Optimal configuration of optical storage microgrid under demand-side response based on cooperative game

Wang Shudong, Mao Yanrong, Jia guangyao, Song huiling, Qiu jinliang, Ding ting
School of Electrical Engineering and Information Engineering, Lanzhou University of Technology, Gansu Lanzhou 730050, China

Abstract. In the power market environment, considering the influence of the demand-side response and energy storage system on the microgrid, the joint optimization and configuration of the system through a cooperative game approach is proposed, and a time-of-use price is proposed when the demand-side user transfers the load appropriately. The microgrid operation mode is used to maximize the revenue and optimal reliability of the microgrid. Firstly, the users of the load transfer, the users and the objective functions and models of the energy storage system under the time-shared price were established; secondly, the three parties were jointly optimized by cooperative game, and the iterative algorithm was used to find the three parties to optimize the Nash equilibrium (optimal configuration scheme). The system achieves optimal returns and optimal reliability. The model and algorithm were applied to a practical photovoltaic microgrid system, and the effectiveness of the model and algorithm was verified.

1. Preface
At this stage, large-scale photovoltaic power generation appears to be difficult to integrate and absorb, and the light is severely discarded[1]. The main reason is that the PV penetration rate is low[2]. Therefore, how to increase the penetration rate of PV and ensure the reliability of the power supply of the system has become a research hotspot. With the improvement of the electricity market, more and more users are participating in the demand-side response. The impact of user response behavior on optical storage microgrids has also become a research hotspot. The energy storage device will reduce the abandonment rate, but the energy storage device is expensive and the configuration capacity will affect the economic efficiency of the microgrid. Therefore, it is very important to find a suitable energy storage capacity. How to combine demand-side with energy storage and optimize configuration is the focus of this article. At present, domestic and foreign scholars have done some researches on the optimal configuration of microgrids. The literature[3] discusses the optimal allocation of different investment entities under the competitive game model, but the user side does not consider it to be comprehensive. Literature[4] proposed a demand-side response model of transferable load, taking into account the closeness of photovoltaic power generation and load, without considering the peak-to-valley difference, and the reliability of microgrid. Literature[5] proposed a demand-side response model for time-of-use tariffs, taking into account the influence of peak-to-valley differences in load and improving the reliability of power supply, but it will reduce the PV penetration rate and require more energy storage devices to be added to the system. The gains brought about some losses. The demand-side response method based on game theory is discussed in literature[6]. This method is only for the study of scheduling, and the solution set obtained may not be the optimal solution set.
The demand-side response is to point out the incentive mechanism and price information for the electricity market. Users change their original power consumption patterns and load usage patterns so as to achieve the coordination of supply and demand interests\(^{(7)}\). Therefore, the way in which the user on the demand-side can transfer the load and the time-of-use price response of the user are proposed. The goal of shifting the load is to increase the PV penetration rate and reduce the use of energy storage devices, but the difference in load peaks and valleys will increase and the reliability of electricity consumption will decrease. The goal of the time-shared tariff response is to reduce the load peak-to-valley difference and improve the reliability of electricity use. However, the penetration rate of PV will decrease, energy storage devices will need to be added, and the economy will be affected. The cooperative game plays an important role in optimizing the configuration as a mathematical theory and method for studying cooperation and competition. Based on this, in the demand-side, a cooperative game method is used to optimize the configuration of the two response modes and energy storage, and an iterative algorithm is used to find the optimal configuration of the tripartite, so as to maximize the revenue and optimal reliability of the microgrid.

2. Micro network system joint configuration optimization model establishment

2.1. Transfer demand-side response

The demand-side response mode in the case of a transfer load refers to the purpose of reaching closer to the photovoltaic power generation power by changing the useable time of the transferable load. The effect of transferring the load is shown in figure 1. The microgrid collects photovoltaic power generation data and user load data, and re-arranges the operating time for the load that can be transferred according to the set method for the transferable load. A part of the load that can be transferred will be transferred to photovoltaic power generation for a sufficient period of time, so that the photovoltaic power generation and the load are closer in time sequence, thereby reducing the use of energy storage devices\(^{(8)}\). This method changes the operating characteristics of the load from the demand-side.

![Figure 1. Transfer of load effect picture](image)

1) Transfer load objective function

The goal of the transfer load is to make the photovoltaic power generation and load curve closer in time sequence, that is, the load is closer to the photovoltaic level after the transfer. The expression is:

\[
Q_A = \sum_{t=1}^{T} (L(t) - P_{PV}(t))
\]

\[
L(t) = L_{bef}(t) + L_{in}(t) - L_{out}(t)
\]

Where: \(Q_A\) is the load transfer close to the photovoltaic power; \(T\) is the transfer load cycle, usually 24 hours; \(P_{PV}(t)\) is the \(t\) period of photovoltaic power generation; \(L(t), L_{bef}(t), L_{in}(t), L_{out}(t)\) are the time to transfer the load after the capacity, transfer the load before the capacity, load transfer capacity and transfer capacity.

2) Transfer load model
Where: $N_L$ is the number of transferable loads; $N_{lo}$ is the number of transfer loads whose running time is greater than one cycle; $h_{max}$ is the maximum value of the duration of the supply of transferable loads; $x_k(t)$ is the number of the $k$ types of loads that are started to run at time $t$. $y_k(t)$ is the number of the $k$ type of load transfer starting at the $t$ time; $P_{lk}$ is the capacity of the $l$ time of the $k$ type of transfer load.

3) Transfer load constraints

$$\begin{align*}
L_{in}(t) &= \sum_{k=1}^{N_L} x_k(t) P_{lk} + \sum_{h=1}^{h_{max}} \sum_{k=1}^{N_L} x_k(t-h) P_{(h+1),k} \\
L_{out}(t) &= \sum_{k=1}^{N_L} y_k(t) P_{lk} + \sum_{h=1}^{h_{max}} \sum_{k=1}^{N_L} y_k(t-h) P_{(h+1),k}
\end{align*}$$

In the formula: $L_{in,min}$ and $L_{in,max}$ are the minimum power and maximum power transferred into the load; $L_{out,min}$ and $L_{out,max}$ are the minimum power and maximum power respectively. When the load is transferred, the demand-side response needs to be performed according to the specified transfer load limit.

2.2. Time-of-use price demand-side response

Time-of-use price refers to the level of load response on the demand-side of the system. Each day is divided into peaks, flats, and valleys. Different periods of time are used to implement different rates. The implementation of peak-to-trough time-of-use price is an effective demand-side response method, which improves the reliability of the microgrid by cutting peaks and filling valleys. Because the electricity price level not only affects the load at this moment, but also affects the load at other moments, the user response can be divided into single-period response and multi-period response[9]. Because the balance of electricity price and electricity price elasticity coefficient can fully characterize the user's response behavior, the electricity fee is higher at the peak period, the user can properly reduce the load or transfer the load to the valley period, at the moment the user buys electricity lower cost Increased user satisfaction[10].

1) Time-of-use price response objective function

$$W_i = (\max R_i - \min R_i)$$

In the formula: $W_i$ is the peak-to-valley difference of the user's electricity in the $i$ period after the demand response. In order to achieve the reliability requirement, the difference between the peak and the valley is as small as possible; $\max R_i$ and $\min R_i$ are the maximum values of the demand electricity in the $i$ period after the time-of-use electricity price is implemented. And minimum value.

2) Time-of-use price response load model

The comprehensive response of the user at $i$ time after the implementation of time-of-use electricity price is the comprehensive load response model based on different price elasticity.
In the formula: $R_i$ is the amount of electricity responded to by the user at time $i$ after the time-of-use electricity price is applied; $R_{i0}$, $I_{i0}$, and $I_{j0}$ are the $i$ time original electricity amount, original electricity price, and the original electricity price of the user's response during the time of $j$; $\rho_u$ and $\rho_{ij}$ are electricity prices from Elasticity coefficient and cross-elasticity coefficient; $\Delta R_i$, $\Delta I_i$, and $\Delta I_j$ are the magnitudes of changes in the user's response power at the time of $i$, the size of the price changes, and the size of the user's response power price changes in the $j$ period.

3) Time-of-use price response load constraints

$$\min. \ R_i \leq R_i \leq \max. \ R_i$$

Where: $R_{i,\min}$ and $R_{i,\max}$ are the maximum and minimum values of the user's response to electricity after the time-of-use price is applied. This formula indicates that the time-of-use price demand response should be performed within the specified limits, which are determined by the nature of the load.

2.3. Comprehensive User Response Model

The user comprehensive response model refers to the demand-side integrated response method that considers the time-of-use price in the case of a transfer load. As the user's PV penetration increases after the load is transferred, the load peak-to-valley difference increases. On the other hand, considering the reduction in load peak-to-valley difference in time-of-use tariff, user satisfaction increased. Therefore, some users will adopt a comprehensive response mode, that is, to perform a time-of-use tariff response after the load is transferred.

1) User comprehensive response objective function

$$H = Q_i + W_i$$

Where: $H$ is the sum of the near-load power of the PV and the peak-to-valley difference of the user load, that is, the smaller the $H$ is, the better the overall response of the user.

2) User comprehensive response load model

$$D = L_{in} + R_i - L_{out}$$

Where: $D$ is the user's overall response load power. The user side performs comprehensive demand response constraint conditions such as the above-mentioned transfer load response model and time-of-use price response model, and will not be described here.

2.4. Battery Energy Storage Model

Since the battery still occupies a large proportion in the energy storage application at this stage, this article only discusses the impact of the energy storage battery on the demand-side. In operation, the stored energy of the battery energy storage system is measured by the state of charge $S_{soc}(t)$. The expression is as follows:

$$S_{soc}(t+1) = S_{soc}(t) - \frac{E_{BESS}(t)}{V_{BESS}}$$
In the formula: $E_{\text{BESS}}(t)$ is the charging and discharging size of the battery energy storage system at the moment $t$, $E_{\text{BESS}}(t)$ is negative for charging, $E_{\text{BESS}}(t)$ is positive for discharging, and $V_{\text{BESS}}$ is the total capacity of the battery energy storage device.

2.5. Optimization Indicators
This article discusses the demand-side response system model that considers time-of-use tariffs under transfer load. The total cost of the micro-grid is the annual cost of the photovoltaic system, the annual cost of the energy storage system, the annual cost of the energy-storage bi-directional converter module, the user's transfer load compensation, photovoltaic compensation, and the maintenance and operation cost. The cost of operation and maintenance includes the cost of maintenance, management, labor, and related upgrades for reasonable expenses in daily operations.

1) Annual Net Profit of Micronet System

\[
C_{\text{net}} = CR - C_0
\]

\[
C_1 = \sum_{n=1}^{270} e_d(t) P_d(t) + e_v(t) P_v(t) + e_p(t) P_{pv}(t) + e_t(t) P_{tet}(t) - e_i(t) P_{it}(t)] \Delta t
\]

\[
C_0 = C_{\text{PV}} + C_{\text{BESS}} + C_{\text{CC}}
\]

\[
C_{\text{PV}} = Q_{\text{PV}}[r_0(1+r_0)^n]/(1+r_0)^m] + u(A)
\]

\[
C_{\text{BESS}} = Q_{\text{BESS}}[r_0(1+r_0)^n]/(1+r_0)^m] + u(B)
\]

\[
C_{\text{CC}} = P_{\text{CC}}[r_0(1+r_0)^n]/(1+r_0)^m] + u(C)
\]

In the formula: $C_{\text{net}}$ is the annual net profit of the micro-net system; $C_1$ and $C_0$ are the annual returns of the micro-grid system and the annual cost of the micro-net system investment; $R$ is the similar day, taking 270 similar days, equivalent to get the annual system revenue; $e_d(t)$, $e_v(t)$, $e_p(t)$, $e_t(t)$, $e_i(t)$ respectively the user electricity price, the photovoltaic electricity price, the photovoltaic subsidy electricity price, the user transfer load subsidies and the microgrid purchase price from the grid, where $e_d(t) = e_v(t)$, $P_d(t) = P_v(t)$, $P_{pv}(t) = P_{pv}(t)$, $P_{tet}(t) = P_{tet}(t)$ respectively for the user The load power, the power of the micro-grid network, the amount of the photovoltaic power generation, the total amount of user transfer load, and the power consumption of the micro-grid to the grid. $C_{\text{PV}}$, $C_{\text{BESS}}$, $C_{\text{CC}}$ are the annual cost of the photovoltaic system, the annual cost of the energy storage system, and the annual cost of the energy storage converter module; $Q_{\text{PV}}$ and $Q_{BESS}$ are the system photovoltaic capacity and the energy storage system capacity; $I_{\text{PV}}$, $I_{\text{BESS}}$, $I_{\text{CC}}$ are photovoltaic modules, respectively. Unit price, unit price of energy storage battery, and unit price of energy storage converter; $R_E$ is the number of energy storage battery replacement; $u(A)$, $u(B)$, $u(C)$ are the annual operation and maintenance costs of photovoltaic, energy storage and energy storage converters; $r_0$ is the discount rate.

2) Photovoltaic permeability
The PV penetration rate refers to the proportion of the users' use of PV power in the whole year's load, expressed as

\[
S_{\text{new}} = \frac{Q_{\text{PV,one}} + Q_{\text{PV,BESS}}}{Q_{\text{load,all}}}
\]
Where: $S_{\text{new}}$ is the PV penetration rate; $Q_{\text{PV,one}}$ is the PV direct supply load capacity; $Q_{\text{PV,BESS}}$ is the size of the PV generation capacity after storage and recharge of the battery; $Q_{\text{load,all}}$ is the total user load.

### 3. Model Solving

#### 3.1. Game Theory

In the optical storage microgrid, the users considering the transfer of load, the users considering the time-of-use tariff response and the interests of the energy-storage investors are related to each other, and there is a certain competition and restriction relationship. In addition, consider the user's comprehensive demand response, that is, the user's interest relationship between the demand response of the interest price and the energy storage under the transfer load. How to enable the three parties to cooperate with each other or the user's comprehensive response and energy storage to cooperate with each other in order to achieve the maximum net income of the photovoltaic microgrid, and to meet the microgrid reliability and maximum penetration of photovoltaic energy. This article adopts a cooperative game approach that enables three-way or two-way configurations to reach Nash equilibrium. Under the cooperation game, the three-party strategy is the percentage of the transferable load capacity, the percentage of the load response capacity under the time-shared price, and the capacity of the energy storage system. The two strategies are the user's comprehensive response capacity percentage and the capacity of the energy storage system. Under the given constraint conditions, the optimal values of the respective optimization goals are pursued, so that the system goals are optimized and the Nash equilibrium under the parties is finally achieved. There are four possible alliance modes for the three-party cooperation game, namely, the cooperation mode between any two alliances and the other party and the three parties forming the total alliance. The following uses $[{\{Q,W\},\{E\}},{\{Q, E\}, \{W\}},{\{Q\}, \{W, E\}}]$ and $[\{Q, W, E\}]$ represent these four cooperative game modes. The two-party cooperation game has only one mode, and $[D, E]$ represents this cooperative game mode. In the following, $[{\{Q,W\},\{E\}]}$ is taken as an example to give a tripartite game strategy model. The two-party model will be given later. Among them, Q represents the user who transfers the load, W represents the user who responds to the time-of-use tariff response, D represents the user who considers the time-shared price response under the transfer load, and E represents the accumulator.

1) $[{\{Q,W\},\{E\}}]$ game strategy model

Participants: $\{Q,W\}, \{E\}$

Policy Set: $S_{QW}=[P_{Q,\text{min}}, P_{Q,\text{max}}, P_{W,\text{min}}, P_{W,\text{max}}], S_{E}=[P_{E,\text{min}}, P_{E,\text{max}}]$

Information set: load, electrical parameters, economic parameters, power, etc.

Objective function: $I_{QW}(P_{Q}, P_{W}, P_{E}), I_{E}(P_{Q}, P_{W}, P_{E})$

Among them, $P_{Q}, P_{W},$ and $P_{E}$ are the percentages of the transferable load capacity, the percentage of the load response capacity under the time-shared price, and the number of energy storage batteries; $P_{Q, \text{min}}, P_{W, \text{min}}, P_{E, \text{min}}$ are the minimum percentages of the two parties respectively. The minimum number of batteries; $P_{Q, \text{max}}, P_{W, \text{max}}, P_{E, \text{max}}$ are the maximum capacity percentage of the two parties and the maximum number of energy storage batteries; $I_{QW}$ is the objective function of the alliance of users under the transfer load and time-shared price; $I_{E}$ is the energy storage objective function. The target function, ie, the size of the return, is related to its own strategy, its opponent strategy, and its set parameters. The objective function of this article uses the system's total objective function, namely $S_{\text{new}}$ and $C_{\text{net}}$. If there is a Nash equilibrium point $(P_{Q}^*, P_{W}^*, P_{E}^*)$ in the above-mentioned cooperative game model, according to the definition of Nash equilibrium, it is expressed that $(P_{Q}^*, P_{W}^*)$ and $P_{E}^*$ are each other under the opponent's choice of optimal strategy. The optimal countermeasure is that the transfer load user, the time-of-use electricity price user, and the energy storage party can achieve the maximum benefit in the sense of Nash equilibrium. The other three cooperative game modes are similar to this mode and will not be described here.
2) [D, E] Game Strategy Model
Participants: D, E
Policy set: $S_D = [P_{D, \text{min}}, P_{D, \text{max}}], S_E = [P_{E, \text{min}}, P_{E, \text{max}}]$
Information set: load, electrical parameters, economic parameters, power, etc.
Objective function: $I_D (P_D, P_E), I_E (P_D, P_E)$

Among them, $P_D$ is the percentage of the user's comprehensive response load capacity; $P_{D, \text{min}}$ and $P_{D, \text{max}}$ are the minimum and maximum percentages of the user's comprehensive response load capacity; $I_D$ is the user's comprehensive response objective function. The target function, ie, the size of the return, is related to its own strategy, its opponent strategy, and its set parameters. The objective function of this article uses the system's total objective function, namely $S_{\text{new}}$ and $C_{\text{net}}$. If there is a Nash equilibrium point $(P_D^*, P_E^*)$ in the above cooperation game model, and according to the definition of Nash equilibrium, it is expressed that both $P_D^*$ and $P_E^*$ are optimal strategies under the optimal strategy selected by the other party, that is, the strategy combination. Under the user's comprehensive response and energy storage can achieve the maximum benefit in the sense of Nash equilibrium.

3.2. Solving steps
For the above game model optimization problem, this paper uses an iterative search algorithm to solve.

Step 1: Input raw data and parameters. The data for initializing the game model mainly includes the size of the load, the size of the light, and the price of electricity.

Step 2: Establish a game model. According to the model design method described in the previous section, an optimization model based on cooperative game is established.

Step 3: Set the initial value of the equilibrium point. The equilibrium point initial value $(P_{Q, 0}, P_{W, 0}, P_{E, 0})$ and $(P_{D, 0}, P_{E, 0})$ are randomly selected in the strategy space of each decision variable.

Step 4: Each game alliance independently optimizes the decision. The results of the $j$-th round of optimization for each league in the game are $(P_{Q,j}, P_{W,j}, P_{E,j})$ and $(P_{D,j}, P_{E,j})$. In the $j$-th round of optimization, each coalition passes the optimization results $(P_{Q,j-1}, P_{W,j-1}, P_{E,j-1})$ and $(P_{D,j-1}, P_{E,j-1})$ of the previous round. The optimization algorithm obtains the optimal combination of strategies $(P_{Q,j}, P_{W,j}, P_{E,j})$ and $(P_{D,j}, P_{E,j})$, which is

$P_{Q,j} = \text{argmax}_{Q,j} (P_{Q,j}, P_{W,j}, P_{E,j})$;

$P_{W,j} = \text{argmax}_{W,j} (P_{Q,j}, P_{W,j}, P_{E,j})$;

$P_{E,j} = \text{argmax}_{E,j} (P_{Q,j}, P_{W,j}, P_{E,j})$;

$P_{D,j} = \text{argmax}_{D,j} (P_{D,j}, P_{E,j})$;

$P_{E,j} = \text{argmax}_{E,j} (P_{D,j}, P_{E,j})$.

Step 5: Information sharing. Share each player's strategy.

Step 6: Determine if the system finds a Nash equilibrium. If each game participant has the same optimal solution obtained in the adjacent two times, ie $(P_{Q,j}, P_{W,j}, P_{E,j}) = (P_{Q,j-1}, P_{W,j-1}, P_{E,j-1}) = (P_{Q}^*, P_{W}^*, P_{E}^*)$ and $(P_{D,j}, P_{E,j}) = (P_{D,j-1}, P_{E,j-1}) = (P_{D}^*, P_{E}^*)$. According to the definition of Nash equilibrium, it can be considered that the game under this strategy combination reaches the Nash equilibrium point. If a Nash equilibrium point is found, step 7 is entered and the result is output; if Nash equilibrium is not reached, step 4 is returned.

Step 7: Output system Nash equilibrium points $(P_{Q}^*, P_{W}^*, P_{E}^*)$ and $(P_{D}^*, P_{E}^*)$. Considering the influence of the initial value on the solution of the equilibrium point, if the algorithm does not converge, you can reselect the initial value in step 3.

4. Analysis of examples
Select the load data of a typical PV microgrid typical day. The maximum photovoltaic power in a typical day is 368kW, and the maximum load power is 313kW. Here, a typical daily-seasonal proportionality factor $K$ is introduced. The typical day-seasonal proportionality coefficient refers to the typical daily load data multiplied by a proportional coefficient as the seasonal load data. In the summer, the typical daily ratio coefficient $K_{s}=1$; in the winter, the typical daily ratio coefficient...
$K_d=1.2$; in the autumn, the typical daily ratio coefficient $K_q=0.8$; in the spring, the typical daily ratio coefficient $K_c=0.8$. The coefficient of proportionality in different seasons may slightly change with the fluctuation of load, but it cannot exceed the constraint range, ie

$$K_{\text{min}} \leq K \leq K_{\text{max}}$$  \hspace{1cm} (12)

Where $K_{\text{min}}$ and $K_{\text{max}}$ are the maximum and minimum values of the seasonal scale factor.

Based on the above model and algorithm, the Nash equilibrium calculation result of the tripartite cooperative game is shown in Table 1:

| Mode number | Game mode       | $P_D^*/\%$ | $P_W^*/\%$ | $P_E^*/N$ | $Q_A/kW$ | $Q_A/kW$ | $S_{\text{new}}/\%$ | $C_{\text{net}}$/Ten thousand yuan |
|------------|-----------------|-----------|-----------|----------|---------|---------|----------------------|-------------------------------|
| 1          | {Q,W,E}         | 6.4       | 3.6       | 230      | 40      | 102     | 89                   | -21                           |
| 2          | {Q,W},{E}       | 6.2       | 3.3       | 202      | 35      | 89      | 93                   | -17                           |
| 3          | {Q,E},{W}       | 5.5       | 4.1       | 261      | 42      | 85      | 88                   | -23                           |
| 4          | {Q},{W,E}       | 6.8       | 2.5       | 272      | 33      | 110     | 95                   | -24                           |

From the above data, we can see that when [{Q,W},{E}] is used in the game mode, that is, the cooperative game model of time-shared electricity price load response and energy storage system at the Nash equilibrium point $(P_Q^*, P_W^*, P_E^*)$ can make the system maximize profit. Compared to the Nash equilibrium points in the other three cases: the [{Q},{W,E}] model has the closest load to the photovoltaic power, that is, the photovoltaic power generation is closest to the load power, because of the transferable load percentage $P_Q^*$. Compared with other modes, the mode has the best PV penetration rate, but the energy storage battery configuration $P_E^*$ is also more than other modes. Because the energy storage battery is expensive, the system revenue is the lowest in this mode; the difference in load peak and valley in [{Q,E},{W}] mode is the smallest, because the percentage of $P_W^*$ considered in this mode is more than other modes, so the peak-to-valley difference is the smallest. However, in this mode, the energy storage capacity is configured more, so the revenue of the micro-grid is poor compared to other modes; the load in the [{Q,W,E}] mode is close to the photovoltaic power, peak-to-valley load difference, and system revenue are not optimal; [{Q,W},{E}] model system under the best return, the load close to the photovoltaic power is only less than [{Q},{W,E}] mode, the load peak difference is only less than [{Q,E},{W}] model, because load transfer and load response under time-of-use tariffs can form a cooperative and complementary relationship to a certain extent, making PV permeability is improved, reducing the capacity of the energy storage device configured to make the system economical optimal. Through the above analysis, the [{Q, W}, {E}] model can basically meet the requirements of the economic reliability of the system. Compared with the other three methods, the use of [{Q, W}, {E}] cooperative game method can enable the micro-grid system to achieve better expected optimization goals. Then, we can compare the difference between the user's comprehensive response mode and the transferable load response mode alone and the time-of-use price response mode alone. As shown in Table 2:

| Model name | $P_Q^*/\%$ | $P_W^*/\%$ | $P_D^*/\%$ | $P_E^*/N$ | $Q_A/kW$ | $W_A/kW$ | $S_{\text{new}}/\%$ | $C_{\text{net}}$/Ten thousand yuan |
|-----------|-----------|-----------|-----------|----------|---------|---------|----------------------|-------------------------------|
| Q         | 9.5       | —         | —         | 173      | 9       | 185     | 97                   | -28                           |
| W         | —         | 5.8       | —         | 354      | 118     | 55      | 82                   | -34                           |
| {D},{E}   | —         | —         | 9.5       | 202      | 35      | 89      | 93                   | -17                           |
From Table 2, it can be seen that adopting the [{D}, {E}] mode is more profitable than using the transferable load mode Q alone and the time-of-use price-demand response mode alone. In this mode, although the PV penetration rate is slightly less than the Q mode, the system load peak-to-valley difference is much smaller than that of the Q mode. This is because Q has more transferable load and there is no load response under time-shared electricity price, although the energy storage capacity ratio in Q This model is less, but considering the factors such as user income under time-of-use price, the [{D}, {E}] model has better economics and reliability; the system load of the [{D}, {E}] model Although the peak-to-valley difference is slightly larger than the W mode, the system PV is closer to the load and the PV penetration rate is better. This is because there are more load-sharing times in W, and there is no transferable load, so [{D}, {E}] model can reduce the configuration of energy storage capacity for better system benefits. Through the above analysis, the [{D}, {E}] model has better economic reliability.

5. Conclusions

In order to achieve a more stable and economical operation of the photovoltaic microgrid, this paper establishes a microgrid system model considering the time-shared tariff response under load transfer, and uses the cooperative game method to solve the optimized configuration of the model. The results show:

1) The grid-connected optical storage microgrid can achieve system stability or economy when considering the demand-side response. This paper lists two demand-side response methods. Under the condition of transferable load, the PV penetration rate can be improved, but this will increase the load peak-to-valley difference; in the case of time-shared electricity prices, the load peak-to-valley difference can be reduced, but the PV penetration rate decreases.

2) Due to the above reasons, this paper uses cooperative game to solve two kinds of demand-side response modes and optimal configuration of energy storage system, uses comprehensive response model and optimal configuration of energy storage system, and uses iterative algorithm to find the Nash equilibrium point (system Excellent configuration). The validity of the proposed model and algorithm is verified by practical examples.

References

[1] Zachar, M., & Daoutidis, P. (2017). Microgrid/macrogird energy exchange: a novel market structure and stochastic scheduling. IEEE Transactions on Smart Grid, PP(99), 1-1.
[2] Tushar, M. H. K., Assi, C., & Maier, M. (2017). Distributed real-time electricity allocation mechanism for large residential microgrid. IEEE Transactions on Smart Grid, 6(3), 1353-1363.
[3] Zhang, D. D., Tong, Y. B., Jin, X. M., & Liang, J. G. (2016). Optimal allocation of energy storage in micro-grid considering demand response. Power Electronics.
[4] Yang, M., & Han, X. (2015). Research on real-time scheduling strategy for micro-grid operation in island mode based on the demand-side response. Modern Electric Power.
[5] Philippou, N., Hadjipanayi, M., Makrides, G., Efthymiou, V., & Georgiou, G. E. (2015). Effective dynamic tariffs for price-based demand-side Management with grid-connected PV systems. PowerTech, 2015 IEEE Eindhoven (pp.1-5). IEEE.
[6] Li, M. A., Liu, N., Zhang, J., Lei, J., Zeng, Z., & Liu, W. (2016). Optimal operation model of user group with photovoltaic in the mode of automatic demand response. Proceedings of the Csee.
[7] Qadrdan, M., Cheng, M., Wu, J., & Jenkins, N. (2016). Benefits of demand-side response in combined gas and electricity networks. Applied Energy, 192.
[8] Aghajani, G. R., Shayanfar, H. A., & Shayeghi, H. (2017). Demand-side management in a smart micro-grid in the presence of renewable generation and demand response. Energy, 126, 622-637.
[9] Huang, T., Xiyuan, M. A., Lei, J., Aidong, X. U., Guo, X., & Peng, L. I., et al. (2015). Optimal operation of household user-side microgrid considering time-of-use price and demand response. Southern Power System Technology.

[10] Hai, L. U., Peng, X., Zhang, B., Zhou, J., & Chen, X. (2017). Operation strategy of time-of-use electricity price for demand-side considering output uncertainty of grid-connected distributed energy resource. Electric Power Construction.