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# Power grid peak shaving strategies based on electric vehicles and thermal storage electric boilers

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**Abstract.** Due to the rapid progress of electrification and the rising accommodation of renewable energy, the peak-to-valley difference of power grids has been increasing, and the peak loading pressure of power grids has arisen. It has become a trend to use controllable loads to participate in power grid peak shaving. At present, electric vehicles and thermal storage electric boilers, which are widely implemented in northern China, provide a reliable source for controllable loads. Based on the analysis of the operational characteristics of electric vehicles and thermal storage electric boilers, this paper studies the charge and discharge control strategies for auxiliary peak shaving. The Monte Carlo method is used to simulate the charging behavior of electric vehicle users. Under the premise of considering the constraints of electric vehicle charging and discharging power, battery capacity and the power consumption of the thermal storage electric boilers, the mathematical model is established with the goal of suppressing the daily load curve, and the particle swarm optimization algorithm is used to solve the optimization problem. The simulation results show that electric vehicles and thermal storage electric boilers are jointly involved in load balancing, and the daily load curve is significantly levelled compared with the original curve.

## 1. Introduction

Power system operation requires real-time balance of power generation and power consumption. In order to ensure the reliability of the system operation, the grid needs to carry out early power generation resource planning. In the traditional concept, the construction of more power generation and transmission infrastructures is the main way to adapt to the development of power load. However, with the increasing use of electricity in industry and household, the load curve of the power grid fluctuates more violently. The operating characteristics of the power grid are more complicated and the management mode needs to be changed accordingly. For the peak load, the peaking resources are not limited to the power supply side resources. The demand side resources can also play the role as important peaking resources. In the distribution network of 110 kV and below, there are a large number of controllable loads. Under the requirements of the power supply department, the power consumption time or its working state can be adjusted according to the demand, guiding the users to rationally use electricity, transferring the electricity consumption period, and optimizing the load demand distribution, which could improve the quality of power system operation. Controllable load is a kind of loads with flexible and controllable working modes, wide spatial distribution and convenient time domain [1-2]. It can be directly controlled by the power company according to needs, or induced by economic measures (such as time-of-use electricity tariff). The user selectively controls the load



curve to achieve load management, to optimize load waveforms, and to cut peaks and valleys. By analyzing the control characteristics of the controllable loads such as cold storages, electric heat storage boilers, air conditionings and electric vehicles, the control strategy of peak load control for the controllable load in power grids is obtained. This paper mainly selects two controllable loads of electric vehicles and thermal storage electric boilers to participate in power grid peak shaving. Domestic and foreign scholars have proposed different peak shaving strategies. For example, literature [3] discussed the design, simulation and implementation phases related to an Open UPQC installed in a real LV distribution grid in the city of Brescia (Italy) within the smart domo grid project, co-funded by the Italian Ministry of Economic Development. Literature [4] represented power electronics device for PQ improvement and introduces Open UPQC as possible solution to improve whole system PQ level with more features for specific end users. Literature [5] presented a new approach to the load shedding program to guarantee the correct electrical system operation by increasing the number of participants.

At present, the state strongly encourages the development of electric vehicles from both policies and incentives, making more and more electric vehicles popular in cities [6]. Kempton and Letendre proposed the vehicle to grid (V2G) technology. The core idea is that when a large number of electric vehicles are idle, their power batteries are used as distributed energy storage devices to achieve bi-directional interaction between the grid and electric vehicles [7-8]. V2G technology has attracted a great deal of attention from academic researchers. For example, literature [9] proposed a regional electric vehicle charging and discharging control strategy considering the dispersion and time randomness of electric vehicle charging and discharging locations. In literature [10], an optimal charging and discharging scheduling scheme for electric vehicles is proposed and solved by improved particle swarm optimization algorithm. In the aspect of electric vehicles participating in power grid peak shaving, literature [11] pointed out that electric vehicles participating in V2G are technically feasible to meet the demand on the scale and to support electric vehicles. Literature [12] proposed an interconnected V2G model for electric vehicles and power grids, and an analysis model for participating in power grid peak shaving to analyze the effect of electric vehicles participating in power grid peak shaving. Literature [13] analyzed the realization of the peak-filling problem of load curve through the synergistic utilization of electric vehicles and wind power, and mainly analyzed the coordinated optimization scheduling strategy of electric vehicle power battery and wind power.

The heat storage electric boiler has the function of shifting peaks and filling valleys, and it is an important measure to optimize resource allocation and protect the ecological environment. Due to the encouragement of time-sharing electricity tariff, the heating technology of thermal storage electric boilers has been gradually developed and applied in electric heat storage boilers. In the heating system, it is the heat accumulator that directly supplies heat to the user. Literature [14] proposed a method to evaluate the effect of peak-shaving and valley-filling of the thermal storage electric boiler system. Literature [15] carried out the increase of night electricity load as the inlet. Based on the analysis, the method of increasing the load of the heat storage electric boiler is proposed, so as to improve the utilization hours of wind power on the grid and improve the utilization rate of green energy. In Literature [16], the optimal model for abandoning wind and solar energy is established. By optimizing the charging power of the thermal storage electric boiler and the wind and photovoltaic power, the goal of eliminating wind and light curtailment is achieved.

In order to utilize the electric vehicle and the thermal storage electric boiler to assist the peak shaving, this paper firstly establishes a mathematical model of electric vehicle and thermal storage electric boiler with the goal of leveling the daily load curve, and puts forward the electric vehicle charging and discharging power, battery capacity and storage. The power consumption of the thermal storage electric boiler is constrained, and then the particle swarm optimization algorithm is used to optimize the power of the two loads. Finally, the effectiveness of the peak shaving strategies of electric vehicles and thermal storage electric boilers is verified, and the peak-shaving and valley-filling of the load curve is realized.

## 2. Model of peak shaving for electric vehicles and thermal storage electric boilers

By monitoring the acquisition device to obtain the daily load curve of the power grid and the relevant parameters of the electric vehicle and the thermal storage electric boiler, the particle swarm optimization algorithm is used to optimize the time and power of the electric vehicle and the thermal storage electric boiler participating in the peak shaving of the power grid. According to the reasonable dispatching instructions of the electric vehicle control center and the electric power signal to the thermal storage electric boiler, the electric vehicle can reasonably arrange to charge and discharge according to the received dispatching instructions, and the thermal storage electric boiler participates in the peak shaving of the electric grid. Under the premise of meeting the driving demand of the electric vehicle and the running time of the thermal storage electric boiler, the load curve is leveled as much as possible by reasonably dispatching the electric power consumption time of the electric vehicle and the thermal storage electric boiler.

### 2.1. Objective function

Assuming that the electric vehicle and the thermal storage electric boiler jointly assist the peak shaving in response to the regional load. One day can be divided into 24 time periods, and the standard deviation of the daily load curve is the minimum objective function. The variable is in each time period, the electric vehicle charge and discharge power and power consumption of the heat storage electric boiler. The objective function is:

$$\min f = \sqrt{\frac{\sum_{k=1}^{24} (P_L(k) - P_{av} - P(k))^2}{24}} \quad (1)$$

$$P(k) = \sum_{i=1}^n P_{ei}(k) + \sum_{j=1}^m P_{ij}(k) \quad (2)$$

$$P_{av} = \frac{\sum_{k=1}^{24} P_L(k)}{24} \quad (3)$$

Where  $f$  is the standard deviation of the daily load curve in the region,  $n$  is the number of electric vehicles participating in peak shaving,  $m$  is the number of thermal storage electric boilers participating in peak shaving,  $P_L(k)$  is the power of the grid load during the  $k$  period, and  $P_{av}$  is the average power of the load of the grid within one day.  $P(k)$  is the demand power of the grid during the  $k$  period, that is, the sum of the electric vehicle exchanged power and the electric storage electric boiler used during the  $k$  period.

### 2.2. Constraints

The overall load of the transformer after the electric load of the electric vehicle and the thermal storage electric boiler participating in the peak shaving of the power grid should be less than the maximum load power of the transformer, and there is a new transformer capacity constraint:

$$P_L(k) + \sum_{i=1}^n P_{ei}(k) + \sum_{j=1}^m P_{ij}(k) \leq P_{k,\max} \quad (4)$$

Where  $P_{k,\max}$  is the maximum capacity of the transformer during the  $k$  period

When an electric vehicle participates in peak shaving, its control method is constrained by conditions such as charge and discharge power, electric vehicle energy, transmission line transmission power, and user-set minimum battery capacity.

(1) Electric vehicle power constraints:

The power constraint is mainly reflected in the charge and discharge current constraint, the maximum charge current is  $1/3I_{iN}$ , and the maximum discharge current is  $2I_{iN}$ . which is:

$$\begin{cases} 0 \leq I_{ic} \leq 1/3 I_{iN} \\ 0 \leq I_{id} \leq 2 I_{iN} \end{cases} \quad (5)$$

Consider the line power capacity constraint, no more than 15 kW, ie:

$$-15 \leq P_{ei}(k) \leq 15 \quad (6)$$

Combine (5) and (6):

$$P_{ei}^{\min}(k) \leq P_{ei}(k) \leq P_{ei}^{\max}(k) \quad (7)$$

$$\begin{cases} P_{ei}^{\max}(k) = \min(15, U_{ik} \cdot 2 I_{iN}) \\ P_{ei}^{\min}(k) = \max(-15, -U_{ik} \cdot 1/3 I_{iN}) \end{cases} \quad (8)$$

Where  $I_{ic}$  is the charging current value (positive value) of the electric vehicle  $i$ ;  $I_{id}$  is the discharge current value (positive value) of the electric vehicle  $i$ ;  $I_{iN}$  is determined by the battery model of the electric vehicle;  $U_{ik}$  is the real-time voltage value of the battery;  $P_{ei}(k)$  is the power of the electric vehicle  $i$  when it is charged (discharged), the positive (negative) number indicates that the electric vehicle is in the state of discharging (charging);  $P_{ei}^{\min}(k)$  is the minimum power of the electric vehicle  $i$  during charging and discharging; and  $P_{ei}^{\max}(k)$  is the maximum electric power of the electric vehicle  $i$  during the  $k$  period.

(2) Electric vehicle energy constraints:

The capacity of the electric vehicle battery is constant, and the actual capacity ( $Q_N$ ) refers to the discharge capacity of the battery during discharge from the fully charged state to the discharge termination voltage under a certain discharge condition. The capacity of the battery should not exceed the actual capacity value. Consider the battery life capacity not less than 20% of the battery capacity.

$$\Delta Q_{ei}^{\min}(k) \leq \Delta Q_{ei}(k) \leq \Delta Q_{ei}^{\max}(k) \quad (9)$$

$$\begin{cases} \Delta Q_{ei}^{\max}(k) = (SOC_i(k) - SOC_{\min}) \cdot Q_{eiN} \\ \Delta Q_{ei}^{\min}(k) = (SOC_i(k) - SOC_{\max}) \cdot Q_{eiN} \end{cases} \quad (10)$$

$$SOC = Q_{re} / Q_N \quad (11)$$

Where  $\Delta Q_{ei}(k)$  is the charging (discharging) capacity of the electric vehicle  $i$  during the  $k$  period,  $\Delta Q_{ei}^{\min}(k)$  and  $\Delta Q_{ei}^{\max}(k)$  are the maximum and minimum values of the charging (discharging) capacity of the electric vehicle  $i$  during the  $k$  period, respectively;  $SOC_i(k)$  is the electric vehicle  $i$ . The state of charge of the  $k$  period;  $SOC_{\max}$  is the maximum value of the state of charge of the battery, taking 1;  $SOC_{\min}$  is the lowest value of the state of charge of the battery when considering the constraint of the battery itself, taking 0.2;  $Q_{eiN}$  is the actual capacity value of the electric vehicle  $i$ .  $Q_{re}$  is the remaining battery power of the electric vehicle  $i$  during the  $k$  period, and  $Q_N$  is the actual capacity value of the electric vehicle.

(3) Minimum battery capacity when the user sets to leave

Considering the user's setting constraints on the battery capacity according to their own travel needs, the charging and discharging time of the electric vehicle can be reasonably arranged under the premise of satisfying the user's setting. The user's setting value can be defined by the following expression.

$$SOC_i(k_{depart}) \geq SOC_i^{set} \quad (12)$$

Where  $SOC_i(k_{depart})$  is the state of charge of the electric vehicle  $i$  when it leaves;  $SOC_i^{set}$  is the desired state of charge of the user.

When the thermal storage electric boiler participates in the peak shaving of the power grid, its control method is constrained by the conditions of the power consumption of the thermal storage electric boiler at different time periods. If the operating period of the thermal storage electric boiler is limited to 10 hours within the power low period, that is, 22:00 to 8:00 the next day, the power storage of the thermal storage boiler is:

$$\begin{cases} 0 & 9 \leq k \leq 21 \\ P_{tj}^{\min}(k) \leq P_{tj}(k) \leq P_{tj}^{\max}(k) & 0 \leq k \leq 8, 22 \leq k \leq 24 \end{cases} \quad (13)$$

Where  $P_{tj}^{\min}(k)$ ,  $P_{tj}^{\max}(k)$  are the lower and upper limits of the power of the thermal storage electric boiler  $j$  during the  $k$  period.

### 3. Peak shaving control strategy for electric vehicles and thermal storage electric boilers based on particle swarm optimization

Due to the diversity of electric vehicles and thermal storage electric boilers, the particle swarm optimization algorithm with simple principle is adopted. After knowing the daily load curve of a certain area, the goal of the combined auxiliary peak shaving of electric vehicles and thermal storage electric boilers is to level the load curve as much as possible. Therefore, the particle swarm algorithm is used to control each electric vehicle or thermal storage electric boiler at each time interval. The switching power is optimized. The  $n$  electric vehicles and  $m$  thermal storage electric boilers involved in the peaking can generate a particle with a dimension of  $24 \times (m+n)$  for 24 hours a day. Therefore, the particle positions of electric vehicles and thermal storage electric boilers participating in peak shaving can be set to:

$$X_1 = \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,24} \\ X_{2,1} & X_{2,2} & \cdots & X_{2,24} \\ \vdots & & & \vdots \\ X_{n,1} & X_{n,2} & \cdots & X_{n,24} \\ X_{n+1,1} & X_{n+1,2} & \cdots & X_{n+1,24} \\ \vdots & & & \vdots \\ X_{n+m,1} & X_{n+m,2} & \cdots & X_{n+m,24} \end{bmatrix} \quad (14)$$

The various constraints of the above-mentioned corresponding electric vehicle charging and discharging process and the use of the thermal storage electric boiler can also be handled as constraints in the particle swarm algorithm.

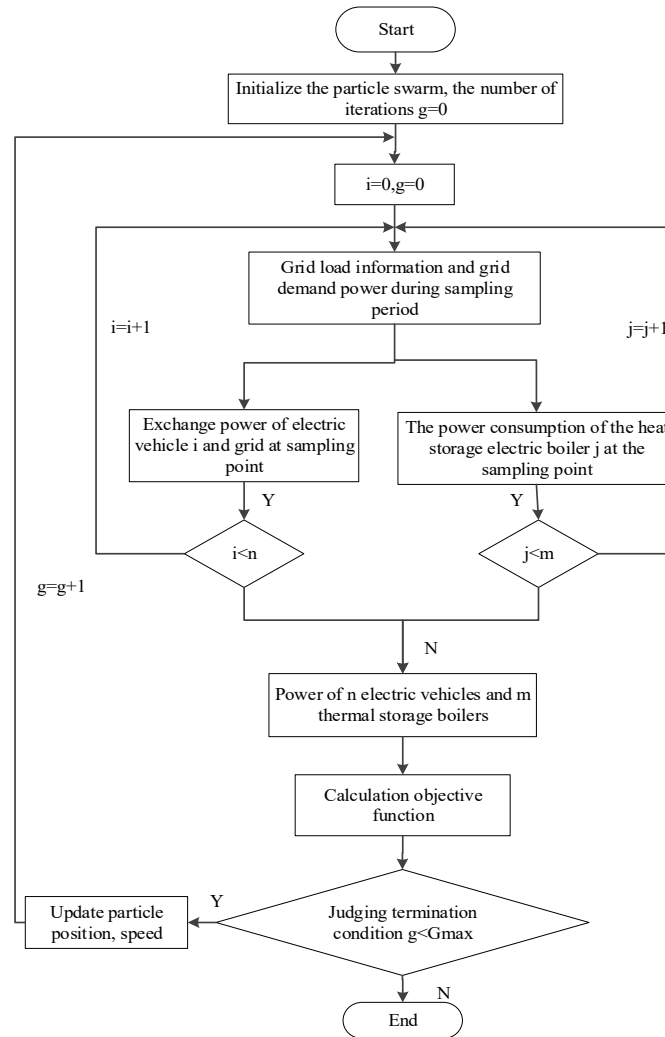
In this paper, the user's energy setting of the battery is added to the target function for processing, so that the objective function can be changed to the following expression.

$$F(x) = f(x) + GU \quad (15)$$

$$U = \sum_{k=1}^{24} (\min(0, u(x)))^2 \quad (16)$$

$$u(x) = SOC_i^{set} - SOC_i(k_{depart}) \quad (17)$$

Where  $f(x)$  is the original objective function;  $G$  is the penalty coefficient;  $k_{depart}$  is the outbound time of the electric vehicle;  $SOC_i(k_{depart})$  is the remaining capacity of  $k$  period.



**Figure 1.** Peak shaving process of electric vehicle and thermal storage electric boiler based on particle swarm optimization.

For the constraints of charge and discharge power and battery capacity during charging and discharging, the variation constraints of particles in the particle swarm optimization algorithm can be processed, and the constraints can be transformed into the expressions of (18) ~ (20).

$$P_{ei}(k) = \begin{cases} 0 & (t \notin t_{available}) \\ P_{ei}^{\max}(k) & (P_{ei}(k) > P_{ei}^{\max}(k)) \\ P_{ei}^{\min}(k) & (P_{ei}(k) < P_{ei}^{\min}(k)) \end{cases} \quad (18)$$

$$\begin{cases} P_{ei}^{\max}(k) = \min(P_{ei}^{\max}(k), \Delta Q_{ei}^{\max}(k)/\Delta t) \\ P_{ei}^{\min}(k) = \max(P_{ei}^{\min}(k), \Delta Q_{ei}^{\min}(k)/\Delta t) \end{cases} \quad (19)$$

$$\begin{cases} \Delta Q_{ei}^{\max}(k) = (SOC_i(k) - SOC_{\min}) \cdot Q_{eiN} \\ \Delta Q_{ei}^{\min}(k) = (SOC_i(k) - SOC_{\max}) \cdot Q_{eiN} \end{cases} \quad (20)$$

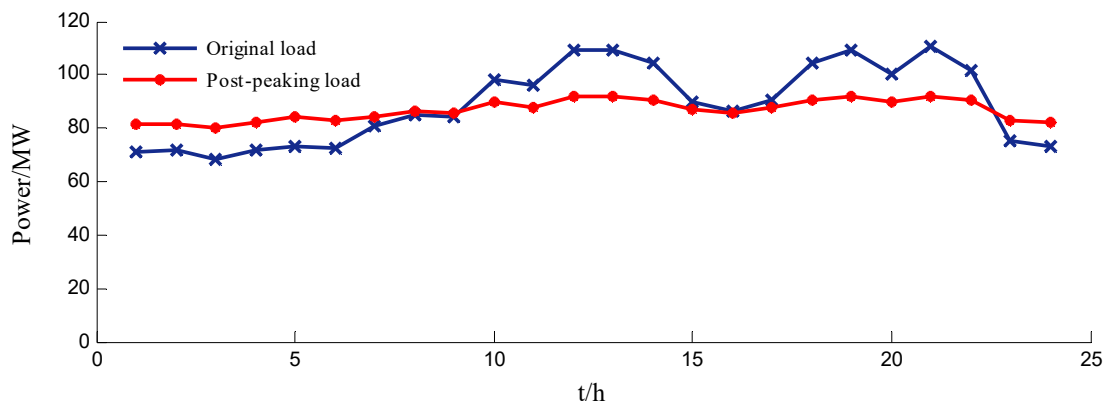
For the constraint of the power consumption of the thermal storage electric boiler in different time periods, the variation constraint of the particles in the particle swarm optimization algorithm can be processed, and the constraint condition can be transformed into the expression of formula (21).

$$P_{ij}(k) = \begin{cases} 0 & (t \notin t_{available} \cup 9 \leq k \leq 21) \\ P_{ij}^{\max}(k) & (P_{ij}(k) > P_{ij}^{\max}(k), 0 \leq k \leq 8, 22 \leq k \leq 24) \\ P_{ij}^{\min}(k) & (P_{ij}(k) < P_{ij}^{\min}(k), 0 \leq k \leq 8, 22 \leq k \leq 24) \end{cases} \quad (21)$$

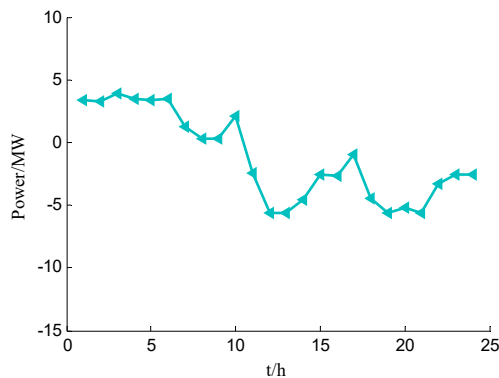
Where  $\Delta t$  is a period of time, 1h. The randomly generated particle position is modified to satisfy the constraint condition.

The flow chart of the combined auxiliary peak shaving control strategy for electric vehicles and thermal storage electric boilers based on particle swarm optimization is shown in Figure 1.

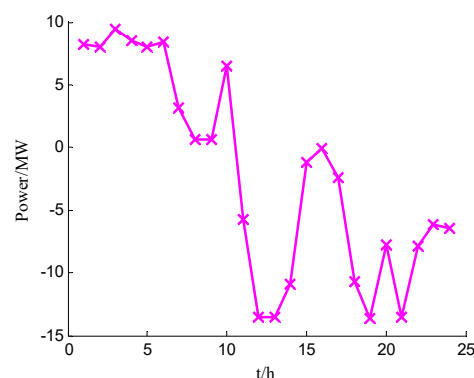
#### 4. Examples and analysis



**Figure 2.** Peak shaving results based on electric vehicle and thermal storage electric boiler.



**Figure 3.** Electric vehicle power curve.



**Figure 4.** Thermal storage electric boiler power curve.

Assume that the number of electric vehicles participating in power grid peak shaving is 500 and that of thermal storage electric boilers is 200. Taking the typical daily load in a certain area as an example, the typical daily load data of a node in the regional power grid is shown in the solid line in Figure 2.

It can be clearly seen from Figure 2 that on the original load curve, the load during the 1~6 hour period is the low period, and the load during the 12~14 hour period and the 19~21 hour period are the peak period. The average power of the grid load is about 89MW. It is hoped that the electric vehicle and the thermal storage electric boiler will jointly assist in peak shaving, so that it can play the role of peak shaving and valley filling.

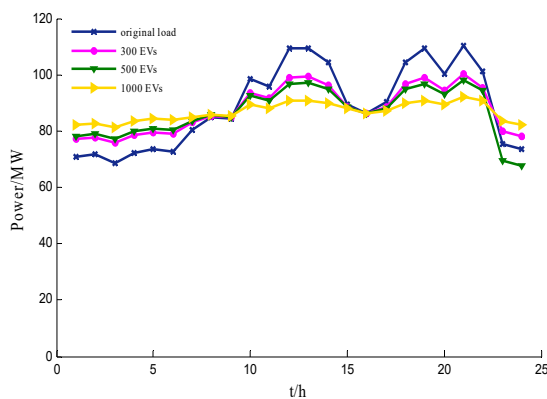


Matlab is used to simulate, and the optimization results are shown in Figure 2 ,Figure 3 and Figure 4 show the power curve of the electric vehicle and the thermal storage electric boiler during peak shaving.

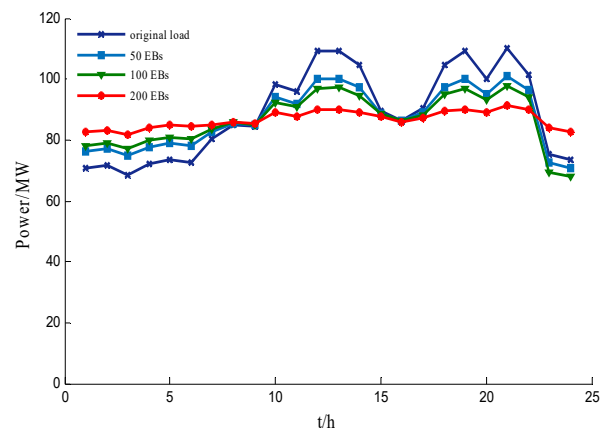
It can be seen from Figure 2 that the electric vehicle and the thermal storage electric boiler are charged during the low load period. The electric vehicle is discharged during the peak load period, and the thermal storage electric boiler stops using electricity, so that the load peak is lowered. By optimization, the load curve is basically leveled, and the daily load curve is significantly improved compared to the original curve.

It can be seen from Figure 3 and Figure 4 that the electric vehicle participates in the peaking power more smoothly, while the thermal storage electric boiler has more peaking output.

When the number of electric vehicles or thermal storage electric boilers participating in power grid peak shaving is changed respectively, the effects are shown in Figure 5 and Figure 6.



**Figure 5.** Different numbers of electric vehicles.



**Figure 6.** Different number of thermal storage electric boilers.

Figure 5 shows that when the number of electric vehicles participating in peak shaving is 300, 500 and 1000, respectively. After the peak shaving of electric vehicles and thermal storage electric boilers, the peak-to-valley difference is 23.5MW, 20.1 MW and 9.5 MW, and the standard deviation of the daily load curve are 20.5, 21.2 and 25.64, respectively.

Figure 6 shows that when the number of thermal storage electric boilers participating in peak shaving is 50, 100 and 200, respectively. After the peak shaving of electric vehicles and thermal storage electric boilers, the peak-to-valley difference is 30.4MW, 20.1 MW and 9.3 MW, and the standard deviation of the daily load curve are 19.5, 21.2 and 26.1, respectively.

Comparing the effects of different numbers of electric vehicles and thermal storage electric boilers involved in peak shaving, it can be seen that with the increase of the number, the optimal peaking effect is better and the peak-to-valley difference is smaller, and the daily load curve is more gradual.

## 5. Conclusions

According to the operating characteristics of electric vehicles and thermal storage electric boilers, a model of power grid peak shaving strategy based on electric vehicles and thermal storage electric boilers is established. The model uses particle swarm optimization to search for the optimal value. The conditional treatment method realizes the functions of electric vehicles and thermal storage electric boilers participating in power grid peak shaving. Through the simulation of the daily load curve of a certain regional power grid, the simulation results show that when the electric vehicle and the thermal storage electric boiler participating in the peak shaving of the power grid reach a certain scale, a better peak shaving effect can be obtained, and the fluctuation of the grid load can be effectively suppressed. Increasing the economics and stability of the grid operation will correspondingly reduce the peak reserve capacity required by the grid.

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