Day-Ahead Optimization Scheduling for Islanded Microgrid Considering Units Frequency Regulation Characteristics and Demand Response

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ABSTRACT With the increase of distributed generation penetration, the economic operation of microgrid has been fully developed. For islanded microgrid, due to the lack of large grid support and the limited capacity of the distributed generation (DG), the energy supply of microgrid may not meet the need of users in real time. Therefore, it is of great significance to solve the problem of insufficient power supply of islanded microgrid and improve the economy of its operation. Firstly, this paper analyses the frequency characteristics of DG, and establishes power models oriented to the frequency regulation characteristics of microgrid and introduces the mathematical model of DG. Then, an islanded microgrid day-ahead optimization scheduling model considering frequency regulation characteristics of units and demand response (DR) is proposed. The frequency characteristics of controllable units and DR are considered in the model, and different strategies are selected to analyze their impact on microgrid economy. The example shows that the optimization scheduling model of microgrid established in this paper can reduce the power supply pressure during peak load periods, alleviate the problem of insufficient power supply, and effectively improve the overall benefit of microgrid, which verifies the rationality of the model.

INDEX TERMS Islanded microgrid, distributed generation, particle swarm optimization, frequency, demand response.

I. INTRODUCTION

With the development of DG technology, microgrid has widely attracted attention of the power industry. Due to the characteristics of DG, it has played an important role in resolving the energy shortage in remote mountainous areas, reducing the power supply pressure of large grid, and promoting energy conservation and emission reduction and improving the utilization of clean energy. According to its operation mode, it can be divided into two categories, one is grid-connected operation mode, the other is island operation mode.

The island operation mode usually occurs in large grid failure, planned maintenance and some remote mountainous areas or islands. Without the support of large grid, islanded microgrid becomes more difficult and complex in control, operation and management. Therefore, It is of great significance that reasonable generation planning and efficient management methods arranged to improve the economy and stability of islanded microgrid operation. At present, the research on microgrid operation is mostly focused on the economic optimization scheduling model [1]–[4]. Shen [5] improves the economy of microgrid operation by taking into account the life loss of Energy Storage System, formulating reasonable generation plan and obtaining optimal cost. Guo [6] proposed an optimization scheduling model for microgrid considering load classification, which integrates the day-ahead and day-to-day scheduling plans of microgrid, and formulates scheduling strategies with the total operation cost of microgrid as the optimization objective. Zhang [7]
proposed an islanded microgrid optimization scheduling model based on load classification, and obtained the optimal cost of the microgrid. Zhao [9] synthetically considered the generation cost and environmental control cost of DG, aiming at the optimization of total operation cost of microgrid and the minimum transaction cost of microgrid and large grid, a multi-objective mathematical model based on dynamic economic dispatch of microgrid was established, and the model was solved by dynamic programming method, and the optimization scheduling strategy was obtained. Sun [10] proposed a generation unit combination model considering the uncertainty of wind power, which fully considered the uncertainty of wind power and formulated the optimal strategy of day-ahead optimization scheduling. Molzahn [11] introduced the distributed algorithm to solve discrete optimal power flow problems, the optimal frequency control, the optimal voltage control and the optimal wide area control problems, and applied it to electric power system optimization and control. Firdaus [12] proposed an economic dispatch model for multi-microgrid systems, which was solved by Particle Swarm Optimization, and considered the problem of renewable energy consumption. Arefifar [13] considers both demand response and unit age and DR, and formulated a generation plan for DG by taking into account both energy storage characteristics and DR, Literature [15] considers both demand response and unit output smoothness. At present, the research on optimization scheduling of microgrid focuses on the economic benefits of microgrid as the objective function. By considering certain factors, the research on microgrid is carried out from the perspective of environmental protection, security and stability. However, the frequency regulation characteristics of DG and the insufficient power supply of islanded microgrid are generally neglected. Therefore, this paper proposes an islanded microgrid day-ahead optimization dispatching model considering the frequency regulation characteristics of units and DR. The operation cost, environmental control cost and load shedding cost of the microgrid are comprehensively considered. Finally, the rationality of the model is verified by example analysis.

The rest of this paper is organized as follows. Section II introduces the frequency characteristics of the DG interface. Section III introduces the mathematical model of DG. Section IV establishes an islanded microgrid day-ahead optimization scheduling model considering frequency regulation characteristics of units and DR. Section V introduces the PSO algorithm. Section VI solves the model through an example, and the conclusion is given in the Section VII.

II. ANALYSIS OF FREQUENCY CHARACTERISTICS OF DG INTERFACE

The frequency characteristics of the microgrid in the island operation mode are the basis for studying the operation mechanism and control strategy of the microgrid [16]. For different interface types of micro sources, its frequency regulation characteristics are different, which can be divided into three different frequency modulation functions: differential frequency modulation, non-differential frequency modulation and non-frequency modulation. The frequency characteristics of the microgrid are determined by all the micro sources in the microgrid [17].

There are two common control strategies for inverters, one is voltage and frequency \((V - f)\) control, the other is active and reactive power \((P - Q)\) control.

\((V - f)\) control, also known as droop control, refers to the active power and reactive power required by users by changing the output voltage and frequency of the inverters, thus maintaining the stability of the voltage and frequency. This type of micro source can achieve differential frequency modulation. The calculation formula of the unit regulating power \(K_G\) for the micro source is as follows:

\[
K_G = \frac{\Delta P_G}{\Delta f} \tag{1}
\]

\((P - Q)\) control, adopting \(P - Q\) decoupling current control strategy, refers to the output power of the inverter according to the given reference value of active and reactive power. The frequency of this type of inverter is determined by the frequency of the microgrid. The output power of the inverter is determined by the power reference value, which is independent of the frequency, that is, the inverter does not have the frequency modulation effect.

Therefore, the frequency characteristics of the inverter interface micro sources are related to the inverter control strategy, that is, the \(V - f\) control type inverter can adjust the frequency difference, and the \(P - Q\) control type inverter does not participate in the frequency modulation.

A. FREQUENCY CHARACTERISTIC ANALYSIS OF MICRO TURBINE (MT)

For MT, because of its constant output power, and the control strategy is easy to implement. In this paper, a control mode is adopted. The dynamic simplified model of MT is shown in Fig. 1.

Assuming that MT works in normal state, combined with the rotor motion equation of synchronous generator (SG),
the overall transfer function can be obtained, as shown in Fig. 2.

Simplified:

\[ T_M = (-T_C + \omega_{ref} (-J_s)) \frac{G_1(s)}{1 - G_1(s)} \]  

(2)

Formula:

\[ \frac{G_1(s)}{1 - G_1(s)} = \frac{k_p}{Js^2 (1 + T_1s) (1 + T_2s) + k_p} \]

The expression of SG speed is obtained as follows:

\[ \omega = \frac{T_m - T_c}{J_s} = -\frac{T_c}{J_s} \left( \frac{G_1(s)}{1 - G_1(s)} + 1 \right) - \omega_{ref} \frac{G_1(s)}{1 - G_1(s)} \]

(3)

The change of the load corresponds to the change of the electromagnetic torque \( T_c \), so that the \( T_c \) step changes, its time domain steady state value is \( T_c \), the corresponding frequency domain is \( T_c/s \). The speed reference time domain is \( \omega_{ref} \), and the corresponding frequency domain is \( \omega_{ref}/s \). According to the final value theorem, the steady state value of \( \omega \) can be obtained as shown in the following equation:

\[ \lim_{s \to \infty} \omega(t) = \lim_{s \to 0} s\omega(s) = -\frac{T_c}{k_p} + \omega_{ref} \]

(4)

According to formula (4), the time domain expression of the steady state value of the rotational speed can be obtained as follows:

\[ \omega(t) = -\frac{T_c(t)}{k_p} + \omega_{ref} \]

(5)

It can be seen that the steady state value of the rotational speed is related to \( T_c \) and \( \omega_{ref} \), according to formula (5):

\[ \omega(t') - \omega(t) = -\frac{(T_c(t') - T_c(t))}{k_p} \]

(6)

\[ \omega(t') - \omega(t) = -\frac{(P_c(t') - P_c(t))}{k_p} \]

(7)

Equation (7) shows that there is an inverse relationship between the MT frequency change and the output power change. That is, MT has a drooping frequency characteristic and can participate in the differential frequency modulation. The unit adjustment power \( K_G \) is the coefficient \( k_p \) of the proportional link, as shown in the following equation:

\[ K_G = -\frac{\Delta P_g}{\Delta f} = k_p \]

(8)

Therefore, this paper considers that the MT participates in differential frequency modulation, and the unit adjustment power is \( K_G \).

FIGURE 2. Transfer function.

FIGURE 3. Microgrid system structure diagram.

B. ANALYSIS OF FREQUENCY CHARACTERISTICS OF WIND TURBINE (WT)

WT is an asynchronous machine, and its output power has obvious intermittent and volatility. Its control goal is to ensure the maximum utilization of renewable energy. Therefore, the \( P-Q \) control strategy is adopted.

WT generally needs to be connected in parallel with other micro sources while operating in the island operation mode. At this time, the frequency of WT varies with the frequency of microgrid, and the output power is determined by the mechanical power of the prime mover. Therefore, this paper considers that WT do not participate in frequency modulation.

C. ANALYSIS OF FREQUENCY CHARACTERISTICS OF PHOTOVOLTAIC (PV)

PV is similar to WT, and its output power is intermittent and volatile. \( P-Q \) control strategy is adopted. Therefore, this paper considers that PV do not participate in frequency modulation.

III. MATHEMATICAL MODEL OF DG

The microgrid system model studied in this paper is shown in Fig.3. The microgrid contains WT, PV, MT, energy storage system (ESS) and loads.

A. MATHEMATICAL MODEL OF MT

\[ C_{MT}(t) = C \Delta t \frac{1}{LHV} \sum_{i=1}^{24} \frac{P_{MT}(t)}{\eta_{MT}} \]

(9)

\[ P'_{MT}(t) = P_{MT(t)} - K_G \Delta f(t) \]

(10)

\[ \Delta f(t) = \frac{P_{LOAD(t)} - P_{LOAD(t-1)} - (P_{MG(t)} - P_{MG(t-1)})}{K_{MG}} \]

(11)

where: \( C_{MT}(t) \) is the fuel cost of MT, \( LHV \) is the low calorific value of natural gas, take 9.7kWh/m³. \( C \) is the price of fuel gas of MT, take 2.5 yuan, \( \Delta f(t) \) is the frequency fluctuation in the \( t \) period, taking the increase to positive; \( P_{LOAD(t)} \), \( P_{LOAD(t-1)} \) respectively represent the active power load of the \( t \) period and the \( t-1 \) period; \( P_{MG(t)} \), \( P_{MG(t-1)} \) respectively represent the active power MG of the \( t \) period and the \( t-1 \) period; \( P_{MT(t)} \) is not consider the frequency characteristics of MT of the actual power. \( P'_{MT(t)} \) is consider
the frequency characteristics of MT of the actual power;

\[
\eta_{MT} = 0.0753 \left( \frac{P_{MT}}{65} \right)^3 - 0.3095 \left( \frac{P_{MT}}{65} \right)^2 + 0.4174 \left( \frac{P_{MT}}{65} \right) + 0.1068 \quad (12)
\]

where: \( \eta_{MT} \) is the generation efficiency of MT and \( \Delta t \) is the scheduling time interval.

**B. MATHEMATICAL MODEL OF ESS**

\[
SOC(t) = \begin{cases} 
SOC(t - \Delta t) + \frac{P_{ch}(t)\Delta t}{\eta_D} & \text{if } P_{ch}(t) > 0 \\
SOC(t - \Delta t) - P_{dis}(t)\Delta t\eta_C & \text{if } P_{dis}(t) > 0
\end{cases} \quad (13)
\]

where: \( SOC(t) \) is the state of charge of ESS in \( t \) period, \( P_{ch}(t) \) and \( P_{dis}(t) \) are charging and discharging power in \( t \) period, \( \eta_D \) and \( \eta_C \) are ESS charging and discharging efficiency.

**C. LOAD MODEL**

Islanded microgrid is mainly used for power demand in remote mountainous areas. The classification of demand loads is helpful for energy management and reasonable scheduling plan [18]. According to the reliability of power supply, the loads can be divided into three categories: the first is the important load, which refers to the uninterruptible supply, the loads can be divided into three categories: the

1) LOAD-SHIFTABLE MODEL

\[
P_{SF}(t) = \sum_{i=1}^{24} U_i P_{SF}(t') \quad (14)
\]

where: \( P_{SF}(t) \) is the load of the \( t' \) period shift to the \( t \) period, and \( U_i \) is the state variable, taking 0 or 1, \( P_{SF}(t') \) indicates the \( t' \) period shift to the load, and when \( P_{SF}(t') > 0 \) indicates the \( t' \) period load shift to the \( t \) period; When \( P_{SF}(t') \leq 0 \) indicates the \( t \) period shift to the \( t' \) period load.

2) LOAD-CURTAILABLE MODEL

\[
C_{INT}(t) = \sum_{i=1}^{24} K_{INT} P_{INT}(t) \quad (15)
\]

where: \( K_{INT} \) represents the penalty coefficient for cutting off the unit charge; \( C_{INT}(t) \) represents the total penalty cost for the \( t \) period; \( P_{INT}(t) \) represents the removable load for the \( t \) period.

**IV. DAY-AHEAD OPTIMIZATION SCHEDULING FOR ISLANDED MICROGRID CONSIDERING UNITS FREQUENCY REGULATION CHARACTERISTICS AND DEMAND RESPONSE**

**A. OBJECTIVE FUNCTION**

The scene selected in this paper is an islanded microgrid. Due to the limited output of micro sources supply, the power supply is seriously insufficient during peak load, resulting in imbalance of active power of the system, which in turn causes the frequency of the islanded microgrid, and the frequency shifting offset will affect the MT’s output, so this paper considers the impact of frequency on MT’s active output in the model, and then studies the economics of the microgrid [20]. In this paper, we do not consider the revenue from the microgrid to sell electricity to the load, and divide the day into 24 time segments to solve the objective function without considering the internal power loss of the microgrid. For WT and PV, no fuel is consumed, only its operation and maintenance costs are counted. For other micro sources, investment is not considered, and only the operation and maintenance costs are considered. Under the condition of ensuring the normal operation constraints of the system, a reasonable output plan is formulated to minimize the total operating cost of the microgrid [21].

\[
\min C_{eco} = C_{WT} + C_{PV} + C_{MT} + C_{SB} + C_{INT} + C_{EC} + C'_{MT} \quad (16)
\]

\[
C_{WT} = \sum_{t=1}^{24} C_{WT,OM} P_{WT}(t) \quad (17)
\]

\[
C_{PV} = \sum_{t=1}^{24} C_{PV,OM} P_{PV}(t) \quad (18)
\]

\[
C_{MT} = \sum_{t=1}^{24} (C_{MT,fuel} P_{MT}(t) + C_{MT,OM} P_{MT}(t)) \quad (19)
\]

\[
C'_{MT} = \sum_{t=1}^{24} C_{MT,OM} (P'_{MT}(t) - P_{MT}(t)) \quad (20)
\]

\[
C_{SB} = \sum_{t=1}^{24} C_{SB,OM} |P_{SB}(t)| \quad (21)
\]

\[
C_{EC} = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} P_i \quad (22)
\]

where: \( C_{WT} \) is the WT operation and maintenance costs, and \( C_{WT,OM} \) is the WT unit operation and maintenance cost coefficient; \( P_{WT}(t) \) is WT output in \( t \) period; \( C_{PV} \) is the PV operation and maintenance costs; \( C_{PV,OM} \) is the PV unit operation and maintenance cost coefficient; \( C_{MT} \) is the MT generation costs, including the operation and maintenance cost and fuel cost; \( C_{MT,fuel} \) and \( C_{MT,OM} \) are respectively the fuel cost coefficient of MT and the unit operation and
maintenance cost coefficient; \( C_{MT} \) represents the cost of the increasing in MT due to frequency shifting; \( C_{SB} \) is the operation and maintenance costs of the ESS; \( C_{SB,OM} \) is the ESS operation and maintenance cost coefficient; \( P_{SB}(t) \) is the charge and discharge power of the ESS in \( t \) period, which is positive when discharging, and negative when charging; \( C_{Ec} \) is the environmental treatment cost, \( i \) is the micro sources type, \( j \) is the pollution gas \( CO_2, SO_2, \) and \( NOX \) type, and \( C_{ij} \) is the treatment cost of the type \( j \) gas generated by the \( i \) micro source. \( P_i \) represents output the \( i \) micro source.

### B. CONSTRAINTS

1) **POWER BALANCE CONSTRAINTS**

\[
P_{WT}(t) + P_{PV}(t) + P_{SB}(t) + P'_{MT}(t) = P(t) + P_{SF}(t) - P_{INT}
\]  
(23)

2) **MICRO SOURCES OUTPUT CONSTRAINTS**

\[
P_{WT,\text{min}} \leq P_{WT}(t) \leq P_{WT,\text{max}}
\]  
(24)

\[
P_{PV,\text{min}} \leq P_{PV}(t) \leq P_{PV,\text{max}}
\]  
(25)

\[
P_{MT,\text{min}} \leq P_{MT}(t) \leq P_{MT,\text{max}}
\]  
(26)

where: \( P_{WT,\text{max}} \) and \( P_{WT,\text{min}} \) are the upper and lower limits of WT output respectively, \( P_{PV,\text{max}} \) and \( P_{PV,\text{min}} \) are the upper and lower limits of PV output respectively, and \( P_{MT,\text{max}} \) and \( P_{MT,\text{min}} \) are the upper and lower limits of MT output respectively.

3) **MT CLIMBING RATE CONSTRAINTS**

\[
f_{\text{down}} \leq P_{MT}(t + 1) - P_{MT}(t) \leq f_{\text{up}}
\]  
(27)

4) **ESS CONSTRAINTS**

\[
SOC(t) = S_0 + \sum_{i=1}^{24} P_{ch,t} X_t - \sum_{i=1}^{24} P_{dis,t} Y_t
\]  
(28)

\[
E_i = X_t + Y_t \leq 1
\]  
(29)

\[
SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}}
\]  
(30)

\[
P_{ch,\text{min}} \leq P_{ch}(t) \leq P_{ch,\text{max}}
\]  
(31)

\[
P_{dis,\text{min}} \leq P_{dis}(t) \leq P_{dis,\text{max}}
\]  
(32)

where: \( SOC(t) \) is the state of charge of the ESS during the \( t \) period; \( X_t \) and \( Y_t \) represent the state of charge and discharge of the ESS, taking 0 or 1; \( S_0 \) represents the state of charge of the initial time ESS of a scheduling period; \( SOC_{\text{max}} \), \( SOC_{\text{min}} \) are upper and lower limits of ESS charging state; \( P_{ch,\text{max}} \) and \( P_{ch,\text{min}} \) are upper and lower limits of ESS charging power constraint; \( P_{dis,\text{max}} \) and \( P_{dis,\text{min}} \) are upper and lower limits of ESS discharge power constraint.

5) **DR CONSTRAINTS**

\[
0 < P_{INT}(t) < P_{INT,\text{MAX}}
\]  
(33)

\[
0 < P_{SF}(t) < P_{SF,\text{MAX}}
\]  
(34)

![Flow chart of PSO algorithm.](image)

**FIGURE 4.** Flow chart of PSO algorithm.

\[
0 < P_{SF}(t') < P_{SF,\text{MAX}}
\]  
(35)

\[
\sum_{i=1}^{T} P_{SF}(t') = 0
\]  
(36)

where: \( P_{INT,\text{MAX}} \) indicates the maximum Load-shiftable load, and \( P_{SF,\text{MAX}} \) indicates the maximum Load-curtailable load.

### V. PSO ALGORITHM

Intelligent optimization algorithm is more and more widely used in the field of microgrid optimization. In this paper, PSO algorithm is applied to solve the optimization model. PSO is inspired by the random food search model of birds. It is assumed that a group of birds randomly search for food in a certain area. There is only one piece of food in this area, and all birds do not know where the food is. The birds randomly search for food in this area, but the specific location of the food is not exposed. The simplest and most efficient way for birds to find food quickly is to search the surrounding area of birds with the shortest distance from food. PSO arithmetic is generated in the context of this natural phenomenon and applied to solve optimization problems [22]–[24].

The flow chart of PSO algorithm is shown in Fig. 4:

### VI. EXAMPLE ANALYSIS

#### A. MODEL PARAMETERS

To verify the rationality of the scheduling strategy and model algorithm proposed in this paper, taking an islanded micro-grid with multiple micro sources as an example, the basic parameters of the example are as follows: The biggest technical output of MT is 80 kW, a maximum up-climb rate of 30 kW/h, a maximum down-climb rate of \(-30\) kW/h, The capacity of ESS is 300 kWh, and its SOC variation range is 0.2-0.9, the initial SOC value is 0.3, the maximum charging and discharging power is 60 kW, the charging and discharging efficiency is 0.9. The compensation cost of load shedding is 0.58 yuan/kWh; Fig. 5 is the forecast result of WT, PV and loads in each period of a typical day [25]–[29]. The output
VII. RESULT ANALYSIS

To verify the effectiveness and feasibility of the program, this paper established four comparison schemes:

Strategy 1: Do not consider the units frequency regulation characteristics and DR;
Strategy 2: Only consider the units regulation characteristics;
Strategy 3: Only consider the DR;
Strategy 4: Consider both the units frequency regulation characteristics and DR.

1) Micro sources output power situation in the Strategy 1 is shown in Fig. 6. The state of charge of the ESS is shown in Fig. 7. From 0:00 to 5:00, due to the abundant wind resources at night, the WT output power is high. In addition to the supply load, the WT stores excess wind energy in the ESS. At this time, the MT is in the outage state because the MT output cost is higher than the WT, so it does not work during this period.

After 8:00, the load rises and the MT starts to work. From 10:00 to 15:00, the wind resources decrease; the WT output power is reduced; the MT output power is increased, and the ESS continues to charge. The 18:00-22:00 is the peak load period. The MT output power is stable, and the wind output power is limited by the wind resources. At this time, the ESS discharge power has reached the maximum value. However, due to the high load during this period, the microgrid output power still can not meet the loads demand, so part of the loads is removed during this period. The load shedding situation is shown in Fig. 8. In strategy 1, the total operating cost of the microgrid is 965 yuan, of which the micro sources operating cost, environmental treatment cost and load shedding cost are 569 yuan, 171 yuan and 225 yuan respectively.

2) Micro sources output power situation in the Strategy 2 is shown in Fig. 9. The state of charge of the ESS is shown in Fig. 10. The power output of micro sources is similar to the strategy 1 in the period from 0:00 to 8:00 (the wind output is high; the ESS is charged, and the MT is not working). After 8:00 the load rises and the output power is low. At the peak hours of the load from 18:00 to
22:00, it can be seen from Fig. 6 and Fig. 9 that the MT output power increases and can be kept stable. The main reason for this situation is: due to the high load power, the micro sources output power cannot meet the load demand, which will cause the fluctuation of the microgrid frequency, while the strategy 2 considers the frequency fluctuation factor and allows the frequency fluctuation 0.2HZ. According to the frequency characteristics of the MT, as the frequency decreases, the MT output power will increase. Therefore, in the case of Strategy 2, it can be found that the MT output power is greatly increased and can be kept stable during this period due to its frequency response role. The frequency fluctuation in Strategy 2 is shown in Fig. 11. Limited by the MT rated power and the allowable frequency fluctuation range, the total output power of the micro sources still cannot meet the load demand during this period, so it is still necessary to cut off part of the loads. The comparison between strategy 1 and strategy 2 is shown in Fig. 12. The total operating cost of strategy 2 is 835 yuan, which is 13.5% lower than that of Strategy 1, and the environmental management cost is 187 yuan. Compared with Strategy 1, the load shedding cost is 120 yuan, which is greatly reduced compared with Strategy 1. The main reason is that due to the frequency characteristics of the MT, its output power is increased, and the load shedding cost is greatly reduced.

3) Micro sources output power situation in the Strategy 3 is shown in Fig. 13. The SOC state of the ESS state of charge is shown in Fig. 14. Comparing Fig. 13 and Fig. 6, it can be found that the MT is not working and the WT output is increased during the period of 0:00-5:00. The main reason is that the DR is considered, and the load shifting during the peak period. The WT output power increased. In the peak load period from 18:00 to 22:00, in addition to load shifting, part of the load is cut off during this period to meet the power supply balance. The comparison load curve between strategy 1 and the strategy 3 is shown in Fig. 15, and it can
be found that considering the DR can effectively reduce the load peak-to-valley difference and improve the stability of the microgrid operation. The total cost of the microgrid in Strategy 3 is 895 yuan, which is 7.3% lower than the total cost of Strategy 1. Therefore, considering the DR can also effectively improve the economics of the microgrid operation.

4) Strategy 4 comprehensively considers the units regulation characteristics and DR. The micro sources output situation is shown in Fig. 16. The ESS state of charge SOC changes is shown in Fig. 17. Microgrid cost composition under four strategies is shown in Table 4. Strategy 4 Load-shiftable and Load-curtailable action mount is shown in Table 5. During the period of 0:00-5:00, Strategy 4 is similar to the strategy 3 for result of micro sources output power. Due to the load shift during peak hours, the WT output power is high and can be kept stable; the ESS is charged, and the MT starts working when wind resources are insufficient in 8:00. During the peak load period from 18:00 to 22:00, the ESS is discharged, and the discharge power reaches the maximum value, and the MT output also reaches the maximum value. However,

![FIGURE 14. SOC changes situation of ESS in the strategy 3.](image1)

![FIGURE 15. Compared strategy 1 with strategy 3 of load power curve.](image2)

![FIGURE 16. Micro sources output power situation in the strategy 4.](image3)

![FIGURE 17. SOC changes situation of ESS in the strategy 4.](image4)

![FIGURE 18. Comparison of load shedding under four strategies.](image5)

| TABLE 4. Microgrid cost composition under four strategies. |
|-----------------------------------------------------------|
| Cost | Micro sources output cost/yuan | Environmental governance cost/yuan | Load removed cost/yuan | Total cost/yuan |
|------|--------------------------------|-----------------------------------|-----------------------|----------------|
| Strategy 1 | 569 | 171 | 225 | 965 |
| Strategy 2 | 528 | 187 | 120 | 835 |
| Strategy 3 | 538 | 159 | 198 | 895 |
| Strategy 4 | 537 | 158 | 40 | 735 |

| TABLE 5. Strategy 4 Load-shiftable, Load-curtailable action mount. |
|---------------------------------------------------------------|
| Serial number | time | Amount/kW |
|----------------|------|-----------|
|                | 17:00-18:00 to 1:00-2:00 | 8 |
| Load-shiftable  | 17:00-18:00 to 2:00-3:00 | 12 |
|                | 18:00-19:00 to 1:00-2:00 | 15 |
|                | 18:00-19:00 to 2:00-3:00 | 10 |
|                | 19:00-20:00 to 0:00-1:00 | 20 |
|                | 19:00-20:00 to 1:00-2:00 | 5 |
| Load-curtailable | 19:00-20:00 | 15 |
|                | 21:00-22:00 | 15 |
considering the power supply balance, some load needs to be removed during this period. Fig. 18 shows load shedding situation. It can be seen from Fig. 18 that the strategy 1 has the highest load shedding and the strategy 4 is the least amount of load shedding. This shows that considering the unit regulation characteristics and the DR can improve the reliability of the operation and alleviate the problem of insufficient power supply of the islanded microgrid. The total operating cost of Strategy 4 is 735 yuan, which is 23.8%, 11.9%, and 17.8% lower than the total operating costs of Strategy 1, Strategy 2, and Strategy 3, respectively. This indicates that the model proposed in this paper can effectively improve the economics of the microgrid.

VIII. CONCLUSION AND OUTLOOK
In this paper, due to the lack of support of the large grid and the limitation of the capacity of the DG for the islanded microgrid, the power supply shortage problem is caused. The power supply is seriously insufficient during peak load period, resulting in imbalance of active power of the system, which in turn causes the frequency shifting of the islanded microgrid, and the frequency shifting will affect the output of MT. This paper considers the impact of frequency offset on MT’s active output in the model, So the islanded microgrid optimization scheduling model considering the frequency regulation characteristics of units and DR is proposed. The effects of units frequency regulation characteristics and DR on the economics of the island system are analyzed under different strategies. The following conclusions can be drawn:

1) By considering the frequency adjustment characteristics of units, the load shedding cost caused by the insufficient power supply of the island system can be reduced, the user satisfaction is improved and the overall benefit of the microgrid is increased; in addition, according to the drooping characteristics of the MT, the output of the MT can be increased by increasing its unit adjustment power, which not only contributes to the economic benefits of the microgrid, but also reduces the frequency fluctuation range of the microgrid and contributes to the reliable operation of the microgrid.

2) Considering the DR can effectively reduce the load peak-to-valley difference, improve the stability of the microgrid operation, alleviate the power supply pressure of the islanded microgrid, and improve the economics of operation.

3) By comprehensive considering the frequency regulation characteristics of units and the DR, the problem of insufficient power supply in the island system can be alleviated, and the economics of the microgrid operation is greatly improved. Compared with the two factors alone considering, the model is more effective.

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