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Optimal configuration of integrated microgrid systems with distributed generations and electric vehicle charging stations

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Abstract. Energy shortage and environmental pollution problems have led to the development of electric vehicles (EVs). However, charging EVs through power grid could not reduce fossil energy consumption and pollution emission fundamentally. Therefore, an integrated system consisting of distributed generations (DGs) and EV charging stations can be connected with power grid in the form of microgrid to achieve more local consumption of renewable energy and reduce the environmental pollution. Firstly, this paper analyses the adaptability of EV charging facilities and DGs integration mode. And then predict the charging demand of EVs based on Monte Carlo method. Finally, a bi-objective optimization model with the lowest economic cost and minimum load fluctuation is established and use particle swarm optimization to solve the optimal configuration of integrated microgrid system with wind turbines (WT), photovoltaic generations (PV), diesel engine (DE), energy storage systems (ESS) and EV charging stations. The example compares the optimal configuration results of microgrid in the two scenarios of disorderly and orderly charging modes and studies the influence of the orderly charging mode on the results. Effectiveness of the proposed method was verified with simulations.

1. Introduction

With the shortage of energy resources and air pollution, renewable energy such as wind and photovoltaic resources and EVs have received widespread attention. However, the output of DGs such as WT and PV is random and intermittent. And according to China's current coal-based energy structure, EVs directly get electricity from power grid. The pollutants emitted by power generation will not fundamentally reduce the pressure of environmental pollution. Therefore, this paper integrates DGs and EV charging station to optimize the configuration of integrated microgrid system.

At present, domestic and foreign scholars have achieved relevant results in the research of microgrid and EVs. The literature [1] considers the voltage stability margin and power loss, which selects the location of the EV fast charging station, and evaluates the maximum acceptable capacity of the charging station based on the grid reliability. A meshing-based EV charging station planning method is proposed in the literature [2], which divides the planning area with the goal of minimizing the driving consumption of EV users, and calculates the best location of charging station by genetic algorithm considering the traffic density and charging station capacity constraints. The literature [3] combines the traffic factor with the charging station planning model comprehensively considering the distribution of the traffic network and the grid structure, and optimizes the configuration of charging



station with the aim of economy. In the research on the microgrid optimal configuration without EVs, the literature [4] discusses the combined operation mode of diesel engine, taking the co-operation of ESS and DE and the reserve capacity of microgrid into account, and studies the optimization configuration including microgrid cost, environmental pollution discharge and power supply reliability. The literature [5] studies the problem of optimizing the configuration of grid-connected microgrid with PV and ESS, taking the life cycle net income as the objective function and considering the time-of-use electricity price and photovoltaic subsidies.

In the research on the optimal configuration of microgrid with EVs, the literature [6] proposes an energy storage capacity planning strategy in microgrid based on the response speed of energy storage equipment to match different types of loads, and optimizes the capacity of microgrid considering the influence of EV dispatching on ESS. The literature [7] fully considers the energy storage characteristics of EVs, and constructs a mathematical model for minimizing the total cost of planning and operation of microgrid with annual cycle, the particle swarm simulation annealing algorithm is used to calculate the capacity of each energy unit in the microgrid considering EVs. The literature [8] designs a hierarchical energy management strategy in the microgrid for large-scale access of EVs to improve the economy and reliability of microgrid operation. The literature [9] considers the EV mobile load characteristics and energy storage characteristics, and propose different EV energy management strategies based on the price incentive mechanism. Study the influence of energy management strategy on microgrid DGs optimal configuration. The literature [10] use the Monte Carlo method to simulate the use characteristics of EVs, and establish a mathematical model that minimizes the total cost of microgrid planning and operation after the EVs are connected to the network in the life cycle. The literature [11] generates three EV charging loads by Monte Carlo method under the guidance of time-of-use electricity price, and optimizes the capacity of power in microgrid under different EV energy management modes with the aim of lowering the economic cost. The above literatures study the planning of DGs and EV charging station separately, and do not consider the two systems as the integrated system accessing to microgrid for optimal configuration.

Based on the analysis of the adaptability of DGs and EV charging station integrated system, this paper establishes a bi-objective planning model for integrated microgrid system with the goal of reducing the overall economic cost of microgrid and EV users and reducing the total load fluctuation of microgrid. Two scenarios of disorderly and orderly charging of EVs are constructed. The particle swarm optimization algorithm is used to solve the target. Then compares and analyses the optimal configuration results in two scenarios.

2. Adaptability analysis of the integrated system

Integrated system consisting of DGs and EV charging stations can take full advantage of the adjustability of EVs' charging demand to realize local consumption of renewable energy and fundamentally reduce the consumption of fossil energy. However, the natural conditions and resources of different regions are different. The EV users in various regions are also affected by local economic development level, living habits, weather and other factors. EV charging location, charging time and charging mode have strong uncertainties, resulting in different charging demands. The key issue is how to match various types of EV charging facilities with different DGs in the integrated microgrid system.

1) Charging piles and DGs. Charging piles are mostly built in residential areas, business areas and public places. Considering the small footprint of these sites and the high land prices, we can make full use of the business, residential areas and other related building roof idle locations to build PV. Therefore, the charging piles are suitable for integration with PV on the roof.

2) Charging stations and DGs. According to geographical location and climate characteristics, the DGs' types and capacities can be configured. Wind resources in high latitudes are generally sufficient, and small wind turbines can be installed in or near the charging station. Low-latitude cities have strong solar irradiance, and PV can be built on the roof of charging stations. The rest of the region integrates the wind-photovoltaic hybrid generation system with the charging facilities in the charging station and

configures the energy storage system. It can meet the charging demand of EVs while restraining the output fluctuation of WT and PV to a certain extent.

3) Large-scale charging and swapping stations and DGs. In general, the driving characteristics and charging habits of EVs (such as buses, taxis and sanitation vehicles) used for public services have certain regularity and fixed charging mode. These types of EVs can be centrally charged or swapped by Large-scale charging and swapping stations and connected to small wind farms and photovoltaic generation stations in the vicinity to achieve local consumption of renewable energy.

3. EV users behavior analysis

The charging behavior of EV fully complies with the user's private will, and it is greatly affected by the user's driving habits. This paper uses the relevant data in the American family car survey report to simulate the travel rules of EVs [12]. The travel end time t_0 is approximately normal distribution, and daily driving mileage s is approximately lognormal distribution. The travel end time is actually the earliest time for EVs connected to power grid. Considering the user's driving habits, this paper assumes that the EV is charged immediately after the end of the travel in the case of disorderly charging, that is, the end time of the travel is the charging start time. The number of daily driving mileage which determines the state of charge of the EV at the end time of travel is an important factor affecting the charging duration.

The travel end time t_0 obeys normal distribution, which is $t_0 \sim N(\mu_t, \sigma_t^2)$, and its probability density function is as shown in equation (1):

$$f_t(x) = \begin{cases} \frac{1}{\sigma_t \sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu_t)^2}{2\sigma_t^2}\right) & \mu_t - 12 < x < 24 \\ \frac{1}{\sigma_t \sqrt{2\pi}} \exp\left(-\frac{(\ln x - (\mu_t - 24))^2}{2\sigma_t^2}\right) & 0 < x < \mu_t - 12 \end{cases} \quad (1)$$

Where μ_t is set to 17.6 and σ_t is set to 3.4 [13].

The daily driving mileage s obeys lognormal distribution, which is $s \sim \log N(\mu_s, \sigma_s^2)$, and its probability density function is as shown in equation (2):

$$f_s(x) = \frac{1}{x} \frac{1}{\sigma_s \sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu_s)^2}{2\sigma_s^2}\right) \quad (2)$$

Where μ_s is set to 0.88 and σ_s is set to 3.2 [13]. Due to the constraints of EV's state of charge of the battery capacity, the maximum value of the daily mileage s_{max} is the number of miles corresponding to the battery capacity from the upper limit to the lower limit.

4. Optimized configuration model for integrated microgrid system

4.1. Objective function

4.1.1. Economic cost objective

$$C = C_i + C_{om} + C_{cs} + C_{ex} + C_{charge} + C_{loss} \quad (3)$$

Where C is the total planning cost, C_i is the construction cost of four types of DGs including WT, PV, DE and ESS. C_{om} is the operating cost, C_{cs} is the construction cost of charging station, C_{ex} is the interaction cost with the distribution network, C_{charge} is the charging cost of EV users, C_{loss} is the cost of loss of load. And all price units are yuan.

1) Installation cost C_i

This paper uses the annual equivalent cost method to calculate the installation cost:

$$C_i = \sum_{b=1}^B C_b \frac{r(1+r)^b}{(1+r)^b - 1} \quad (4)$$

Where B is the number of the types of DGs, b is the type of DG, C_b and l_b are the construction cost and the life cycle of DG b th, r which represents discount rate is set to 8%.

2) Operating cost C_{om}

Use operational management coefficient to calculate operating costs for DGs:

$$C_{om} = \sum_{b=1}^B \sum_{t=1}^T k_{om_b} P_b^t \quad (5)$$

Where T is the operation hours of integrated microgrid system, k_{om_b} is the DG b th operational management coefficient, P_b^t is the output of DG b th at time t .

3) Interaction cost with the distribution network C_{ex}

The interaction cost with the distribution network is the difference between the cost of purchasing electricity from the distribution network and the income of selling electricity to the distribution network:

$$C_{ex} = \sum_{t=1}^T (c_{buy}^t P_{buy}^t - c_{sell}^t P_{sell}^t) \quad (6)$$

Where c_{buy}^t and c_{sell}^t are the electricity price for purchase and sale electricity at time t , P_{buy}^t and P_{sell}^t are the purchase power and sale power to the distribution network at time t .

4) Construction cost of charging station C_{cs}

$$C_{cs} = S_v c_{charge} \quad (7)$$

Where c_{charge} is the construction cost unit capacity of charging station, S_v is the capacity of EV charging station.

5) EV charging cost C_{charge}

$$C_{charge} = \sum_{t=1}^T c_{buy}^t P_{EV}^t \quad (8)$$

Where P_{EV}^t is the charging demand for all EVs at time t .

6) Cost of loss of load C_{loss}

$$C_{loss} = \sum_{t=1}^T c_{loss} P_{loss}^t \quad (9)$$

Where c_{loss} is the cost of loss of load, P_{loss}^t is the load loss power of integrated microgrid system at time t .

4.1.2. Load fluctuation objective. By reducing load fluctuations, on the one hand, it can reduce the loss during the power transmission and distribution process, and on the other hand, ensure the safe and stable operation of the power grid. The total load mean square deviation can be used to characterize the fluctuation of the microgrid load. The smaller the mean square deviation is, the more stably the load changes [14]:

$$P_{load-fluctuation} = \frac{1}{T} \sum_{t=1}^T [P_{EV}^t + P_{basicload}^t - \frac{1}{T} \sum_{t=1}^T (P_{EV}^t + P_{basicload}^t)]^2 \quad (10)$$

Where $P_{load-fluctuation}$ is the load fluctuation, $P_{basicload}$ is the basic load of microgrid at time t .

4.2. The constraints

1) Microgrid power balance constraint

$$P_{WT}^t + P_{PV}^t + P_{DE}^t + P_{ESS}^t + P_L^t - P_{abandon}^t = P_{basicload}^t + P_{EV}^t - P_{loss}^t \quad (11)$$

Where P_{WT}^t , P_{PV}^t , P_{DE}^t and P_{ESS}^t are the output power of four types of DGs: WT, PV, DE and ESS at time t , $P_{abandon}^t$ and P_{loss}^t are the power of abandoning wind and solar photovoltaic resources and loss of load at time t , P_L^t is the exchanging power of tie-line at time t . If it is positive, it indicates that the microgrid purchases electricity from the distribution network. Otherwise, it indicates that the microgrid sells electricity to the distribution network.

2) DGs' capacity upper limit constraints

$$\begin{cases} 0 \leq S_{WT} \leq S_{WT-max} \\ 0 \leq S_{PV} \leq S_{PV-max} \\ 0 \leq S_{DE} \leq S_{DE-max} \\ 0 \leq S_{ESS} \leq S_{ESS-max} \end{cases} \quad (12)$$

Where S_{WT} , S_{PV} , S_{DE} and S_{ESS} are the configuration capacity of four types of DGs: WT, PV, DE and ESS, S_{WT-max} , S_{PV-max} , S_{DE-max} and $S_{ESS-max}$ are these DGs' configuration capacity upper limit.

3) Tie-line's capacity upper limit constraints

$$0 \leq P'_L \leq P_{L-max} \quad (13)$$

Where P_{L-max} is the tie-line power limit.

4) State of charge constraints for ESS batteries

$$SOC_{ESS-min} \leq SOC'_{ESS} \leq SOC_{ESS-max} \quad (14)$$

Where $SOC_{ESS-min}$ and $SOC_{ESS-max}$ are the upper and lower limits of the state of charge of the energy storage system battery, SOC'_{ESS} is the state of charge of the energy storage system battery at time t .

5) Charge and discharge power output constraints of ESS

$$\begin{cases} 0 \leq P'_{ESS} \leq \eta_{discharge} \times S_{ESS} \\ -S_{ESS} / \eta_{charge} \leq P'_{ESS} \leq 0 \end{cases} \quad (15)$$

Where η_{charge} and $\eta_{discharge}$ are the ESS charging and discharging efficiency. If P'_{ESS} is positive, it indicates that the ESS discharges at time t . Otherwise, energy storage system charges at time t .

6) State of charge constraints for EV batteries

$$SOC_{EV-min} \leq SOC'_{EV} \leq SOC_{EV-max} \quad (16)$$

Where SOC_{EV-min} and SOC_{EV-max} are the upper and lower limits of the state of charge of EV battery, SOC'_{EV} is the state of charge of EV battery at time t .

7) Microgrid self-balancing degree constraint

$$Sa_{min} \leq Sa = \frac{P_{load-total} - P_{buy-total}}{P_{load-total}} \leq Sa_{max} \quad (17)$$

Where Sa_{min} and Sa_{max} are the upper and lower limits of the microgrid self-balancing, $P_{load-total}$ is the total load power, $P_{buy-total}$ is the total power purchased by microgrid.

8) Loss of load constraint

$$L_{oep} = \frac{P_{loss-total}}{P_{load-total}} \geq L_{oep-max} \quad (18)$$

Where $L_{oep-max}$ is the maximum proportion of load shedding, $P_{loss-total}$ is the total load shedding.

4.3. Optimization model solving

The solution of the above model is a bi-objective planning problem. If one of the objective functions is solved separately, it may cause the other one to have poor results. If only the economic cost is the optimization objective, it may cause the charging demand to be too large in a certain period of time and cause the total load to fluctuate greatly, which is harmful to the safe and stable operation of the integrated microgrid system. Considering only the fluctuation of load as the optimization objective may make the planning scheme economically poor. This paper uses the fuzzy membership function to calculate the satisfaction of economic cost and load fluctuation objective separately. And find the maximum value of standardized satisfaction as the optimal compromise solution.

The fuzzy membership function is defined as follows:

$$u_i = \frac{f_i - f_{i-min}}{f_{i-max} - f_{i-min}} \quad (19)$$

where i represents the two objectives, f_i is the solution to the optimization objective, f_{imin} is the minimum solution to the optimization objective, f_{imax} is the maximum solution to the optimization objective.

Standardized satisfaction can be obtained according to the following equation:

$$u = \frac{1}{N} \sum_{i=1}^N u_i \quad (20)$$

where u is the standardized satisfaction, N is the number of optimization objectives.

The flow diagram of microgrid optimal configuration is shown in Figure 1.

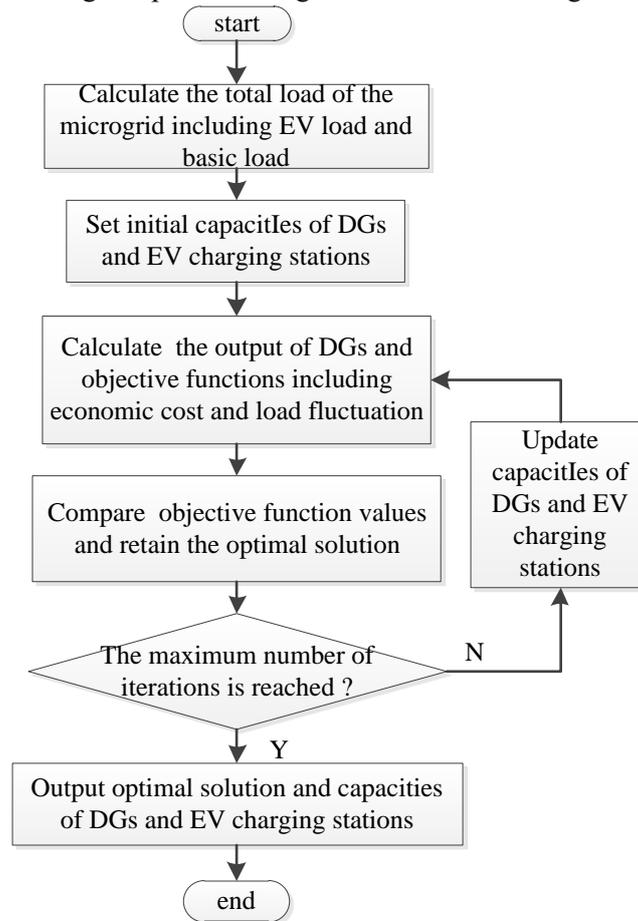


Figure 1. The flow diagram of microgrid optimal configuration.

5. Simulation and results

5.1. Case parameters setting

In this paper, the particle swarm optimization algorithm is used to simulate each day in four quarters as a typical day. The unit time is one hour and the research time period is one year. Assuming that there are 200 EVs in the integrated microgrid system, the charging and discharging efficiency of the ESS is 0.2, the charging power of the EV is 2 kW, the EV consumes 0.139 kW per kilometre, battery capacity is 17.5 kW · h, the upper and lower limits of the state of charge are 100% and 20%, the EV charging station's unit capacity construction cost is 71400 yuan and its life cycle is 20 years. The loss of load constraint when the integrated microgrid system is connected to the grid is set to 0.1%, and the self-balancing degree constraint range is set to 40% to 60%. The various types of DGs economy and

technical parameters are shown in Table 1. The time-of-use electricity price data used in this paper is shown in Table 2.

Table 1. Parameters of DGs.

| | installation cost(yuan/kW) | operational management coefficient | life cycle(year) |
|-----|-------------------------------|--|---------------------|
| WT | 10000 | 0.0296 | 10 |
| PV | 66500 | 0.0096 | 20 |
| ESS | 900 | 0.009 | 10 |
| DE | 3000 | 0.088 | 10 |

Table 2. Time-of-use electricity price.

| time | purchase (yuan/kWh) | sell (yuan/kWh) |
|-------------|------------------------|--------------------|
| 0:00-7:00 | 0.37 | 0.28 |
| 8:00-11:00 | 0.87 | 0.72 |
| 17:00-20:00 | 0.69 | 0.53 |
| 12:00-16:00 | | |
| 21:00-23:00 | | |

5.2. EVs charging demand

According to equation (1) and equation (2), this paper uses Monte Carlo method to simulate the user's charging start time and daily driving mileage. Then combined with EVs' electricity consumption per kilometre and charging power, the charging demand for EVs in the case of disorderly charging is obtained. The disorderly charging power demand curves for 100, 200, and 300 EVs is shown in Figure 2.

5.3. Optimization results and analysis

This paper establishes two scenarios: 1) Optimized configuration scheme of integrated microgrid system under the condition of disorderly charging of EVs. 2) Optimized configuration scheme of integrated microgrid system under the condition of orderly charging of EVs. And compare and analyse the optimal configuration results in the two scenarios.

5.3.1. Scenario one. The optimal configuration scheme of integrated microgrid system under the condition of disorderly charging of EVs is as follows. The total planning cost is 68595550 yuan, of which the installation cost is 4799750 yuan, the operating cost is 134070 yuan, the interaction cost with the distribution network is 676180 yuan, the charging station construction cost is 799950 yuan, the EV charging cost is 287250 yuan, the load loss cost is 64150 yuan; the load fluctuation is 25825 (kW)²; the configured capacity is 195 kW for WT, 670 kW for PV, 50 kW for DE, 350 kW for ESS, and 110 kW for EV charging stations. Analysis of the optimal configuration results shows that the installation cost accounts for the largest proportion of the total economic cost, which accounts for 71.40%. The expensive installation cost is the main reason for the poor economic benefits of the microgrid at this stage.

Figure 3 shows the output of DG when the EVs are disorderly charged, WT is the wind power output curve; PV is the photovoltaic output curve; DE is the diesel engine output curve; ESS is the energy storage system output curve. As we know, the output of PV is greatly affected by the light intensity, which results in large fluctuations in output because of the great randomness of light

intensity. Light intensity varies greatly between seasons and periods. It is much stronger in summer and autumn. And PV only output during the daytime and output no power at night. Therefore, the output of PV is shown in Figure 3. At this time, the ratio of PV installed capacity to the total capacity is 52.96%, and PV is the main DG source.

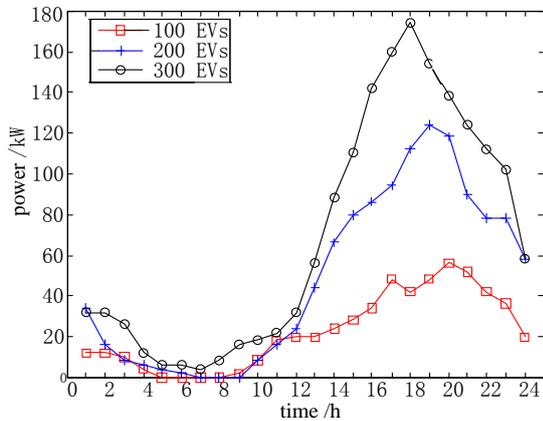


Figure 2. Disorderly charging demand for different number of EVs in one day ($\Delta t = 1h$).

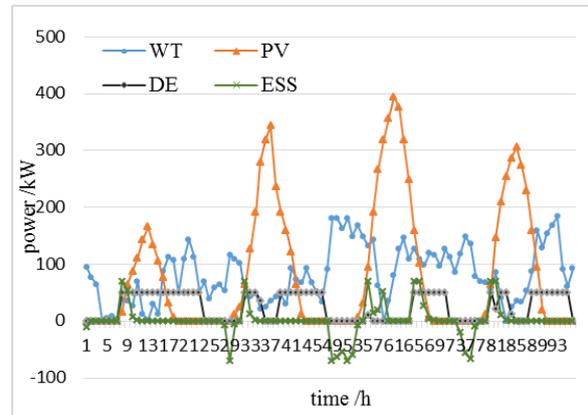


Figure 3. Output of DGs when the EVs are disorderly charged in four typical days ($\Delta t = 1h$).

5.3.2. *Scenario two.* The pareto curve of the bi-objective optimal configuration of the integrated microgrid system in the case of EV orderly charging is shown in Figure 4. The optimal compromise solution is as follows: the total planning cost is 3701716 yuan, of which the installation cost is 759500 yuan, the operating cost is 162730 yuan, the interaction cost with the distribution network is 1011900 yuan, the charging station construction cost is 1410800 yuan, the EV charging cost is 161616 yuan, the load loss cost is 195170 yuan; the load fluctuation is 8961.5 (kW)². The configured capacity is 195 kW for WT, 50 kW for PV, 50 kW for DE, 350 kW for ESS and 194 kW for EV charging station.

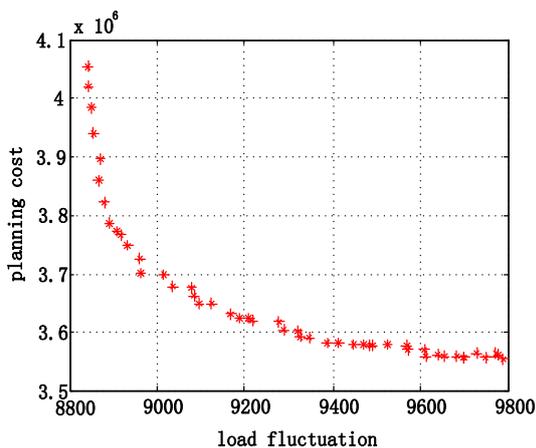


Figure 4. The pareto curve of the bi-objective optimal configuration when the EVs are orderly charged.

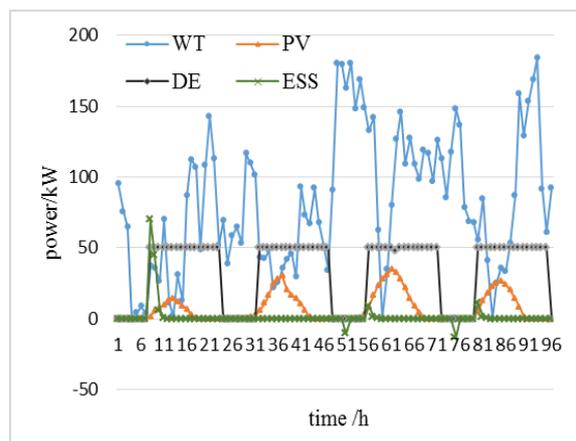


Figure 5. Output of DGs when the EVs are orderly charged in four typical days ($\Delta t = 1h$).

Figure 5 shows the output of each DG when the EVs are orderly charged. At this time, the PV configuration capacity is significantly reduced, and its output is also reduced accordingly. WT is the main DG source in the microgrid.

5.3.3. Comparative analysis of scenario one and scenario two. From the perspective of economic objective, the total planning cost of scenario one is 68595550 yuan, and the total planning cost of scenario two is 3701716 yuan. The planning cost of orderly charging is reduced by 46.04% compared with the cost of disorderly charging planning. In the case of disorderly charging, the DG installation cost is 4799950 yuan, the EV charging cost is 287250 yuan, and the charging station construction cost is 799950 yuan. In the case of orderly charging, the DG installation cost is 759500 yuan, the EV charging cost is 161616 yuan, the charging station construction cost is 1410800 yuan. It can be seen that the optimized scheduling strategy of the EV's orderly charging reduces the cost of the DG of the microgrid, and also reduces the charging cost of the user, which achieves a win-win effect. However, at this time, the charging construction cost is obviously improved. This is because under the guidance of peak-valley electricity prices, the EV users charge EVs during the valley period in order to reduce their own charging costs. In order to meet the charging demand of EVs, more charging stations need to be built, the cost of charging station construction is also increased.

From the perspective of technical objective, the load fluctuation of scenario one is 25825 (kW)^2 . The load fluctuation of scenario two is 8961.5 (kW)^2 , and the load fluctuation is reduced by 65.30% compared with the disorderly charging. The microgrid load curve before and after the optimal dispatching of EVs is shown in figure 6. As it can be seen from figure 6, the disorderly charging will have the effect of “peak on the peak” on the microgrid load, and the load fluctuation will increase significantly, which brings hidden dangers to the safe and stable operation of the power grid. After the implementation of the orderly charging strategy, the EV is charged in the valley period, which plays a role of “peak load shifting” for the microgrid load, so the load fluctuation is also significantly reduced.

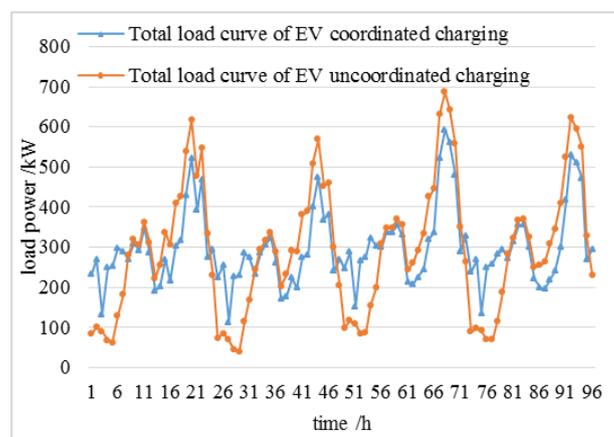


Figure 6. Microgrid load curve before and after optimal dispatching in four typical days ($\Delta t = 1\text{h}$).

6. Conclusions

This paper focuses on the optimization configuration of integrated microgrid systems with DGs and EV charging stations, and compares the optimal configuration results between disorderly and orderly charging strategy of EVs. The following conclusions are drawn through simulation analysis:

1) DGs and EV charging stations can be integrated and connected to power grid in the form of microgrid. On the one hand, it can realize local consumption of renewable energy and improve energy utilization rate; on the other hand, it can effectively smooth WT and PV output and improve the safety of power grid operation.

2) Orderly charging of EVs reduces the installed cost of DGs while reducing the charging cost of EV users, which achieves a win-win situation for users and microgrid. And it reduces the peak-to-valley difference of the microgrid load after the optimal charging scheduling which significantly reduces the load fluctuation and improves the safety and stability of the grid operation.

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