Economic Optimization Dispatching Strategy of Microgrid for Promoting Photoelectric Consumption Considering Cogeneration and Demand Response

Chunxia Dou, Xiaohan Zhou, Tengfei Zhang, and Shiyun Xu

Abstract—A system combining photovoltaic power generation and cogeneration is proposed to improve the photoelectric absorption capacity. First, a time-of-use price strategy is adopted to guide users to change their electricity consumption habits for participation in the demand response, and a demand response model is established. Then, particle swarm optimization (PSO) is used with the aim of minimizing the operation cost of the microgrid to achieve economic dispatching of the microgrid. This considers power balance equation constraints, unit operation constraints, energy storage constraints, and heat storage constraints. Finally, the simulation results show the improved level of photoelectric consumption using the proposed scheme and the economic benefits of the microgrid.

Index Terms—Photoelectric absorption, cogeneration, energy storage, time-of-use electricity price, demand response, particle swarm optimization (PSO).

I. INTRODUCTION

THE consumption of renewable energy power generation has gradually become a research hotspot in the field of power systems [1]. A large amount of direct light energy exists in the western and northern parts of China. At the same time, there is a large heat load demand in these places. In the last few years, the photovoltaic (PV) power generation industry in China has flourished. However, the intermittence of PV power generation has caused the problem of light curtailment. Moreover, the problem of photoelectric absorption has become increasingly serious. Thus, the interaction between the energy and microgrid demand needs to be considered, which can effectively reduce the serious influence of

PV light.

The connection between power supply and heating systems has been continuously strengthened, and some studies on the optimization of cogeneration microgrid have been reported. An optimization model for multi-time scales of microgrids containing wind power, energy storage, and cogeneration units was proposed in [1]. In [2] and [3], electric boilers were used to decouple the heat-set constraint and solve the wind power consumption problem in the thermal power plant outside the range of power system. A photothermal power station was introduced in the cogeneration microgrid in [4] to assist in system operation, which provided an effective way to solve the PV power generation problem. In [5]-[9], an electro-thermal combined dispatching model was proposed, which used heat storage devices to increase the elasticity of the cogeneration units. The combination of PV power generation and cogeneration was summarized in [10], [11], which is generally equipped with a certain capacity of heat storage to compensate for the instability of PV power output. A summary of the application prospects of an electro-thermal system with a large heat storage capacity to deal with the renewable energy consumption problem was presented in [12]. In [13]-[15], a combined operation system for wind storage was proposed, with a certain schedulability. However, the cost of energy storage is high, and needs to be carefully considered in practical applications. The discussions in the above-mentioned literature on the cogeneration microgrid did not consider demand response in the operation of microgrid.

In recent years, researches on demand response and energy storage have increased. Large-scale photoelectric consumption can be divided into cost-based consumption and delivery. Promoting local consumption of photoelectronics needs to be achieved using price incentives and demand response. Based on the combination of the price elasticity matrix and energy storage technology, an optimization model for wind power absorption was constructed in [16], which verified the impact of the demand response on the wind power consumption. Wind power on-site consumption by switching high-energy load, electricity storage devices, and direct purchase of electricity by users at time-of-use tariffs were

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promoted in [17]-[19]. The scope of wind power consumption through external delivery was expanded in [20], [21], which is an important way to solve the problem of large-scale wind curtailment.

The traditional photoelectric consumption model mostly combines PV power generation and energy storage systems, ignoring the demand response with time-of-use electricity prices. The model does not consider the role and benefits of the cogeneration system in promoting photoeletric consumption. Therefore, this study discusses the optimization of the microgrid, taking into consideration the demand response and cogeneration system with a heat storage device to promote photoelectric absorption. Firstly, a microgrid system containing PV power generation system, cogeneration system with heat storage, energy storage and demand response is proposed, and corresponding mathematical models are established. On this basis, the established mathematical model is settled by the particle swarm optimization (PSO) algorithm. Finally, the effectiveness of the proposed optimization operation model is verified by simulation results.

The main contributions of this paper are as follows:

1) For the PV and cogeneration complex system, an economic dispatching model is established to improve the photoelectric absorption capacity.

2) In the hybrid system model, the time-of-use electricity price mechanism is introduced to adjust the load distribution, which improves the photoelectric absorption level.

3) Considering the model is a mixed-integer linear programming problem, PSO is used to solve it. The effectiveness of the method for improving photoelectric absorption levels is verified by the analysis of experiment results.

II. Microgrid Model

This study establishes an optimized economic dispatching model with PV generator sets, cogeneration units with heat storage and energy storage systems, as shown in Fig. 1. In this system, both electrical and thermal systems are involved and interacted with each other. To promote PV consumption and solve the serious problem of light curtailment, continuously adjusting the operation mode of the energy storage system and the output of the cogeneration unit achieves the best economic benefits and ensures the secure and steady running of the microgrid.
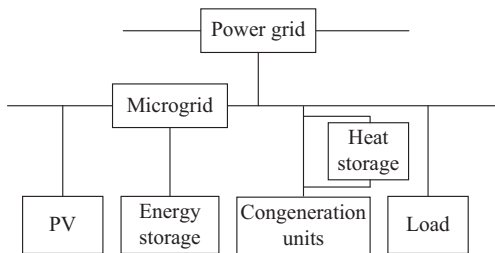

Fig. 1.   Diagram of system structure.

A. Output Power Model of PV

The output power of PV is closely related to the intensity of light. PV cells generally run in the maximum power point tracking (MPPT) mode, and their output power can be expressed as [22]:

$$P_V(t)=\zeta(t)\eta_M S_V \eta_V \cos\theta(t) \tag{1}$$

where $P_V(t)$ is the actual output power of PV at time t; $\zeta(t)$ is the light intensity of the sun at time t; η_M is the efficiency in the MPPT mode; S_V is the area of the PV panel; η_V is the efficiency of the PV panel; and $\theta(t)$ is the angle of incidence of the moment of illumination at time t.

B. Demand Response Model

The demand response controls the use of electric energy by changing the user's power consumption mode, improving the power efficiency and reducing the power loss, while satisfying the user's power usage. Based on the time-of-use electricity price, this study looks into the impact of demand-side management on energy use efficiency and promotes photoelectric absorption. The time-of-use electricity price reduces the electricity demand of user at the peak time, and shifts the demand to the normal or valley time. If necessary, the load is cut during the peak period to alleviate the voltage force, so that the output curve of the power system load becomes more gradual.

This model uses the time-of-use electricity price strategy [23] to promote photoelectric consumption and improve the efficiency of PV utilization. Firstly, the load curve is optimized by implementing the time-of-use electricity price, the spare capacity of the load during peak hours is reduced, and the number of switch times of the generator set is reduced. Hence, a demand response model is established.

$$E(ii)=\frac{\Delta Q(i)/Q(i)}{\Delta p(i)/p(i)} \tag{2}$$

$$E(ij)=\frac{\Delta Q(i)/Q(i)}{\Delta p(j)/p(j)} \tag{3}$$

where $E(ii)$ is the self-elastic coefficient of the response of the time period at time i, respectively; $E(ij)$ is the mutual elastic coefficient of the multi-period response at time i and time j, $i\neq j$; $\Delta Q(i)$ and $Q(i)$ are the amounts of change in the load and initial load after implementing the peak-to-valley time-of-use electricity price at time i, respectively; $\Delta p(i)$ and $p(i)$ are the changes in the price of electricity and initial price after implementing the peak-to-valley time-of-use electricity price at time i, respectively; and $\Delta p(j)$ and $p(j)$ are the changes in the price of electricity and initial electricity price after implementing the peak-to-valley time-of-use electricity price at time j, respectively. From the two types above, the amount of change in the load is:

$$\Delta Q(i)=\sum_{j=1}^{T} E(ij)\frac{\Delta p(j)}{p(j)}E(ii) \tag{4}$$

where T is the time period.

Based on the analysis of the load curve, the fuzzy clustering method of semi-gradient membership function is used to divide the peak-to-valley period. An elastic matrix containing electricity and electricity prices is introduced to describe the price response of the load in each peak-to-valley period. Therefore, the power consumption of the load in each period

is obtained after putting the time-of-use power price into practice [17]:

$$\begin{bmatrix} \Delta Q(1) \\ \Delta Q(2) \\ \vdots \\ \Delta Q(T) \end{bmatrix} = \begin{bmatrix} Q(1) & 0 & \cdots & 0 \\ 0 & Q(2) & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & Q(T) \end{bmatrix} E \begin{bmatrix} \Delta p(1)/p(1) \\ \Delta p(2)/p(2) \\ \vdots \\ \Delta p(T)/p(T) \end{bmatrix} \quad (5)$$

where E is the elastic matrix containing the electricity and electricity prices.

The energy storage system has dual characteristics and can be used as a load or power source for effective transfer.

C. Energy Storage and Discharging Model

In the traditional power production process, the generation and use of electric energy are carried out simultaneously, so the operation and control of power system are deeply affected. Applying the energy storage system to the power system solves the real-time balance problem between power supply and demand side. When the energy storage system is widely applied to the power generation side, it effectively reduces the peak-to-valley difference between day and night, improves the power quality, and facilitates the large-scale integration of renewable energy into the power grid.

The energy storage system has dual characteristics. It can be used as a load or as a power source to properly transfer electric energy. In the microgrid, there is a PV power generation system, which needs to be equipped with a certain energy storage capacity. The aim is to balance the randomness and volatility of the PV output and improve power quality. During the valley load period, the energy storage system acts as a load to store excess energy. During the peak load period, the energy storage acts as a power source to release the stored electric energy. The energy storage system will have a certain loss during the dynamic procedure, including the charging and discharging process. At some time, the energy storage capacity and the charging/discharging power satisfy the following relationship:

$$E_{bat}(t) = (1-\tau)E_{bat}(t-1) + [u\eta_{cbat}(t)P_{cbat}(t) - (1-u)P_{dbat}(t)/\eta_{dbat}(t)]\Delta t \quad (6)$$

where $E_{bat}(t)$ is the energy storage capacity of the energy storage device at time t; τ is the loss coefficient; u is a charging and discharging state variable, 1 for charging and 0 for discharging; $\eta_{cbat}(t)$ and $\eta_{dbat}(t)$ are the charging and discharging efficiencies of the energy storage device at time t, respectively; and $P_{cbat}(t)$ and $P_{dbat}(t)$ are the charging and discharging power of the energy storage device at time t, respectively.

D. Combined Heat and Power Model

The volatility of PV output increases the difficulty of power system regulation. To improve the regulation capacity of the system, a cogeneration unit with a heat storage device is added, as shown in Fig. 2. When the PV output is large, a space for photoelectric consumption is provided by reducing the output of the cogeneration unit. When the photoelectric is abandoned, the cogeneration unit increases the forced output caused by heat setting. To reduce the forced output, it is

necessary to compensate for the insufficient heating portion. The heat storage device in the cogeneration unit can avoid the disadvantage of insufficient heating.
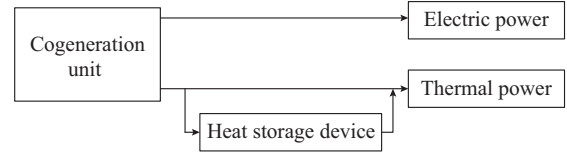

Fig. 2.   Combined heat and power unit with heat storage.

However, to meet the high heat load demand, the cogeneration unit needs a higher output, which causes serious light curtailment problems. With the guidance of the electricity price strategy during the peak and valley periods, the cogeneration unit and heat storage device are used to decouple the heat-set constraint.

III. OPERATION EFFICIENCY OF MICROGRID

A. Objective Function

The operation income of microgrid is composed of the income of selling electricity from microgrid to power grid, the cost of purchasing electricity from power grid, and the cost of generation for the cogeneration unit. The optimal operation model can be described as:

$$\min F = U_{bP}(t)P_{bgrid}(t)c_{bP}(t) - U_{sP}(t)P_{sgrid}(t)c_{sP}(t) + C_{chp}(t) \quad (7)$$

$$C_{chp}(t) = a_i P_{chp}^2(t) + b_i P_{chp}(t) + c_i P_{chp}(t)H_{chp}(t) + d_i H_{chp}^2(t) + e_i H_{chp}(t) + f_i \quad (8)$$

where F is the operation efficiency of microgrid; $U_{bP}(t)$ is the state of purchasing electricity from power grid to microgrid at time t (0 means no electricity purchased; 1 otherwise); $P_{bgrid}(t)$ is the electric power purchased from power grid to microgrid at time t; $c_{bP}(t)$ is the unit price of microgrid purchasing electricity from power grid to microgrid at time t; $U_{sP}(t)$ is the state of selling electricity from power grid to microgrid at time t (0 means no electricity sold; 1 otherwise); $P_{sgrid}(t)$ is the electric power sold from microgrid to power grid at time t; $c_{sP}(t)$ is the unit price of selling electricity from microgrid to power grid at time t; $C_{chp}(t)$ is the power generation cost of cogeneration unit at time t; a_i, b_i, c_i, d_i, e_i, f_i are the coefficients of the cost function; $P_{chp}(t)$ is the electric power generated by cogeneration unit at time t; and $H_{chp}(t)$ is the thermal power emitted by cogeneration unit at time t.

B. Constraints

1) Constraint of electric power balance:

$$P_{bgrid}(t) - P_{sgrid}(t) + P_{chp}(t) + \mu P_{bat}(t) + P_V(t) - P_{load}(t) = 0 \quad (9)$$

where μ is the state of energy storage (0 means neither charging nor discharging; 1 means charging; −1 means discharging); $P_{bat}(t)$ is the charging and discharging power of energy storage device at time t; $P_V(t)$ is the predicted power of PV at time t; and $P_{load}(t)$ is the power demand of power load at time t.

2) Thermal power balance constraint:

$$H_{chp}(t)+H_s(t)-H_s(t-1)=H_{load}(t) \tag{10}$$

where $H_s(t)$ is the heat storage capacity of heat storage device at time t; and $H_{load}(t)$ is the heat demand of heat load at time t.

3) Output power constraint of generator:

$$P_{chp,\min} \leq P_{chp}(t) \leq P_{chp,\max} \tag{11}$$

where $P_{chp,\min}$ and $P_{chp,\max}$ are the lower and upper limits of electric power of cogeneration unit, respectively.

4) Climbing rate constraint of generator:

$$R_{down} \leq P_{chp}(t)-P_{chp}(t-1) \leq R_{up} \tag{12}$$

where R_{down} and R_{up} are the minimum and maximum uphill rates of cogeneration unit, respectively.

5) Energy storage constraints:

$$\begin{cases} \sum_{t=1}^{T}(P_{cbat}(t)+P_{dbat}(t))=0 \\ 0 \leq P_{cbat}(t) \leq P_{cbat,\max}(t) \\ 0 \leq P_{dbat}(t) \leq P_{dbat,\max}(t) \end{cases} \tag{13}$$

where $P_{cbat,\max}(t)$ is the maximum charging power of energy storage device at time t; and $P_{dbat,\max}(t)$ is the maximum discharging power of energy storage device at time t.

6) Heat storage constraints:

$$\begin{cases} 0 \leq H_s(t) \leq H_{s,\max}(t) \\ 0 \leq H_f(t) \leq H_{f,\max}(t) \end{cases} \tag{14}$$

where $H_{s,\max}(t)$ is the maximum heat storage capacity of heat storage device at time t; $H_f(t)$ is the heat release capacity of heat storage device at time t; and $H_{f,\max}(t)$ is the maximum heat release capacity of heat storage device at time t.

7) Electricity price constraint:

$$p_{\min} \leq p(t) \leq p_{\max} \tag{15}$$

where $p(t)$ is the power price at time t; and $p_{\min}(t)$ and $p_{\max}(t)$ are the lower and upper limits of power price at time t, respectively.

8) Demand response constraint:

$$\sum_{t=1}^{T} \Delta Q(t)=0 \tag{16}$$

At time t, some loads are cut off and transferred without affecting the operation of power system. The amount of change in load during a cycle is 0.

IV. OPTIMIZATION MODEL

In the proposed optimization model of microgrid, the cost and benefit of trading between microgrids and large-scale power grid, and the power generation cost of cogeneration unit are taken as the objective functions. The optimization model includes a minimum objective function, an equality constraint, and many inequality constraints. In the optimization model, PSO is used to solve the problem iteratively, and the current optimal search solution is continuously followed to find the global optimal value. The flow chart is shown in Fig. 3. In PSO, the updated formulae for the velocity and position of particle are as follows:

$$V_{i,j}(k+1)=W(k)V_{i,j}(k)+C_1 R_1 (P_{i,j}(k)-X_{i,j}(k))+ \\ C_2 R_2 (P_{g,j}(k)-X_{i,j}(k)) \tag{17}$$

$$X_{i,j}(k+1)=X_{i,j}(k)+V_{i,j}(k+1) \tag{18}$$

where $W(k)$ is the inertia weight; $V_{i,j}(k)$ is the iteration speed; $X_{i,j}(k)$ is the spatial position; C_1 and C_2 are the learning factors; R_1 and R_2 are the acceleration factor and random constant between [0, 1], respectively; $P_{g,j}(k)$ is the current global optimal value; and $P_{i,j}(k)$ is the current individual optimal value.
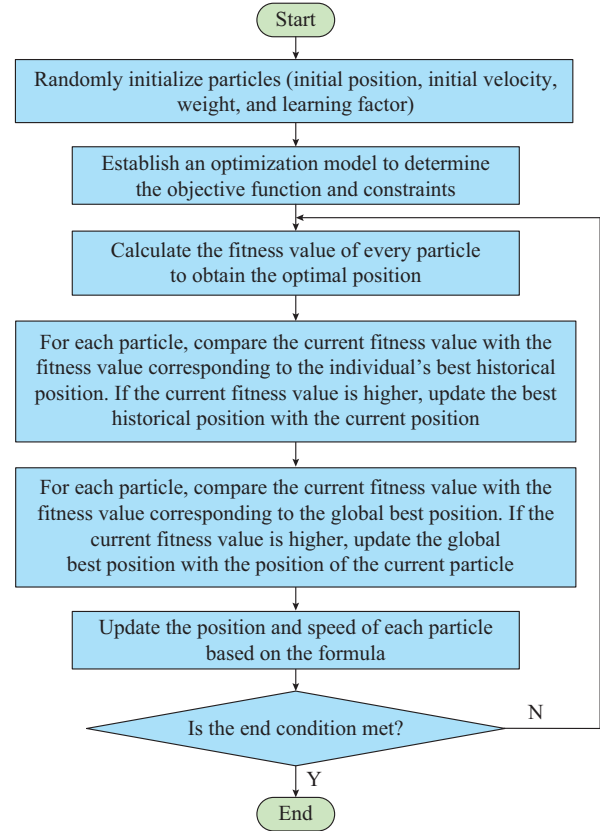

Fig. 3. Flowchart of optimization algorithm.

To improve the speed at which the PSO seeks the optimal value, the inertia weight is dynamically updated, and the updating formula can be expressed as:

$$\omega=\omega_{\max}-(\omega_{\max}-\omega_{\min})\frac{I}{I_{\max}} \tag{19}$$

where $\omega_{\max}$ is the upper limit of inertia weight, which is the initial value; $\omega_{\min}$ is the lower limit of inertia weight, which is the end value; I is the number of iterations; and $I_{\max}$ is the total number of iterations.

V. SIMULATION ANALYSIS

To verify the availability of the proposed method and the effect of cogeneration unit with heat storage on photoelectric consumption, the microgrid system including PV power generation units, energy storage systems and cogeneration generator with heat storage is selected as an illustration example. The PV prediction is shown in Fig. 4. The system uses 20

MW PV, a typical 900 MW cogeneration unit, and the maximum charging and discharging power of the energy storage system is 10 MW. The typical daily load is used as the demand load. The optimization dispatching period is $T = 24$ hours. The unit dispatching time is $\Delta t = 1$ hour. The PSO is used in the model.
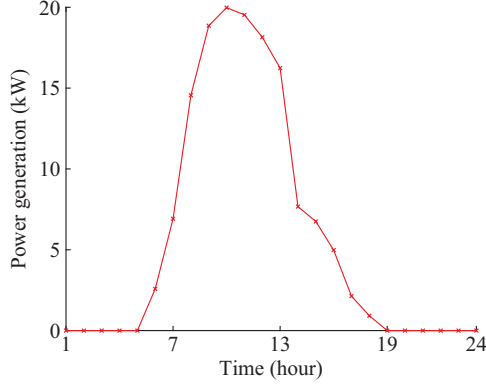

Fig. 4.   Photoelectric prediction.

The division of time and the price of electricity are shown in Table I. The elastic matrix in [17] is as follows:

$$E = \begin{bmatrix} -0.132 & 0.145 & 0.122 \\ 0.211 & -0.114 & 0.154 \\ 0.334 & 0.286 & -0.132 \end{bmatrix} \quad (20)$$

TABLE I
DIVISION OF TIME AND ELECTRICITY PRICE

Time type	Period	Price (CNY/kWh)
Valley	00:00-08:00	0.3139
Normal	12:00-17:00	0.6400
Peak	08:00-12:00, 17:00-21:00	1.0697

In this paper, the simulation analysis of the established optimization model is carried out in the following four operation modes.

1) Operation mode 1: traditional photoelectric storage joint operation mode. Both the time-sharing electricity price and cogeneration unit with heat storage do not participate in the optimal dispatching.

2) Operation mode 2: based on operation mode 1, the time-sharing electricity price participates in the dispatching, and does not consider the role of cogeneration unit with heat storage.

3) Operation mode 3: based on operation mode 1, the cogeneration unit with heat storage participates in the dispatching, regardless of the role of time-of-use electricity price.

4) Operation mode 4: based on operation mode 1, there is a joint optimization of time-of-use electricity price and cogeneration unit with heat storage.

The comparison curves of the photoelectric consumption results in the four modes are shown in Fig. 5. The photoelectric consumption rates of operation mode 1 to operation mode 4 are in ascending order. After the analysis, when the system operates with operation mode 4, the photoelectric

consumption capacity is significantly improved, and almost all the discarded photoelectric energy is consumed. The results of the optimization calculation are shown in Table II. In operation mode 4, the economic cost of the system can save up to 1.9026 million CNY, and the photoelectric consumption rate is 96.53%. From the results, the photoelectric, energy storage, cogeneration unit with heat storage, and integrated operation of time-of-use electricity price can improve the utilization efficiency of light energy and save economic costs. The economic costs and photoelectric consumption rates are shown in Table II.
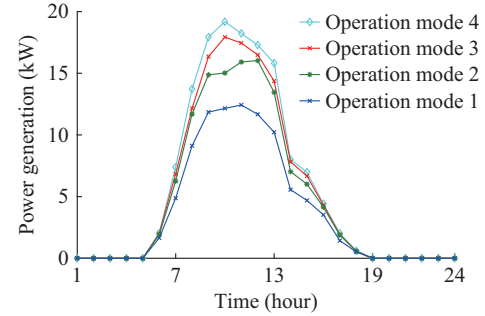

Fig. 5.   Comparison of photoelectric consumption results.

TABLE II
ECONOMIC COSTS AND PHOTOELECTRIC CONSUMPTION RATES

Operation mode	Economic cost (CNY)	Photoelectric consumption rate (%)
Mode 1	2562400	63.29
Mode 2	2175800	83.54
Mode 3	2059700	91.71
Mode 4	1902600	96.53

When the PV output is high, the electricity load is relatively low, and the energy storage device is charged. Simultaneously, the cogeneration unit reduces the output, and the reduced thermal output is provided by the thermal storage device. When the PV output is low, the electricity load is relatively high, and the energy storage is discharged. If in the non-low valley period, the cogeneration unit increases the output and stores the overdose heat in the heat storage device. In the period of light-dissipation, to provide absorption space for PV, the cogeneration unit decreases the power generation output, and further absorbs the photoelectricity at the same time through the heat storage device. Figure 6 shows the change in thermal storage of the heat storage device in operation mode 4.

Figure 7 presents the change in energy storage of the energy storage device. It can be seen that during the low valley period, the system consumes less electricity, and the energy storage device can be treated as the load and then carry out the slave point. During the peak-to-valley period, the system consumes more electricity, and the energy storage device can be treated as the power source for discharging. The energy storage device performs effective charging and discharging, which reduces part of the peak-to-valley gap of power demand and participates in the scheduling of the entire system.
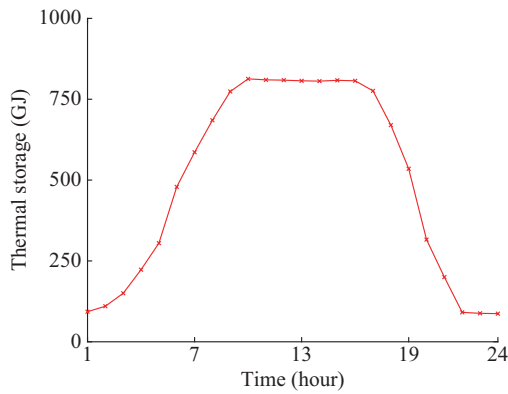
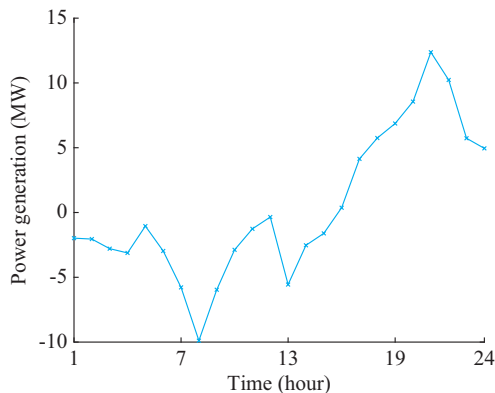Fig. 6.   Change in thermal storage of heat storage device.

Fig. 7.   Change in energy storage of energy storage device.

The mechanism of time-of-use power price and energy storage system is incorporated into the photoelectric consumption model, which is also combined with the cogeneration unit. Load demand is presented in Fig. 8. When the mechanism of time-of-use electricity price and energy storage system are introduced, the peak-to-valley gap of the load demand decreases.
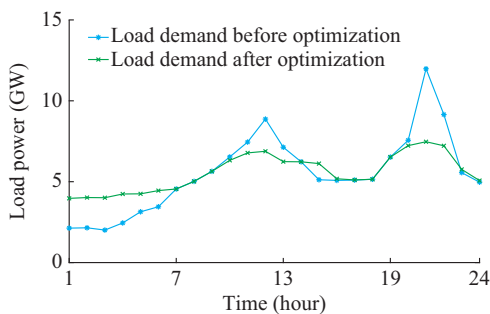

Fig. 8.   Daily load demand.

VI. CONCLUSION

In this paper, a joint system model is proposed for PV, energy storage, and cogeneration units with thermal storage devices. The demand response is considered based on time-of-use tariffs. The following conclusions are obtained through simulation verification.

1) Compared with the traditional combined operation

mode of photoelectric storage, the proposed scheme considering the cogeneration unit with heat storage and the time-of-use electricity price can absorb more PV power. This operation mode greatly increases the photoelectric consumption rate and reduces operation costs.

2) The time-of-use electricity price and energy storage system can help optimize the allocation of load and decrease the difference between the maximum and minimum loads.

3) The heat storage device can use the heat load to adjust the capacity of cogeneration unit, which can be reflected in the microgrid revenue brought about by peak clipping and valley filling.

In-depth research is also needed in subsequent studies. Ways of choosing the heat storage capacity of heat storage device need to be considered to match the PV power generation, energy storage system, and cogeneration unit .

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