Multi-Objective Optimization Scheduling Considering the Operation Performance of Islanded Microgrid

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ABSTRACT In recent years, with the increase of distributed generation (DG) penetration rate, the economic operation of microgrid (MG) has been fully developed, but the energy consumption system based on fossil energy has increased the contradiction of the economy, energy and environment. The process of accelerating the development and utilization of renewable energy are a new focus of social concern. This paper first analyzes the basic characteristics and related policies of the distributed power and demand response (DR) in MG, and introduces the evaluation index of the islanded microgrid. Then, established a multi-objective optimization scheduling model considering the operation performance of islanded microgrid. In model, considered the generation cost of microsources, environmental management cost and power supply reliability of MG, and selected different scene analysis and verification. Used the improved particle swarm optimization-exterior point method (IPSO-EPM) to solve the problem. When the constraint condition is included in the objective function, the problem of falling into the local extremum during planning is avoided as much as possible. Finally, an islanded microgrid is taken as an example to verify the rationality of the proposed model and the effectiveness of the algorithm.

INDEX TERMS Islanded microgrid, economic dispatch, reliability, IPSO-EP, DG.

I. INTRODUCTION

With the development of DG technology, microgrid have received widespread attention from the power industry. Due to the generation characteristics of DG, it has played an important role in solving the shortage of energy supply in remote mountainous areas and reducing the power supply pressure of large power grid. It has also played an important role in improving the utilization of clean energy. According to its operation mode, it can be divided into two types, one is the grid-connected operation mode, and the other is the islanded operation mode.

For islanded operation modes, they usually occur on large power grid failures, planned maintenance, and some remote mountainous areas. Because there is no large power support, islanded microgrid become more difficult and complex in terms of control, operation, and management.

The arrangement of generation plans and the formulation of efficient management methods are of great significance for improving the economics and stability of islanded microgrid operation.

At present, the research on microgrid operation mostly focuses on economic optimized operation model [1]–[4]. Generally, the total operating cost of microgrid is used as the objective function, and certain constraints are established to formulate scheduling strategies in microgrid. Reference [5] proposes a new mathematical model for optimal scheduling of energy resources and smart management of loads which includes smart charging of PEVs, DR, and operation of battery energy storage systems (BESSs), for isolated microgrids. And the proposed model develops energy management strategies considering the network constraints and different objective functions from the perspective of the microgrid operator as well as from the owners of PEVs and BESS. Reference [6] established an AC-DC hybrid microgrid optimization scheduling model by considering the district
demand management, and formulated a distributed power scheduling strategy. Reference [7] proposes an islanded MG, which consists of PV system, tidal turbine (TT), diesel generator (DG), and Li-ion battery, is considered for Ouessant island in Brittany region in France. The economic operation of the MG is achieved by including battery degradation cost, levelized costs of energy of the PV system and TT, operating and emission costs of DG, and network constraints. Reference [8] comprehensively considered the uncertainty of demand response and renewable energy generation, and guided users to change the way they use electricity to reduce microgrid cost. Reference [9] presents an energy management system (EMS) for an islanded microgrid with photovoltaic generation and battery storage. The system uses a predictive approach to set operational schedules in order to minimize system-wide outages in the microgrid. And the approach also features bounds on the battery state-of-charge to account for uncertainties in the estimate of the stored energy. Reference [10] presents a comparative and critical analysis on decision making strategies and their solution methods for microgrid energy management systems, to manage the volatility and intermittency of renewable energy resources and load demand, various uncertainty quantification methods are summarized. A comparative analysis on communication technologies is also discussed for cost-effective implementation of microgrid energy management systems. Finally, insights into future directions and real world applications are provided. Reference [11] introduced the distributed algorithm for discretely solving the optimization power flow problem, as well as the optimization frequency control, optimization voltage control, and optimization wide area control problems, and applied it to the optimization and control of power system.

The above references are all about the economic dispatching model of microgrid, aiming at reducing the total operating cost of microgrid. Under certain constraints, the scheduling plan of DG and the optimization cost of microgrid are obtained. Based on the above references, this paper comprehensively considers the economic, environmental protection, and power supply reliability of microgrid, establishing a multi-objective optimization scheduling model that considers microgrid operation performance, and sets up different schemes for research and comparison, and verifying the validity of the model proposed in this paper.

II. MATHEMATICAL MODEL OF DG

The islanded microgrid model studied in this paper is shown in Figure 1. The microgrid contains distributed generation such as wind turbine (WT), photovoltaic (PV), microturbine (MT), fuel cells (FC), energy storage system (ESS), and load.

A. MATHEMATICAL MODEL OF WT

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.

\[
C_{WT,OM} = \sum_{t=1}^{T} k_{WT,OM} P_{WT}(t) \tag{1}
\]

In the equation, \(C_{WT,OM}\) represents the operation and management cost of WT, \(k_{WT,OM}\) is the unit operation and maintenance cost coefficient of WT; \(P_{WT}(t)\) is the WT output in the t period.

B. MATHEMATICAL MODEL OF PV

\[
C_{PV,OM} = \sum_{t=1}^{T} k_{PV,OM} P_{PV}(t) \tag{2}
\]

In the equation, \(C_{PV,OM}\) represents the operation and management cost of PV, \(k_{PV,OM}\) is the unit operation and maintenance cost coefficient of PV, and \(P_{PV}(t)\) is the PV output in the t period.

C. MATHEMATICAL MODEL OF MT

\[
C_{MT,OM} = \sum_{t=1}^{T} k_{MT,OM} P_{MT}(t) \tag{3}
\]

\[
C_{MT,fuel} = C \Delta t \frac{1}{LHV} \sum_{t=1}^{T} \frac{P_{MT}(t)}{\eta_{MT}} \tag{4}
\]

In the equations, \(C_{MT,OM}\) is the operation and management cost of MT, \(k_{MT,OM}\) is the unit operation and maintenance cost coefficient of MT; \(P_{MT}(t)\) is the MT output in the t period; \(C_{MT,fuel}\) is the fuel cost of MT, \(LHV\) is the low heating value of natural gas, take 9.7 kW · h/m³, and C is the unit price of MT’s fuel gas, take 2.5 yuan /m³, \(\eta_{MT}\) is the generation efficiency of MT.

D. MATHEMATICAL MODEL OF FC

\[
C_{FC,OM} = \sum_{t=1}^{T} k_{FC,OM} P_{FC}(t) \tag{5}
\]

\[
C_{FC,fuel} = C \Delta t \frac{1}{LHV} \sum_{t=1}^{T} \frac{P_{FC}(t)}{\eta_{FC}} \tag{6}
\]

In the equations, \(C_{FC,OM}\) represents the operation and management cost of FC, \(k_{FC,OM}\) is the unit operation and
maintenance cost coefficient of FC; \( P_{FC}(t) \) is the FC output in the t period; \( C_{FC,fuel} \) is the fuel cost of FC, and \( \eta_{FC} \) is the power generation efficiency of FC.

### E. ESS MATHEMATICAL MODEL

\[
SOC(t) = \begin{cases} 
SOC(t - \Delta t) + P_{t} \eta_{C} \Delta t & \text{if } SOC(t - \Delta t) + P_{t} \eta_{C} \Delta t \geq 0 \\
SOC(t - \Delta t) - \frac{P_{t}}{\eta_{D}} \Delta t & \text{if } SOC(t - \Delta t) + P_{t} \eta_{C} \Delta t < 0 
\end{cases} 
\]

\[
C_{ESS,OM} = \sum_{i=1}^{T} k_{ESS,OM} P_{ESS}(t) 
\]

In the equations, \( SOC(t) \) is the state of charge of the ESS in the t period, \( P_{t} \) and \( P_{t} \eta_{D} \) are the ESS charge and discharge power in the t period, \( \eta_{D} \) and \( \eta_{C} \) are the ESS charge and discharge efficiency. \( C_{ESS,OM} \) represents the operation and management cost of the ESS, and \( k_{ESS,OM} \) is the unit operation and maintenance cost coefficient of ESS, \( P_{ESS}(t) \) is the ESS output in the t period.

### III. DR MODEL

The islanded microgrid is mainly used for remote mountainous areas or islands’ electricity demand. Classification of DR is helpful for energy management and the formulation of reasonable dispatch plan [12]. This article divides loads into three categories according to the reliability of power supply: The first is important load, which refers to the uninterruptible power load that can cause significant political or economic impact. Therefore, during the normal operation of the system, the load must ensure continuous and reliable power supply; The second is a reliable load, which refers to the load that has some flexibility in the power supply, such as refrigeration and air conditioning, electric vehicles, etc; The third is interruptible load, which is some three-level load, and the reliability of power supply is low. It can be cut off in certain periods. However, in the environment of demand management, once the load is interrupted, it will affect user satisfaction. Therefore, it is necessary for the system to provide certain economic compensation for power outage users.

### A. SHIFTABLE LOAD MODEL

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

\[
C_{CF}(t) = K_{CF} P_{SF}(t) 
\]

In the equation, \( P_{SF}(t) \) is the equivalent load in the t period after the load is shifted. \( U_i \) is the state variable, and 0 or 1, \( P_{SF}(t') \) is used to shiftable load in the t’ period; \( K_{CF} \) represents the penalty cost for shiftable load; \( C_{CF}(t) \) represents the penalty cost of shiftable load in the t’ period; \( P_{INT}(t) \) represents the shiftable load in the t period.

### B. INTERRUPTIBLE LOAD MODEL

\[
C_{INT}(t) = K_{INT} P_{INT}(t) 
\]

In the equation, \( K_{INT} \) represents the penalty cost for interrupting the unit power; \( C_{INT}(t) \) represents the penalty cost of interrupting the load during all periods; \( P_{INT}(t) \) represents the interruptible load in the t period.

### IV. EVALUATION INDICATORS FOR OPERATION PERFORMANCE OF ISLAND MICROGRID

#### A. ECONOMIC INDICATOR

The economic indicators of microgrid mainly include DG’s generation cost, interruptible load compensation costs, and load shedding costs due to insufficient power supply. Since this paper mainly studies the economic dispatch model of microgrid, the objective function can be used as economic indicator.

#### B. ENVIRONMENTAL INDICATOR

Microgrid is different from traditional large power grid. Due to the characteristics of DG’s generation, environmental protection cost are important characteristics of microgrid, and therefore are important indicators in the evaluation of microgrid operation performance. The environmental protection indicator here mainly considers the cost of environmental treatment, which can be expressed by the following formula:

\[
C_{EC} = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} P_{i}(t) 
\]

In the equation, \( C_{EC} \) is the cost of environmental treatment, \( i \) is the type of microsource, \( j \) is the type of pollution gas \( CO_2, SO_2, NO_x \), and \( C_{ij} \) is the cost of treatment of the \( j \) gas generated by the \( i \) microsource. \( P_{i} \) represents the output of the \( i \) microsource supply.

#### C. RELIABILITY INDICATOR

The power supply reliability indicator is an important indicator for evaluating the performance of microgrid. Its purpose is to give guidance on microgrid equipment types, performance, and user requirements. Its constructed in this paper mainly focuses on insufficient load power consider time and load loss [16].

Define the ratio of system power failure time to power supply time as the system power failure time probability:

\[
\alpha = \frac{N_{a}}{T} 
\]

Define the ratio of load shortage to power consumption during T periods of normal operation as the system power failure rate:

\[
\beta = \frac{\sum_{t=1}^{T} U(t,x) P_{LOAD}(t)}{\sum_{t=1}^{T} P_{LOAD}(t)} 
\]

Taking into account the insufficient time and load loss of the microgrid, define the system reliability indicator to measure the reliability level of the microgrid power supply:

\[
E_{\gamma} = (1 - \alpha)(1 - \beta) 
\]
In the equation, \( \alpha \) represents the probability of power failure time, \( N_\alpha \) represents the number of power failure time periods, \( \beta \) represents the microgrid power failure rate, \( P_{\text{LOAD}}(t) \) represents the system load during \( t \) period, \( U(t, x) \) is a state variable, and 0 or 1 is taken; \( E_y \) represents the system reliability indicator.

V. RESEARCH ON MULTI-OBJECTIVE OPTIMIZATION SCHEDULING OF ISLAND MICROGRID

A. OBJECTIVE FUNCTION

This article divides a day into 24 time periods without considering the internal power loss of the microgrid [13]. A multi-objective optimization scheduling model that considers microgrid operation performance is established with the objectives of the total operating cost of microgrid, the cost of environmental governance, and the reliability of power supply as the optimal objectives. Under the constraints of ensuring the normal operation of the system, a reasonable output plan is formulated to minimize the total operating cost of the microgrid.

\[
F_1 = C_{\text{WT,OM}} + C_{\text{PV,OM}} + C_{\text{MT}} + C_{\text{FC}} + C_{\text{ESS,OM}} + C_{\text{CL}} + C_{\text{INT}} \\
F_2 = C_{\text{EC}} = \sum_{i=1}^{m} \sum_{j=1}^{n} C_i P_i(t) \\
F_3 = E_y = (1 - \alpha)(1 - \beta) \\
\min F = aF_1 + bF_2 + c(1-F_3) \\
C_{\text{CL}} = k_{\text{CL}} P_i(t) \\
C_{\text{INT}} = k_{\text{INT}} P_i(t) 
\]

In the equations, \( C_{\text{MT}} \) and \( C_{\text{FC}} \) respectively represent the generation costs of MT and FC, including fuel cost and operation management cost; \( k_{\text{CL}} \) represents the unit penalty coefficient for cutting off the load when power is insufficient, and \( k_{\text{INT}} \) represents the unit penalty coefficient for interrupting the third type of load.

B. CONSTRAINTS

1) POWER BALANCE CONSTRAINT

\[
P_{\text{WT}}(t) + P_{\text{PV}}(t) + P_{\text{MT}}(t) + P_{\text{FC}}(t) + P_{\text{ESS}}(t) = P(t) + P_{\text{SF}}(t) - P_{\text{INT}}(t) - P_{\text{CL}}(t) 
\]

2) CONSTRAINT OF MICROOURCES IN MG

\[
P_{\text{WTmin}} \leq P_{\text{WT}}(t) \leq P_{\text{WTmax}} \\
P_{\text{PVmin}} \leq P_{\text{PV}}(t) \leq P_{\text{PVmax}} \\
P_{\text{MTmin}} \leq P_{\text{MT}}(t) \leq P_{\text{MTmax}} \\
P_{\text{FCmin}} \leq P_{\text{FC}}(t) \leq P_{\text{FCmax}} 
\]

In the equations, \( P_{\text{WTmax}} \) and \( P_{\text{WTmin}} \) are the upper and lower limits of the WT output, \( P_{\text{PVmax}} \) and \( P_{\text{PVmin}} \) are the upper and lower limits of the PV output, \( P_{\text{MTmax}} \) and \( P_{\text{MTmin}} \) are the upper and lower limits of the MT output, and \( P_{\text{FCmax}} \) and \( P_{\text{FCmin}} \) are the upper and lower limits of the FC output.

3) ESS RELATED CONSTRAINT

\[
SOC(t) = S_0 + \frac{\sum_{i=1}^{T} X_i P_{\text{ch},i} \eta_C - \sum_{i=1}^{T} Y_i P_{\text{dis},i} / \eta_D}{E_b} \cdot \Delta t 
\]

\[
X_i + Y_i \leq 1 \\
SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}} \\
P_{\text{dismin}} \leq P_{\text{dis}}(t) \leq P_{\text{dismax}} \\
SOC(0) = SOC(24) 
\]

4) DR RELATED CONSTRAINTS

\[
0 < P_{\text{INT}}(t) < P_{\text{INT,MAX}} \\
0 < P_{\text{SF}}(t) < P_{\text{SF,MAX}} \\
0 < P_{\text{SF}}(t') < P_{\text{SF,MAX}} \\
\sum_{i=1}^{T} P_{\text{SF}}(t') = 0 
\]

In the equations, \( P_{\text{SF,MAX}} \) and \( P_{\text{INT,MAX}} \) represent the maximum values of the translatable load and the interruptible load, respectively.

VI. IPSO-EPM ALGORITHM

The planning in this paper is a constrained non-linear programming. Out-point method can be used to optimize the objective function. However, all non-linear optimization algorithms have the problem of easily falling into local extreme values [14]. Therefore, this paper uses particle swarm optimization (PSO) to optimize the initial value of the outlier method to avoid the algorithm falling into local extremes as much as possible.

A. OUT-POINT METHOD

The out-point method is an algorithm for solving constrained nonlinear programming. The algorithm introduces constraints into the objective function by constructing a penalty function. The principle of the algorithm is described below. Without loss of generality, considering the following nonlinear programming:

\[
\min f(X) \\
s.t. \ h_i(X) = 0 \quad i = 1, 2, \ldots, m \\
g_j(X) \leq 0 \quad j = 1, 2, \ldots, p 
\]
where \( f(X) \) is the objective function; \( h_j(X) = 0 \) is an equal constraint; \( g_j(X) \leq 0 \) is an unequal constraint. For inequality constraints:

\[
g_j(X) \leq 0 \quad j = 1, 2, \ldots, p
\]

To facilitate the formulation of the penalty function, the equivalent is:

\[
\max \left[ 0, g_j(X) \right] = 0 \quad j = 1, 2, \ldots, p
\]

The following penalty function can be constructed to transform problem formula (36) into an unconstrained problem:

\[
q(X, M) = f(X) + M \sum_{j=1}^{m} [h_j(X)]^2 + M \sum_{j=1}^{p} \left( \max \left[ 0, g_j(X) \right] \right)^2
\]

In the iteration, the value of \( M \) is successively increased. When it approaches infinity, the optimal value of the objective function that satisfies the constraints can be solved. The specific steps are as follows:

step1: Select the variable starting point \( X_0 \), and the initial value \( M \) of \( M \);

step2: Use the nonlinear optimization algorithm to find the position \( X_k \) of the optimization solution of equation (39);

step3: Increase the value of \( M \). The value of \( M \) in each iteration should satisfy the following relationship:

\[
M_{k-1} < M_k \quad \lim_{k \to \infty} M_k = \infty
\]

step4: Use the position of the optimization solution obtained in the previous iteration as the initial point of the next iteration, and repeat steps 2 and 3 until \( |f(X_k) - f(X_{k-1})| < \xi_0 \) is satisfied, where \( \xi_0 \) is the termination accuracy of the algorithm iteration.

It can be known from step 2 that the algorithm used by the outer point method to find the optimization solution is a non-linear optimization algorithm, which may fall into local extreme values.

**B. IMPROVED PSO ALGORITHM**

The PSO originated from bionics, and J. Kennedy and R. C. Eberhart invented the algorithm inspired by the birds’ foraging rules. The initial population of the algorithm is a set of random particles. The direction and position of particle movement are changed according to the individual optimization information and the optimization information of the population at each iteration [16].

\[
v_i^{k+1} = w v_i^k + c_1 r_{1i}^k (p_{bi}^k - q_i^k) + c_2 r_{2i}^k (g_b^k - q_i^k)
\]

\[
d_i^{k+1} = q_i^k + v_i^{k+1}
\]

In the equations, \( v_i^k \), \( q_i^k \), and \( p_{bi}^k \) are the merits of speed, position, and history at the \( k \)-th iteration of the \( i \)-th particle; \( c_1 \) and \( c_2 \) are acceleration factors; \( r \) is a random number; and \( g_b^k \) is the merits of population history at the \( k \)-th iteration, and \( w \) is the inertia factor.

Ordinary PSO algorithm tend to fall into “precocity”. Reference [17] can effectively avoid the prematureness of the algorithm by changing the values of inertia weight and learning factor at different iterations in real time. The calculation method is as follows:

\[
w(k) = \frac{k_{max} - k}{k_{max} - k_{min}} (w_{max} - w_{min}) + w_{min}
\]

\[
c_2(k) = c_{max} - (c_{max} - c_{min}) \frac{k_{max} - k}{k_{max}}
\]

\[
c_1(k) = 4 - c_2(k)
\]

In the equation, \( w(k) \), \( c_1(k) \), and \( c_2(k) \) are the values of inertia weight, learning factor \( c_1 \), and learning factor \( c_2 \) at the \( k \)-th iteration; \( k_{max} \) is the maximum number of iterations; \( w_{max} \) and \( w_{min} \) are the maximum and minimum values of inertia weight; \( c_{min} \) and \( c_{max} \) is the initial and final value of \( c_2 \), \( 0 < c_{min} < c_{max} < 4 \).

The PSO algorithm searches for the best advantage and optimization value of the objective function through particle movement and continuous updating of the best advantages of individuals and populations. It does not use gradient information, and the update process of the algorithm does not end because the gradient modulus value returns to zero. Therefore, the algorithm can avoid falling into local extremes to a certain extent.

**C. IPSO-EPM algorithm**

The reason that the nonlinear optimization algorithm [17] is prone to fall into the local extreme value is that the initial point is not selected properly, which causes the function value to increase in the path from the initial point to the most advantageous, and which also makes the function value decrease each time iterative nonlinear optimization algorithms cannot optimize to the best advantage. Therefore, this paper uses an improved PSO algorithm to optimize the initial value of the outer point method, so that the algorithm can find the global optimization solution and the optimization value of the objective function as much as possible. This paper uses the Levenberg-Marquard (LM) algorithm as the nonlinear optimization algorithm of the outer point method. The specific steps of the algorithm are as follows:

step1: Set the maximum number of iterations of the PSO algorithm and the number of individuals included in the population, and initialize the population particles;

step2: Bring the coordinates of each particle as the initial value of the outer point method variable to the outer point method to find the optimization solution position and optimization value, and using this optimization value as the fitness value \( Z_i \) of the particle, and replacing the particle position with optimization solution position;

step3: Compare the fitness value of each particle with the historical best value of the particle, decide whether to replace
the historical best advantage of the particle, and find the best advantage of the population;

step4: Update the values of inertial weight and learning factor according to equation (43), update the particle speed and position according to equations (41) and (42), and repeat steps 2 and 3 until the number of iterations reaches the maximum number of iterations.

Flow chart of IPSO-EPM shown in Figure 2. \( z_{pbi} \) is the historical optimization value of the i-th particle; \( z_{gb} \) is the historical optimization value of the group; \( a \) is the growth coefficient of \( M \). In this paper, \( a = 10 \).

FIGURE 2. Flow chart of IPSO-EPM.

VII. EXAMPLE ANALYSIS

A. Model Parameters

In order to verify the rationality of the scheduling strategy and model algorithm proposed in this paper, an islanded microgrid with multiple microsources is taken as an example. The basic parameters of the simulation are as follows: The maximum technical output \( P_{MT_{\text{max}}} \) of the MT is 65kW; the maximum technical output \( P_{FC_{\text{max}}} \) of the FC is 40kW; the ESS rated capacity is 300kWh, and the SOC variation range is 0.2-0.9, the initial SOC value is 0.3, and the maximum charge and discharge power is 40kW. Figure 3 shows the forecast results of WT, PV, and load for each period of a typical day. The basic parameters of DG are shown in Table 1. The emissions of microsources and the treatment costs are shown in Table 2 and Table 3. The interruption amount and translation amount are shown in Table 4 and Table 5.

B. RESULT ANALYSIS

In order to verify the effectiveness and feasibility of the model proposed in this paper, this paper has set up four programs perform comparative analysis: Program 1: economic optimization program; Program 2: environmental protection optimization program; Program 3: reliability optimization solution; Program 4: comprehensive consideration of economic, environmental protection and reliability optimization program.

FIGURE 3. WT, PV and load power forecasting results.

TABLE 1. Basic parameters of DG.

| Microsource | Rated power/kW | Upper and lower limit of output/kW | Climbing rate/kW/h | Operation and maintenance cost / yuan |
|-------------|----------------|-----------------------------------|--------------------|---------------------------------------|
| WT          | 250            | 150-300                           | 0.045              |                                       |
| PV          | 100            | 50-150                            | 0.0096             |                                       |
| MT          | 65             | [-30,30]                          | 0.128              |                                       |
| FC          | 40             | [0,40]                            | 0.0293             |                                       |
| ESS         | 40             | [-40,40]                          | 0.045              |                                       |

TABLE 2. DG pollutant emissions.

| Microsource | MT (kg/g) | FC (kg/g) |
|-------------|-----------|-----------|
| CO2         | 724.60    | 635.04    |
| SO2         | 0.004     | 0         |
| NOX         | 0.20      | 0.023     |

TABLE 3. Pollutant treatment costs.

| Contamination type | Pollution control costs (yuan/ton) |
|--------------------|-----------------------------------|
| CO2                | 0.21                              |
| SO2                | 14.84                             |
| NOX                | 62.96                             |

TABLE 4. Shiftable load translation period and maximum translation.

| Period    | Maximum shiftable load/kW | Period    | Maximum shiftable load/kW |
|-----------|----------------------------|-----------|----------------------------|
| 07:00-08:00 | 12                         | 15:00-16:00 | 10                         |
| 08:00-09:00 | 12                         | 17:00-18:00 | 20                         |
| 09:00-10:00 | 15                         | 18:00-19:00 | 25                         |
| 12:00-13:00 | 10                         | 19:00-20:00 | 25                         |
TABLE 5. Interruptible load interruption period and maximum interrupt amount.

| Period       | Maximum interruption/kW | Period       | Maximum interruption/kW |
|--------------|--------------------------|--------------|--------------------------|
| 09:00-09:00  | 8                        | 13:00-14:00  | 10                       |
| 09:00-10:00  | 8                        | 14:00-15:00  | 15                       |
| 09:00-10:00  | 10                       | 19:00-20:00  | 15                       |
| 10:00-11:00  | 10                       | 21:00-22:00  | 15                       |

1) PROGRAM 1: ECONOMICALLY OPTIMIZATION PROGRAM

This program respectively researches not considering the DR (strategy 1) and considering the DR (strategy 2), formulates the microsources generation plan, and obtains the optimization cost of microgrid operation.

The microsources output of strategy 1 is shown in Figure 4. During the period of 00:00-10:00, due to abundant wind resources and high wind output, in addition to the supply load, WT stores excess wind energy in the ESS; During the period from 10:00 to 14:00, the WT output decreases and the PV output increases. Because PV output cost is low, it can reach the full output state; After 14:00, the load rises. Due to the limited WT and PV output, MT and FC start to work. The MT output cost is lower than FC, so the MT reaches the full output state. 17:00-20:00 is the peak time of the load. Both WT and MT have reached the full output state, the energy storage is discharged and the discharge power has reached the maximum value. However, due to the high load during this period, the output of the microgrid is still not satisfied load demand, so part of the load was cut off during this period.

The microsources output of strategy 2 is shown in Figure 5. The comparison of the load curves of strategy 1 and strategy 2 is shown in Figure 6. By considering DR, its load shedding, translation load, and interruption load are paired with the strategy 1, as shown in Table 6, Table 7, and Table 8.

TABLE 6. Comparison between strategy 1 and strategy 2 load shedding.

| Load shedding period | Load shedding quantity/kW |
|----------------------|---------------------------|
| 16:00-17:00          | 2                         |
| 18:00-19:00          | 1                         |
| 19:00-20:00          | 30                        |
| 21:00-22:00          | 36                        |

Strategy 1

Strategy 2

TABLE 7. Comparison between strategy 1 and strategy 2 load translation.

| shiftable load period | shiftable load quantity/kW |
|-----------------------|----------------------------|
| Strategy 1             | 0                          |
| 17:00-18:00 to 1:00-2:00 | 8                           |
| 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                           |

Strategy 2

TABLE 8. Comparison between strategy 1 and strategy 2 load interruption.

| Interruptible load period | Interruptible load quantity/kW |
|---------------------------|--------------------------------|
| Strategy 1                | 0                              |
| 19:00-20:00               | 15                             |

Strategy 2

TABLE 9. Microsources generation cost structure.

| Cost structure                 | Strategy 1 (yuan) | Strategy 2 (yuan) |
|-------------------------------|-------------------|-------------------|
| DG running cost               | 724.17            | 697.5             |
| Load shedding cost            | 103.5             | 0                 |
| Interruptible load cost       | 0                 | 27                |
| Total cost                    | 827.67            | 724.5             |
During the peak load period of 17:00-20:00, the load shifted to 0:00-3:00. Compared with Strategy 1, Strategy 2 increased wind power output during 0:00-3:00. This is due to the low night-time load level, and wind resources are abundant and the cost of generation is low. After the load shifts, not only the dissipation of wind power is increased, but also the generation cost of MG is reduced. Partial load was interrupted from 19:00 to 21:00, this is due to the high load during this period and the limited output of microsources. Compared with the strategy 1, interrupting the load of strategy 2 can improve the economic benefits of microgrid. The composition of the MG generation cost for Strategy 1 and Strategy 2. Compared with Strategy 1 in Table 9, the generation cost of microsources has been reduced by 12.46%, and the reliability of power supply has been increased by 9%. The main reason is that by considering the demand side response, the lower-cost wind power output is increased, and the higher-cost FC and MT output are reduced. At the same time, the second strategy interrupts the load instead of the first strategy due to insufficient power supply, which reduces the penalty cost. Therefore, strategy two has better economic benefits and higher power supply reliability.

2) PROGRAM 2: ENVIRONMENTAL PROTECTION PROGRAM
The output of microsources in program 2 is shown in Figure 7. Compared with the strategy 2 in the program 1, after 15 o’clock, the FC output is higher than the MT, mainly due to the CO2 released by the unit by the MT the amount is higher than FC, so the governance costs are also higher, so during this period, FC output is higher than MT. The total generation cost in this program is 739.7 yuan, which is 2.1% higher than the strategy 2 in the program 1, and the environmental management cost is 135 yuan, which is a 5.5% reduction in environmental governance cost compared to the strategy 2 in the program 1.

3) PROGRAM 3: RELIABILITY PROGRAM
The output of the microsources in the program 3 is shown in Figure 8. The energy storage operation changes in this program are obviously different from other programs. The main reason is to reduce the load shedding, power interruption and other power outages, which will lead to economic decline. The total generation cost was 747.6 yuan, 3.2% increase compared to the strategy 2 in the program 1, and the power supply reliability was 90.75%, 9.55% improvement compared to the strategy 2 in the program 1.

4) PROGRAM 4: COMPREHENSIVE CONSIDERATION OF ECONOMIC, ENVIRONMENTAL PROTECTION AND RELIABILITY OPTIMIZATION PROGRAM
The output of the microsources in this program is shown in Figure 9, and the microgrid index pairs of the four programs are shown in Table 10. By comparison, the total operating cost and environmental governance cost of program 1 and program 2 are the lowest, and the reliability of power supply is the highest in program 3. In program 4, although the
indicators are not optimal compared with the other 3 optimal programs, the overall level is optimal.

VIII. CONCLUSION AND OUTLOOK
Aiming at the problems of low renewable energy consumption rate of islanded microgrid and insufficient power supply due to the limitation of DG’s own capacity, this paper proposes evaluation indexes for the operation performance of islanded microgrid, and establishes multi-objective optimization scheduling model that considers the performance of microgrid, and analyzing the impact of DR on microgrid. Drawing the following conclusions:

(1) By considering DR, the renewable energy utilization rate can be improved, the load shedding cost due to insufficient power supply of the island microgrid can be reduced, the economical efficiency of the microgrid operation can be improved, and the problem of insufficient power supply of the island system can be solved;

(2) The multi-objective optimization scheduling model established in this paper takes into account the economics, environmental protection, and power supply reliability of islanded microgrid. Compared with a single target, the overall benefit is better than a single target solution.

(3) The problem solved in this paper is a non-linear programming problem, which is solved using IPSO-EPM, and the constraints are incorporated into the objective function. At the same time, it solves the problem of non-linear optimization algorithm that easily fall into local extremes.

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