguesa *et al.*, 2021; Fachrizal *et al.*, 2020; Sharma *et al.*, 2023). The first type is a centralized scenario, in which a unified control center coordinates the charging process. The second type is a decentralized scenario, in which the charging power is

entirely chosen by EVs autonomously. Extensive research has been carried out in the existing literature on different charging modes of EVs in centralized and decentralized scenarios.

In references (Moghaddam *et al.*, 2017; Gao *et al.*, 2021; Du *et al.*, 2023; Gong *et al.*, 2020; Wang *et al.*, 2020a), they performed charging control for EVs with constant charging power and incorporate the role of interruptible charging power according to the objective function of the residential area. In (Wang *et al.*, 2021; Gong *et al.*, 2020; Zhang *et al.*, 2020; Turker *et al.*, 2018; Duan *et al.*, 2018; Alilou *et al.*, 2020), they did not only combine the interruptible charging power but also established the charging power constraint model of EVs, which sets upper and lower bounds of charging power. Furthermore, Yin *et al.*, (2021) and Hou *et al.*, (2022) developed a delayed charging strategy for EVs under constant charging power and discriminate the delayable time for each EV by defining the delayed charging coefficient. Huang *et al.*, (2015) reported the EVs are grouped into clusters using the end moment of trip, start moment of trip, charging duration, and maximum charging delay as discriminative quantities, and the delayed charging strategy is developed separately for each subgroup of EVs. In (Zhou *et al.*, 2020), considering the charging demand of different

* Corresponding author
Email: jizhenya@njnu.edu.cn (Z. Ji)

Table 1
Summary of charging modes

Literature	Centralized Scenarios	Decentralized Scenarios	Constant charging	Intermittent charging	Delayed charging	Multi-level charging
Moghaddam et al., 2017; Gao et al., 2021; Du et al., 2023; Gong et al., 2020; Wang et al., 2020a; Wang et al., 2020b	✓	×	✓	×	✓	×
Yin et al., 2021; Hou et al., 2022; Huang et al., 2015	×	✓	×	×	✓	×
Wang et al., 2021; Gong et al., 2020; Zhang et al., 2020; Turker et al., 2018; Duan et al., 2018; Alilou et al., 2020	✓	×	✓	✓	×	×
Zhou et al., 2020; Zhou et al., 2016	✓	×	✓	×	✓	✓

EVs, 7 kW is used for constant charging for EVs that cannot satisfy the minimum charging demand before leaving the residential area, and 3.5 kW is used for intermittent charging for EVs that can satisfy the minimum SOC demand before leaving the residential area. Zhou *et al.*(2016) specified the rated EV charging power at each moment, and each EV is charged intermittently with 0kW or rated charging power. In Wang *et al.*, (2020b), according to the primary load of the residential area and the charging demand of EVs, the total charging power of EVs is optimally controlled, and the charging power of each EV is regulated by a power allocation algorithm based on the calculated each coefficient. Existing literature studies on orderly charging methods are primarily based on constant, intermittent, and delayed charging power. Few involve orderly charging control with multi-level adjustable charging power. Research must further investigate the orderly charging effect of EVs when combined with multi-level adjustable adjustability. A summary of charging modes is shown in Table 1.

In addition, under centralized and decentralized scenarios, several research studies have explored various control techniques for EVs employing consistent charging power. Hui *et al.*, (2022) investigated the effect of orderly charging control of EVs in a centralized control scenario under price and incentives. In a centralized scenario, Wu *et al.*, (2021) examined the effect of orderly charging by adding a constraint that limits the number of charging times. Based on the distribution of EVs entering the residential area, Du *et al.*, (2023); Yin *et al.*, (2021) and Tao *et al.*, (2020) proposed orderly charging strategies in centralized scenarios by combining charging information. According to Yang *et al.*, (2015), the decentralized control unit determined the best time for EVs to charge by considering the load data from the centralized control center and the charging schedules of the EVs that have already accessed the charging stations. Faddel *et al.*, (2018) suggested a charging power purchase strategy for EVs to participate in the day-ahead power market. The strategy uses a decentralized control structure to reduce charging power purchase costs for users while also ensuring the economic operation of the grid. Renzhou *et al.*, (2016) introduced the alternating direction method of multipliers to transform the centralized control problem into a decentralized control problem. Wang *et al.*, (2018) and Al Zishan *et al.*, (2021) proposed a decentralized control method where charging tasks are decided independently by charging piles without the need for centralized communication. Hu *et al.*, (2022) proposed an improved ADMM algorithm in the decentralized scenario to improve the satisfaction of EVs and consider grid benefits. In a decentralized scenario, the EV adjusts the charging time and charging power according to the charging signal it receives (Fan *et al.*, 2020). Currently, the literature mainly focuses on the orderly charging effect of EVs in centralized and decentralized scenarios separately, and there is less research on the orderly

charging strategy in decentralized and centralized scenarios simultaneously. Therefore, it is necessary to design an orderly charging strategy that can support two scenarios simultaneously.

The contributions of this research are as follows: First, the charging strategy has two multi-level adjustable modes. It adjusts the charging time and charging power of EVs based on the information of multi-level adjustable charging power, information about staying in the residential area, and charging demands of EVs. Second, these two charging modes have broad applicability and can have good orderly charging effects in centralized charging mode with complete information and in decentralized charging mode with incomplete information. Third, this research has successfully independently developed a multi-level adjustable charging pile, and the orderly charging strategy can be applied in practical engineering. Through simulation results verification, the results show that our multi-level adjustable charging strategy can satisfy the charging demand of EVs in both centralized and decentralized scenarios while having good peak-shaving and valley-filling effects.

The objective of this research was to design two orderly charging modes for centralized scenarios with complete information and decentralized scenarios with incomplete information. The objective was achieved by integrating the multi-level adjustable function of the charging pile. The primary goal was to effectively implement peak shaving and valley filling while ensuring the charging demand of EVs. This research also proposed a multi-level adjustable orderly charging strategy based on independently developed charging piles, providing a reference for engineering.

2. Method

In the residential area, charging power of EVs is typically 7 kW (Knez et al., 2019) because this slow charging speed is sufficient to satisfy charging demand. To satisfy the charging demand of EVs while minimizing the peak-to-valley difference, charging



Fig 1. The charging pile with multi-level adjustability

piles with 4kW and 7kW have been designed in the literature (Zhou *et al.*, 2016). In order to achieve a better effect of peak shaving and valley filling, this research independently developed a charging pile with a multi-level adjustable function.

The self-developed charging pile has the function of multi-level adjustability and supports the orderly charging of centralized scenarios and decentralized scenarios. It supports various activation methods such as Bluetooth, card swiping, and code scanning. It can communicate with networking platforms, intelligent fusion terminals in residential areas, and smart meters via 4G or HPLC. It provides services for large power grids and residential areas. It helps business users as well as residential users participate in orderly charging.

As shown in Table 1, the existing literature mainly studies the orderly charging strategy under constant charging power, and the charging power has a limited range of adjustment. It is often researched for a single scenario. This research considers that the charging pile supports centralized and decentralized scenarios and designs two charging modes based on the multi-level adjustable charging power of the charging pile.

In the centralized scenario, after the EV is connected to the charging pile, the charging power and charging duration of each charging pile are determined by the centralized control center, so the charging power of the charging pile at each moment can be multi-level adjusted by the centralized control center. In the decentralized control scenario, the user chooses the charging power and charging duration of EVs. It is difficult for users to choose charging power at each moment. Therefore, EVs can select the multi-level adjustable power supported by the charging pile for constant power charging and delay the charging time to achieve a good effect of peak shaving and valley filling. The multi-level adjustable charging pile is shown in Figure 1.

Based on the multi-level adjustable charging function of charging piles, information on EVs staying in the residential area, and charging demand, this research designs a centralized charging mode with complete information and a decentralized charging mode with incomplete information. In different scenarios, EVs select charging time and charging power through Bluetooth or code scanning to meet their charging demand. With the help of this charging pile, it is possible to achieve an excellent peak-shaving and valley-filling effect while engaging EVs in an orderly charging interaction.

2.1 Multi-level adjustable charging function

This work considers that EVs can combine the multi-level adjustable function of charging piles to select the charging power at each moment. In the residential area, according to the charging demand of EVs and the time that EVs stay in the residential area, based on the attached probability distribution of entering the residential area and leaving the residential area (Luo *et al.*, 2016), and its probability distribution can be expressed as (Eq 1 and 2):

$$f(t_i^c) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_{t_i^c}} \exp\left[-\frac{(t_i^c + 24 - \mu_{t_i^c})^2}{2\sigma_{t_i^c}^2}\right] & 0 < t_i^c \leq \mu_{t_i^c} - 12 \\ \frac{1}{\sqrt{2\pi}\sigma_{t_i^c}} \exp\left[-\frac{(t_i^c - \mu_{t_i^c})^2}{2\sigma_{t_i^c}^2}\right] & \mu_{t_i^c} - 12 < t_i^c \leq 24 \end{cases} \quad (1)$$

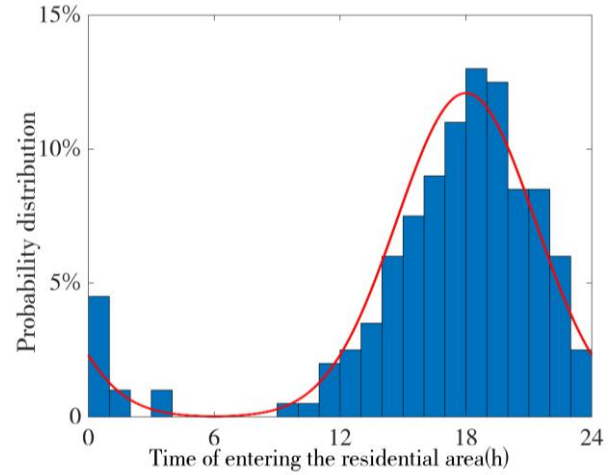


Fig.2 Probability distribution of EVs entering the residential area

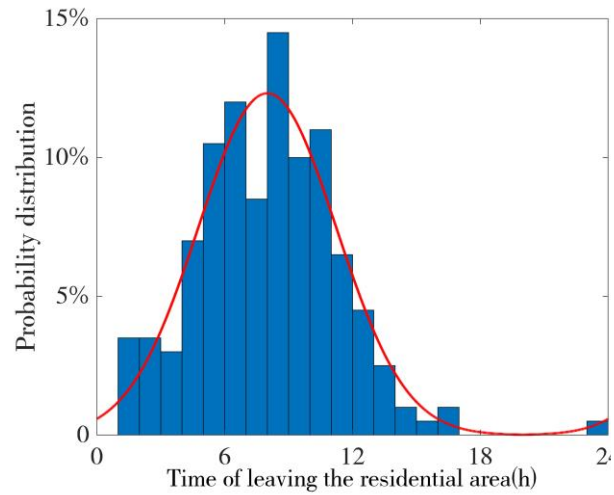


Fig 3 Probability distribution of EVs leaving the residential area

$$f(t_i^d) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_{t_i^d}} \exp\left[-\frac{(t_i^d - \mu_{t_i^d})^2}{2\sigma_{t_i^d}^2}\right] & 0 < t_i^d < \mu_{t_i^d} + 12 \\ \frac{1}{\sqrt{2\pi}\sigma_{t_i^d}} \exp\left[-\frac{(t_i^d - 24 - \mu_{t_i^d})^2}{2\sigma_{t_i^d}^2}\right] & \mu_{t_i^d} + 12 < t_i^d < 24 \end{cases} \quad (2)$$

Where, $\mu_{t_i^c} = 18$, $\sigma_{t_i^c} = 3.3$, $\mu_{t_i^d} = 8$, $\sigma_{t_i^d} = 3.24$. t_i^c is the moment when the i^{th} EV enters the residential area and t_i^d is the moment when the i^{th} EV leaves the residential area.

For disorderly charging, EVs start charging at 7 kW charging power when they enter the residential area. They stop charging until the SOC reaches the maximum charging demand of EVs or EVs leave the residential area. During the charging period, it is not subject to the orderly charging control. The charging load of a single EV is first obtained and then accumulated to obtain the total charging load at each moment. Thus, the disorderly charging load can be expressed as (Eq 3):

$$P_{sum}(t) = \sum_{i=1}^N P_{i,j} \quad (3)$$

Where $P_{i,j}$ is the charging power of the i th EV at moment j . Probability distribution of EVs entering the residential area is shown in Figure 2. Probability distribution of EVs leaving the residential area is shown in Figure 3.

The period of EVs entering the residential area can be expressed by Eq 4.

$$t_i = t_i^d - t_i^c \quad (4)$$

Where t_i is the length of time that the i th EV stays in the residential area.

In order to clearly reflect the effect of orderly charging, the orderly charging is carried out from 12:00 of the day to 12:00 of the next day as a cycle. Each orderly charging cycle is divided into time intervals of equal duration, at which time the period when EVs enter the residential area can be described in Eq 5.

$$T_i = t_i^d \Delta t + \Delta T - t_i^c \Delta t \quad (5)$$

Where ΔT is the number of time intervals in an orderly charging cycle, Δt is the number of time intervals in 1h. The adjustment range of charging piles can be expressed as in Eq 6.

$$P_{EV}^k \in [P_{EV}^0, P_{EV}^1, \dots, P_{EV}^{\max}] \quad (6)$$

Where P_{EV}^k is charging power supported by charging pile, $P_{EV}^{\max}$ is the maximum level of charging power supported by the charging pile.

In this research, two charging modes are designed for centralized and decentralized scenarios, combined with the function of multi-level adjustability of the charging pile. The actual charging power selection of the charging pile can be expressed in Eq 7.

$$P_{EV,i}^j = \begin{cases} P_{EV1,i}^j & \text{centralized charging mode} \\ P_{EV2,i}^j & \text{decentralized charging mode} \end{cases} \quad (7)$$

Where $P_{EV1,i}^j$ is variable at each moment, and $P_{EV2,i}^j$ is constant at each moment. In centralized charging mode, since the centralized control center has full access to the charging information of EVs, it can adjustably select the charging power of EVs at various moments. In decentralized charging mode, no centralized control center is involved, and the user selects the charging power supported by the charging pile to charge at constant power. The corresponding equations are described from Section 2.2 to Section 2.5.

2.2 Charging mode with complete information

In the centralized charging mode, EVs are able to upload their own battery level information and information about the period when they stay in the residential area. If EVs cannot be charged to the minimum charging demand before leaving the residential area, they need to choose the appropriate charging power. The charging demand factor of the i th EV can be expressed by Eq 8.

$$CN_i^k = T_i \Delta t P_{EV}^k \eta - (SOC_i^{\min} - SOC_i^{\text{con}}) C_{EV} \quad (8)$$

Where η is the charging efficiency of EVs, C_{EV} is the battery capacity of EV, $SOC_i^{\min}$ is the minimum charging demand for the

i th EV, and SOC_i^{con} is the battery level that the i th EV enters the residential area.

The charging power selection for each EV can be expressed as follows:

$$P_{EV1,i}^j = \begin{cases} P_{EV}^{\max}, CN_i^{\max-1} < 0 \\ P_{EV}^k, CN_i^{\max-1} \geq 0 \end{cases} \quad (9)$$

Where $CN_i^{\max-1}$ is the charging demand factor for the i th EV charging at power level $(P_{EV}^{\max} - 1)$, $P_{EV1,i}^j$ is the charging power of the i th EV at the moment j .

If charging with $(P_{EV}^{\max} - 1)$ does not satisfy the charging demand of the i th EV, the $P_{EV}^{\max}$ is used to charge. Charging begins at the moment of entering into the residential area. It ends at the moment of leaving the residential area in order to satisfy the minimum power requirements of the i th EV as much as possible. If charged with $(P_{EV}^{\max} - 1)$ can satisfy the charging demand of the i th EV, the P_{EV}^k is used to charge. Until the i th EV is fully charged or when the i th EV leaves the residential area, the i th EV ends charging.

2.3 Charging mode with incomplete information

In decentralized charging mode, EVs do not upload their battery level information and information about the period when they stay in the residential area. EVs select the charging power supported by the charging pile at each moment and complete the charging with constant power. EVs also consider the role of delayed charging time in this mode. To ensure that EVs can charge to their minimum charging demand before leaving the residential area, each EV needs to set a reasonable delayed charging time and charging power. The charging delay factor of the i th EV can be expressed by Eq 10.

$$CL_i^k = (T_i - T_i^l) \Delta t P_{EV}^k \eta - (SOC_i^{\min} - SOC_i^{\text{con}}) C_{EV} \quad (10)$$

Where T_i^l is delayed charging time of the i th EV.

To ensure that the minimum charging demand of the i th EV can be satisfied, the delayed charging time and charging power selection of the i th EV can be shown in Eq 11.

$$\begin{cases} T_i^l = [0, l] \\ P_{EV2,i}^j = [P_{EV}^k, P_{EV}^{\max}] \end{cases} \quad CL_i^{l+1} < 0 \ \& \ CL_i^l \geq 0 \quad (11)$$

Where if $CL_i^{l+1} < 0$ and $CL_i^l \geq 0$, this means that the i th EV is able to satisfy charging demand when choosing $P_{EV2,i}^j$ as its charging power, and the delayed charging time is less than $(l+1)$. Thus the i th EV can be charged by choosing a charging time obeying a uniform distribution of charging delays $[0, l]$ and with a charging power obeying a uniform distribution of $[P_{EV}^k, P_{EV}^{\max}]$.

2.4 Centralized charging mode with complete information

In the centralized scenario, combined with the objective function of orderly charging in the residential area, the centralized control center carries out orderly charging control of EVs. It is easy to achieve the overall optimization by starting from the whole. However, the construction cost is relatively high since the centralized control relies more on the bi-directional communication function between EVs and the centralized control center.

The centralized control scenario is shown in Figure 4. The centralized control center combines the load information of the residential area with the multi-level adjustable charging power information uploaded by the charging pile, EV's information of

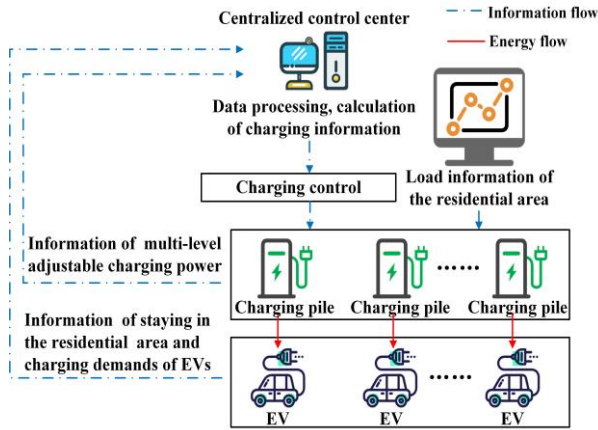


Fig 4. The centralized control scenario

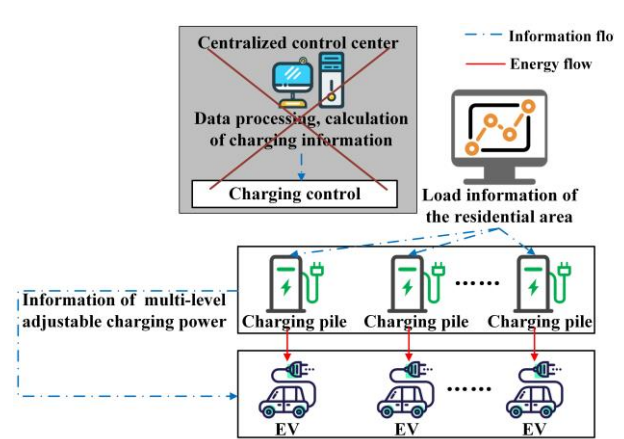


Fig 5. The decentralized control scenario

staying in the residential area and charging demand, performs data processing and calculates the charging information of EVs. To efficiently manage the charging of EVs in the residential area, an orderly charging control strategy is formulated by combining the operational aspects of the residential area with its objective function. The strategy results in issuing charging control commands of EVs to the charging piles.

In the centralized scenario, EVs are controlled by the centralized control center, which can be combined with the centralized charging mode of the charging pile for orderly charging, considering the charging variable of EV as a boolean variable, can be expressed in Eq 12.

$$\begin{cases} P_{EV1,i}^j = k \times x_{i,j} \\ x_{i,j} = 1 \text{ charging} \\ x_{i,j} = 0 \text{ not charging} \end{cases} \quad (12)$$

Where $x_{i,j}$ is the charging state of the i th EV at moment j . In centralized charging mode, $P_{EV1,i}^j$ is the charging power of the i th EV at level k , consisting of a set of Boolean variables $x_{i,j}$.

The charging power of the i th EV at each moment cannot exceed the maximum charging power $P_{EV}^{\max}$, which can be expressed as follows:

$$0 \leq \sum_{k=1}^{\max} x_{i,j} \leq P_{EV}^{\max} \quad (13)$$

If $CN_i^{\max-1} \geq 0$, it needs to satisfy the minimum charging demand of the i th EV and prevent the occurrence of an overcharging situation.

SOC for leaving the residential area can be expressed by Eq 14 and 15.

$$SOC_i^{\min} \leq SOC_i^{\text{dis}} \leq SOC_i^{\max} \quad (14)$$

$$SOC_i^{\text{dis}} = SOC_i^{\text{con}} + \frac{\sum_{j=t_i^{\text{con}} \times \Delta t}^{t_i^{\text{dis}} \times \Delta t + \Delta t} (\Delta t \square P_{EV1,i}^j \square \eta)}{C_{EV}}. \quad (15)$$

Where $SOC_i^{\max}$ is the maximum charging demand for the i th EV.

2.5 Decentralized charging mode with incomplete information

In the decentralized control scenario, EVs have the ability to adjust their charging strategy based on the charging demand.

With decentralized charging control, computational tasks that a centralized control center previously handled are now divided equally among EVs. This approach requires less communication and computational capability, thereby reducing the burden on the centralized control center. However, it is essential to note that achieving the overall optimal control effect can be more challenging with decentralized control when compared to centralized control.

The decentralized control scenario is shown in Figure 5. In the decentralized scenario, EVs select the appropriate charging power and charging time based on the multi-level adjustable charging power information of the charging piles and the load of the residential area. This is done to satisfy the charging demand of EVs before leaving the residential area.

Considering the combination of the multi-level adjustable function in the decentralized control scenario, it is more

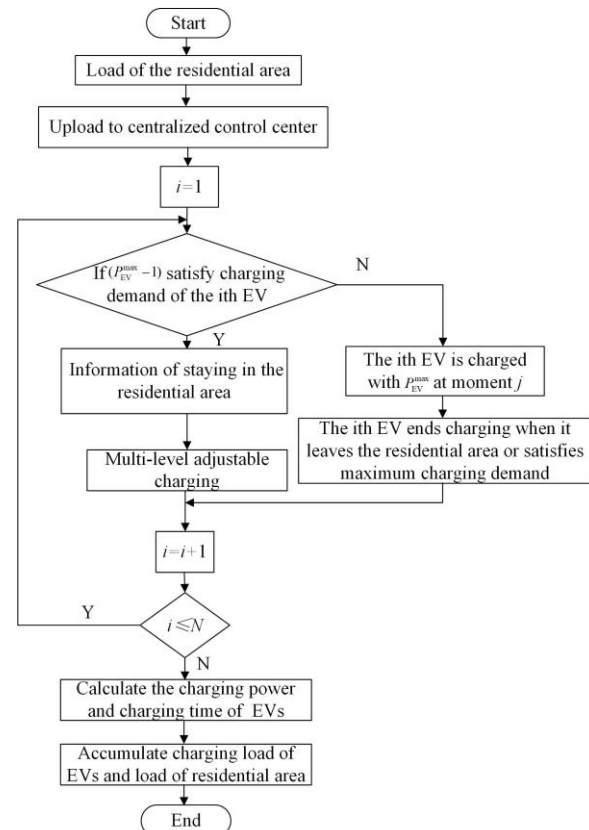


Fig 6. The orderly charging process of centralized scenario

complicated for EVs to set the charging power at each moment. So, it can be combined with the decentralized charging mode to carry out orderly charging. At each moment, EVs only need to select the acceptable delayed charging time and the charging power to satisfy the charging demand. The charging ends before the EV leaves the residential area or is fully charged, and its charging end moment can be expressed in Eq 16:

$$T_i^{end} = \min \left\{ \begin{aligned} &t_i^d \Delta t + \Delta T; \\ &\left[\frac{(SOC_i^{max} - SOC_i^{con}) C_{EV}}{P_{EV2,i} \eta \Delta t} \right] + t_i^c \Delta t + T_i^l \end{aligned} \right\} \quad (16)$$

In order to avoid the delayed charging time is too long for the i th EV to satisfy the minimum charging demand, the charging delayed time of EVs can be expressed as (Eq 17):

$$T_i^l \leq T_i - \frac{(SOC_i^{min} - SOC_i^{con}) C_{EV}}{P_{EV2,i} \eta \Delta t} \quad (17)$$

Except for a small number of EVs that stay for a short period, which cannot satisfy their charging demand, the rest can meet their charging demand. So, there is no need to define the SOC constraints of EVs again. At this time, the charging time of EVs can be expressed as Eq 18.

$$T_i^c = T_i^{end} - T_i^l - t_i^c \Delta t \quad (18)$$

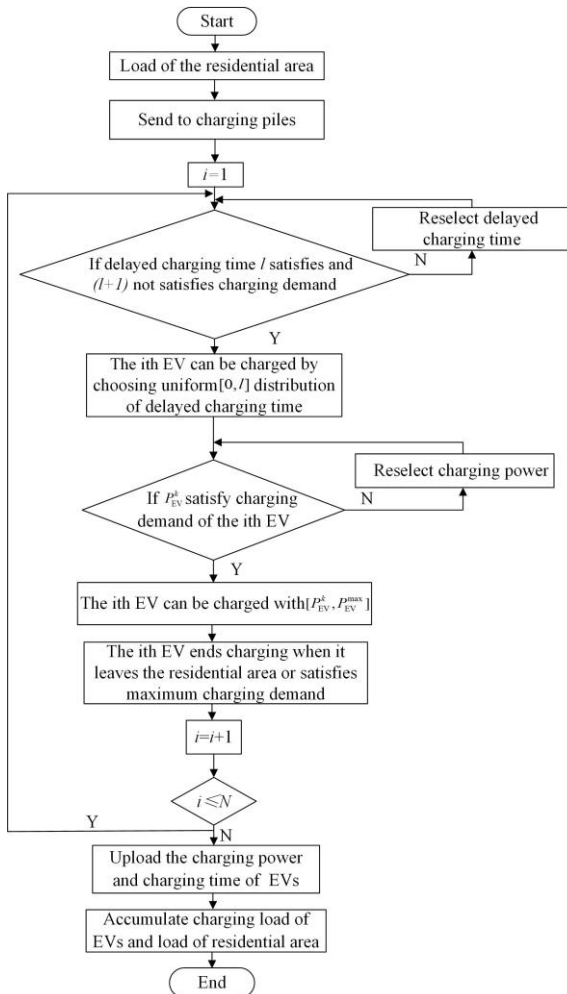


Fig 7. The Orderly charging process of decentralized scenario

2.6. The objective function of orderly charging

The objective function of the residential area is designed to shift EV charging loads from peak hours to valley hours, thereby relieving peak load pressure in the residential area. The total load can be expressed in Eq 19.

$$P_C^j = P_L^j + \sum_{i=1}^N P_{EV,i}^j \quad (19)$$

Where P_L^j is the load of the residential area at moment j , P_C^j is the total load of the residential area at moment j , $P_{EV,i}^j$ is the charging load of the i th EV at moment j .

The optimization objective is to minimize the peak-to-valley difference within the residential station area with an objective function (Eq 20):

$$F = \min(P_C^{j,max} - P_C^{j,min}) \quad (20)$$

Where $P_C^{j,max}$ is the maximum value of the total load in the residential area, $P_C^{j,min}$ is the minimum value of the total load in the residential area.

The orderly charging process of the centralized scenario is shown in Figure 6. The orderly charging process of the decentralized scenario is shown in Figure 7. The centralized and decentralized orderly charging process in the residential area is built in MATLAB/YALMIP.

In the centralized scenario, the load of the residential area needs to be uploaded to the centralized control center. Based on information on staying in the residential area and charging demand of EVs. According to the objective function, the centralized control center Multi-level adjustably selects the charging power of EVs. Finally, the charging load of EVs is added together to obtain the total load of the residential area.

In the decentralized scenario, the load of the residential area is sent to charging piles. The i th EV selects its charging power and delays charging time based on information of staying in the residential area and the charging demand of the i th EV. The objective function of the residential area guides this process. Finally, EVs upload their individual charging power and charging time, which are added to obtain the total load of the residential area.

3. Results and discussions

3.1 Data description

The research assumes that there are a total of 200 EVs participating in orderly charging in the residential area. The battery capacity C_{EV} of EVs is 35kWh. The charging efficiency η is 0.95, the SOC_i^{con} at the moment when EV enters the residential area obeys a uniform distribution of [0.1-0.3], minimum charging demand of EV SOC_i^{min} obeys a uniform distribution of [0.6-0.8], maximum charging demand of EV SOC_i^{max} obeys a uniform distribution of [0.8-1.0] (Jian L *et al.*, 2017). The charging power P_{EV}^k supported by the charging pile is any integer value between 1 kW and 7 kW. ΔT is 96, Δt is 4. Load of the residential area references (Zheng *et al.*, 2018).

Four strategies are set up to conduct a comparative analysis of peak-shaving and valley-filling benefits. In Strategy 1, EVs start charging when they enter the residential area and stop charging until the charging demand is satisfied. In Strategy 2, not all EVs start charging when they enter the residential area. EVs are charged with 7 kW of constant charging power by delaying charging time. In Strategy 3, if EVs can be charged to

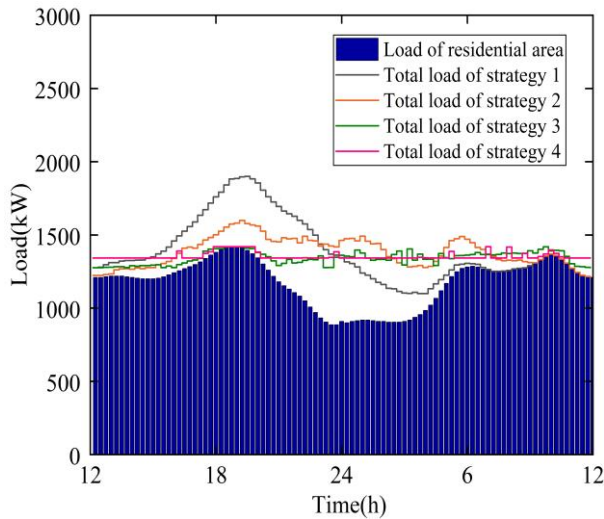


Fig 8. Total loads of the centralized scenario

minimum charging demand, they will have an intermittent charging power of 3.5 kW. If it cannot satisfy the minimum charging demand, EVs will be charged with a constant charging power of 7 kW as soon as they enter the residential area. In Strategy 4, EVs are charged with multi-level adjustable charging power in this research. Four strategies and their references are as follows.

Strategy 1: Disorderly charging strategy.

Strategy 2: Delayed charging strategy with a constant charging power of 7 kW. In particular, this EV orderly charging control has incorporated the role of delayed charging, but EV charging power is still mostly dominated by 7 kW constant charging power (Yin *et al.*, 2021).

Strategy 3: Charging strategy with intermittent charging power of 3.5 kW or constant charging power of 7 kW. Some orderly charging control is also based on the charging demand of EVs; if it can be charged to the minimum charging demand of EVs before leaving the residential area, the charging pile will be charged with an intermittent charging power of 3.5 kW. If it cannot satisfy the minimum charging demand, it will be charged with a constant charging power of 7 kW (Zhou *et al.*, 2020). The charging power of EVs can be expressed as (Eq 21):

$$\begin{cases} P_i^{EV} = 7\text{kW} & \text{constant charging} & SOC_i^{dis} \leq SOC_i^{min} \\ P_i^{EV} = 3.5\text{kW} & \text{intermittent charging} & SOC_i^{dis} > SOC_i^{min} \end{cases} \quad (21)$$

Strategy 4: The multi-level adjustable charging power charging strategy proposed in this research.

3.2 Orderly charging effect in the centralized scenario

Total load of centralized scenario is shown in Figure 8. Charging load of centralized scenario is shown in Figure 9. In Strategy 1, EVs are charged in a plug-and-charge manner after entering the residential area, and EVs are concentrated in entering the residential area at 18:00, resulting in a further increase in total load from 16:00 to 20:00, increasing the peak-to-valley difference in the residential area.

In Strategy 2, EVs are mainly focused on charging in the lower load period from 22:00 to 6:00 since there is no intermittent charging available when charging is delayed if a more significant number of EVs are selected to start charging at this time and since the charging power is 7 kW for all of them, it will increase the total load. It still does not have an excellent peak-shaving and valley-filling effect.

Strategy 3 has reduced charging loads from 16:00 to 20:00 due to the leveling off of the peak period of charging loads. Due to the intermittent charging of 3.5 kW, the total load remains low from 12:00 to 16:00 if the number of EVs entering the residential area is small.

The goal of Strategy 4 is to improve the effect of peak-shaving and valley-filling. Compared to Strategy 3, due to the multi-level adjustable charging power in Strategy 4, it can select a higher charging power for EVs from 12:00 to 16:00, making the load curve smoother. Moreover, it is able to reduce the charging power of EVs from 16:00 to 20:00 under the centralized control center. Under the four strategies, centralized Strategy 4 has a minor peak-to-valley difference of just 86 kW and also has the best orderly charging effect.

Battery level under centralized Strategy 4 is shown in Figure 10. The SOC_s under centralized Strategy 4 is shown in Figure 11. Except for a small number of EVs that stay in the residential area for a short period, they did not reach the minimum charging demand when they leave the residential area. The battery level of the remaining EVs starts to increase significantly after 24:00, indicating that more EVs can continue charging after 24:00 to reduce the peak-to-valley difference in

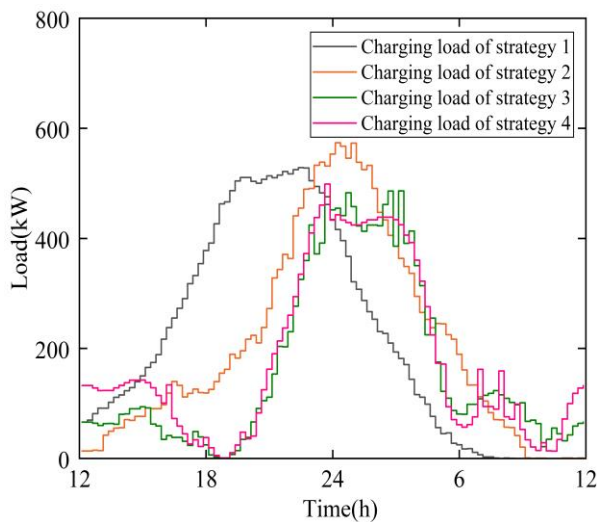


Fig 9. Charging loads of the centralized scenario

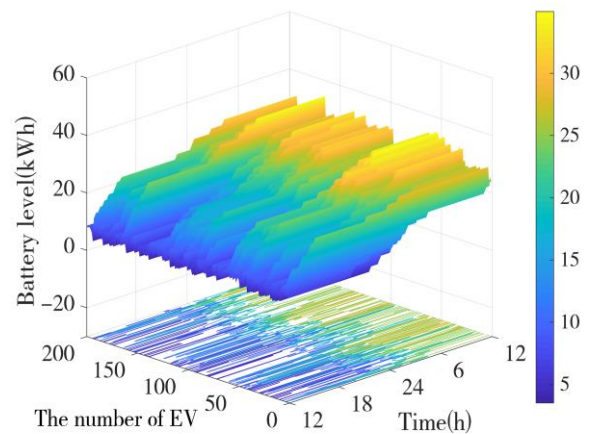


Fig 10. Battery levels under Strategy 4 of the centralized scenario

Table 2
Specific information of some EVs under centralized Strategy 4

The number of EVs	SOC_i^{con}	SOC_i^{min}	SOC_i^{max}	SOC_i^{dis}	t_i^c	t_i^d	Selected Charging Power / kW
1	0.13	0.78	0.93	0.82	19	12	1、2、4、6
2	0.29	0.69	0.96	0.73	13	12	1
3	0.28	0.76	0.99	0.83	17	7	2、3
4	0.28	0.78	0.94	0.83	20	4	5、6
5	0.18	0.73	0.83	0.77	21	10	2、3

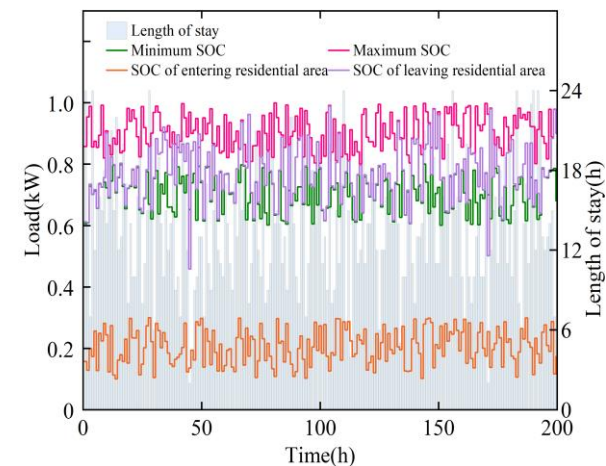


Fig 11. SOC_s under Strategy 4

the residential area. From the projection of the battery level diagram, the battery level of each EV can be charged to more than 25 kWh at the end moment of the orderly charging control, which shows that the multi-level adjustable charging power strategy under the centralized scenario in the residential area is able to satisfy the charging demand of EVs.

Specific information of some EVs under centralized Strategy 4 is shown in Table 2. The SOC of some EVs under centralized Strategy 4 is shown in Figure 12. This research randomly selected 5 EVs from the 200 EVs to show their chosen charging time and charging power. Based on the information in Table 2, it can be seen that they were able to meet their charging demand before leaving the residential area.

Based on the charging power selected in Table 2, the selected 5 EVs were charged in a multi-level adjustable manner.

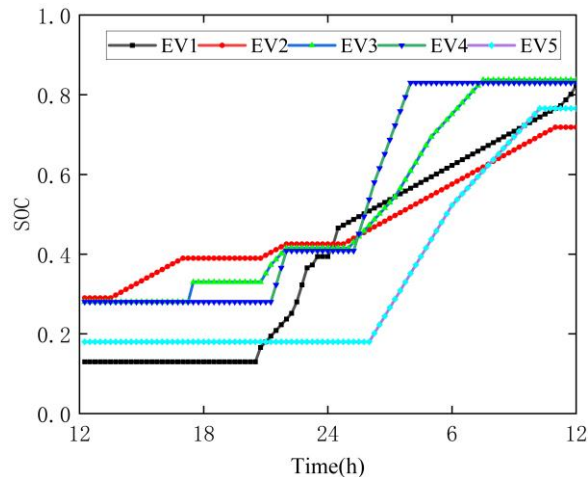


Fig 12. SOC_s of some EVs under Strategy 4

It can be seen that 5 EVs did not start charging immediately after entering the residential area. They did not charge or were charged at a lower charging power before 24:00. They were mainly charged after 24:00, which can avoid charging when the total load is high.

To summarize, as shown in Figure 8, under the centralized scenario, Strategy 1 can satisfy charging demands as soon as EVs enter the residential area. However, the peak-to-valley difference is large. The value is 801 kW. In Strategy 2, since no intermittent charging is available when charging is delayed, the peak-to-valley difference is 354 kW. In Strategy 3, due to the intermittent charging power of 3.5 kW, EVs will stop charging when the total load is high, so the peak-to-valley difference is significantly lower. The value is 141 kW. Strategy 4, due to the function of multi-level adjustable charging power, is able to reduce the charging power of EVs when the total load is high; under the four strategies, Strategy 4 has the minimum peak-to-valley difference, and the value is 87 kW. So, Strategy 4 has the best effect of peak shaving and valley filling under a centralized scenario.

3.3 Ordered charging effects in the decentralized scenario

Total load of the decentralized scenario is shown in Figure 13. Charging load of the decentralized scenario is shown in Figure 14. In Strategy 3, since some EVs use 3.5kW intermittent charging, each EV aims to minimize the peak-to-valley difference in the residential area and chooses to charge in the load valley period from 22:00 to 4:00 to satisfy its charging demand. Although it can lower the total load from 16:00 to 20:00, it will result in a new peak load from 22:00 to 4:00.

The peak loads for orderly charging is flattened in Strategy 2 and Strategy 4. Since EVs do not all choose to start charging as soon as they enter the residential area, they can avoid

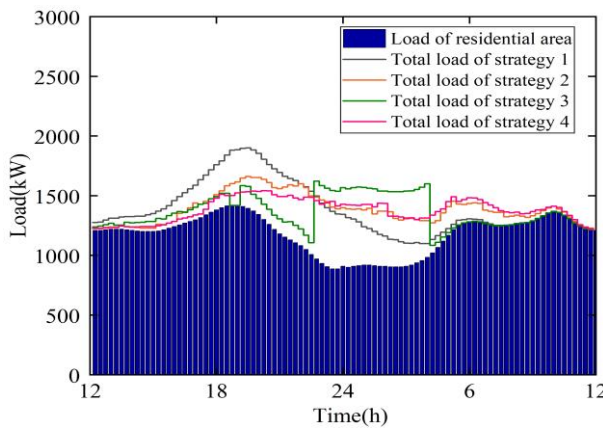


Fig 13. Total loads of the decentralized scenario

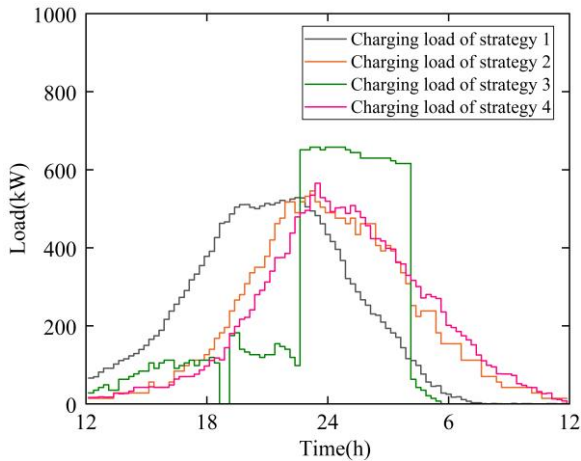
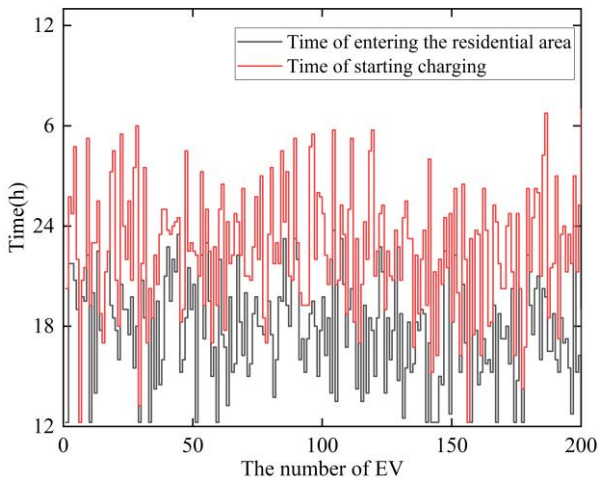


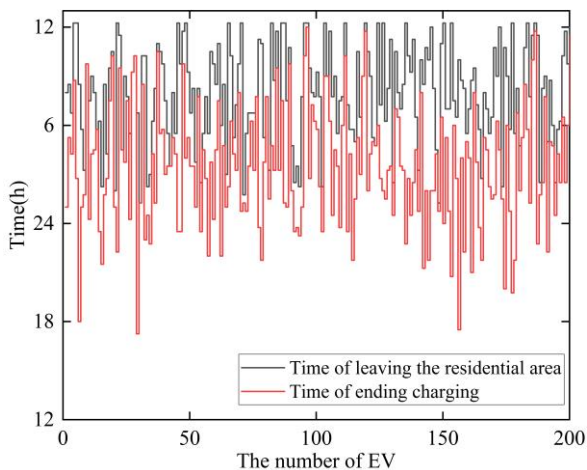
Fig 14. Charging loads of the decentralized scenario

charging during peak load period by postponing a period and charging at a constant power while satisfying charging demand.

Since EVs in Strategy 2 are all charged with 7 kW, it will further increase the total value of the peak load after overlaying the charging loads during the peak period of 16:00-22:00. In Strategy 4, EVs are able to select charging power adjustably. They are able to select a lower power for charging during the peak load period, which has a better effect on peak-shaving and valley-filling.



(a). Time of starting charging



(b). Time of ending charging

Fig 15. Distributions of charging time under Strategy 4

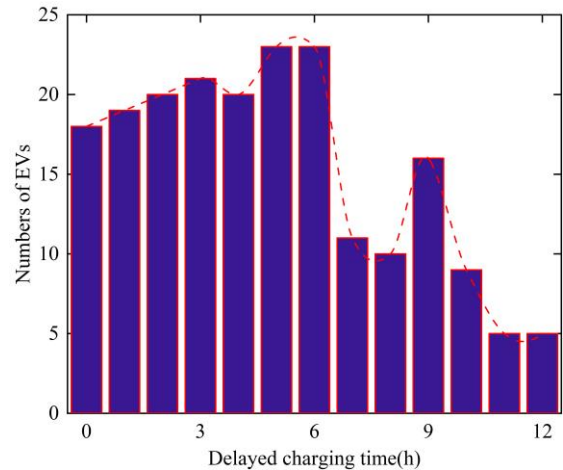


Fig 16. Delayed charging time under Strategy 4

Charging time distribution under decentralized Strategy 4 is shown in Figure 15. Except for some EVs that stay in the residential area for a shorter period and need to be charged by plug-and-charge charging, the rest of the EVs are able to delay for some time after entering the residential area before charging. They are able to end charging before leaving the residential area, which indicates that the decentralized charging strategy can better satisfy the charging demand for EVs.

Delayed charging time under decentralized Strategy 4 is shown in Figure 16. Only 18 EVs did not delay charging time, and the remaining 182 EVs chose to delay charging for a certain charging period. The Delayed charging time of EVs is mainly concentrated in the range of 1h-6h, and the number of EVs choosing to delay charging reaches 90%. Since EVs mainly concentrate on entering the residential area at 18:00, some EVs choose to delay their charging time and reduce the charging power. They can reduce the peak-to-valley difference while satisfying their charging demand.

To summarize, as shown in Figure 13, under the decentralized scenario, the effect of Strategy 1 is the same as the centralized scenario in Figure 8. The peak-to-valley difference is 801 kW. In Strategy 2, due to the function of delayed charging with constant charging power of 7kW, the charging load was delayed; the peak-to-valley difference is 424 kW. Since, under a decentralized scenario, EVs autonomously select the charging power and charging time, the charging load is concentrated in time periods when the total load is low, so the peak-to-valley difference is still high, and the value is 516 kW. In Strategy 4, EVs are able to select charging power adjustably and select a lower charging power during the peak load period; the peak-to-valley difference is only 282 kW. The peak-to-valley difference in Strategy 4 is the lowest of the four strategies, so this research considers that Strategy 4 has the best effect on peak shaving and valley filling under a decentralized scenario.

4. Conclusion

In order to address the issue of increasing peak-valley difference caused by disorderly charging of EVs in the residential area, this research proposes a charging strategy for EVs in residential areas based on multi-level adjustability. The research compares and analyzes the impact of orderly charging under different strategies and finds that strategy 4, proposed in this work, has the best effect in different scenarios.

The multi-level adjustable orderly charging method is introduced to control EVs in the residential area. Compared to

other orderly charging methods, it can satisfy the charging demand of EVs while achieving good peak-shaving and valley-filling effects. Strategy 4 proposed in this research has the best effect of 4 strategies; the peak-to-valley difference is only 87 kW under a centralized scenario, and the peak-to-valley difference is 282 kW under a decentralized scenario. Simulation verification shows good peak-shaving and valley-filling effects in the residential area.

In this work, two charging modes based on self-developed charging piles are designed. Two charging modes can be applied in centralized scenarios with complete information and decentralized scenarios with incomplete information. The multi-level adjustable charging method is more suitable for the orderly charging scenario in the residential area. This research proposes a multi-level adjustable orderly charging strategy based on self-developed charging piles and can provide a reference for engineering related to orderly charging.

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