Multi-objective Planning of the Economic Operation of Microgrid Considering the Energy Loss and the Start-up Cost of Conventional Units

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Abstract. The fluctuation of load and new energy will have an important impact on the operation mode of microgrid. In order to balance the economy and reliability of microgrid, a chance constrained model of microgrid is established firstly. Based on the reliability cost, the operation cost of microgrid under different confidence levels is calculated, and a reasonable confidence level of rotating reserve is obtained. This paper analyzes the impact of energy storage charge and discharge loss and conventional unit start-up cost on the economic operation of the isolated microgrid; for the grid connected microgrid, the economy of its own operation and the effect of auxiliary large grid peak load shedding are taken as the objective function, and the multi-objective programming method proposed in this paper is used to solve the problem. The example analysis shows that the multi-objective programming method in this paper, by combining with particle swarm optimization algorithm, can optimize the weight of different objectives reasonably, which can not only help the large power grid to cut peak and fill valley, but also realize the economy of microgrid operation.

1. Introduction

As microgrid can effectively access the distributed generation represented by new energy through different operation modes and strategies [1-2], it has a good development prospect in terms of ecological environment protection and energy utilization [3-4].

In reference [5], through the analysis of typical scenarios, the economic operation model of micro grid power generation units with various micro power sources and energy storage devices is established; In reference [6], three strategies for operation and control of sodium sulfur battery are proposed based on the charging and discharging characteristics of battery, and the influence of depreciation loss of equipment on multi-objective economic operation of microgrid is considered; In reference [7], the sources and effects of various prediction errors of CHP microgrid are analyzed, and a dynamic economic operation model of CHP microgrid is established; In reference [8], on the economic operation of microgrid, the mathematical model of double objective economic operation is established with the minimum cost of microgrid operation and environmental pollution as the objective function.

Therefore, in view of the economic operation of multi-source complementary micro grid, taking into account the battery charge and discharge cost and the start-up cost of conventional units, this paper establishes the opportunity beam model of micro grid rotating reserve. In addition, on the basis
of the traditional method of solving multi-objective programming by linear weighting, a method of optimizing the weight of each objective by feedback regulation is proposed, and the optimization model is solved by particle swarm optimization algorithm. Finally, a numerical example is used to verify the analysis.

2. Optimal Economic Operation Model of Microgrid

2.1. Charge and Discharge Loss Model of Energy Storage Device

In this paper, lithium battery is used as energy storage device in microgrid, and the maximum cycle times of charge and discharge $N_{bat}$ mainly depend on the depth of charge and discharge $d$ [9], As shown in Figure 1. The corresponding expression is as follows

$$N_{bat} = \alpha_0 e^{\alpha_1 d} + \alpha_2 e^{\alpha_3 d} + \alpha_4$$ (1)

where, $\alpha_0 \sim \alpha_4$ are characteristic parameters provided by the manufacturer. From $N_{bat}$, we can get the loss cost of lithium battery in this charge and discharge loss $C_{bat}$, by this form

$$C_{bat} = \frac{C_{BAT}}{N_{bat}}$$ (2)

where, $C_{BAT}$ is the investment cost of lithium battery.

![Figure 1. Curve of the relationship between the maximum charge/discharge times and charge/discharge depth.](image)

![Figure 2. Operating costs for microgrid operation under different reserve capacity confidence levels.](image)

2.2. Optimal Economic Operation Model of Island Micro Grid

Certain rotating reserve can effectively cope with the fluctuation of load and new energy output [10-11]. However, in order to ensure the reliability of the system operation under extreme conditions, increasing the rotating reserve will increase the operation cost greatly, which is not conducive to the operation economy. According to Figure 2, a reliability penalty cost $C_{pen}$ is added for the case that the current confidence level does not meet the standby requirements. The total operation cost $f$ of microgrid is taken as the sum of its operation cost and reliability cost, and the economic operation model is established with this as the objective function.

2.2.1. Objective function. The objective function of the economic operation under the microgrid island mode can be formulated as

$$f = \min \sum_{i=1}^{T} \left( \sum_{j=1}^{N} u_{i,j} C_{op,i} + \sum_{j=1}^{N} C_{g,i} (1 - u_{i,j-1}) u_{i,j} + C_{bat} + C_{pen} \right)$$ (3)

where, $N$ is the number of conventional units; $T$ is the total number of time periods included in the scheduling cycle, which is set to 24 in this paper; $C_{op,i}$ is the fuel consumption cost of conventional unit $i$ in $t$ period; $C_{g,i}$ is the start-up cost of conventional unit $i$ in $t$ period; $C_{bat}$ is the life loss cost of lithium battery; the unit state $u_{i,j}$ changes between zero and one or vice versa while unit $i$ start up or shut down at time $t$. 


2.2.2. Constraint condition
(1) Rotating reserve constraints[12-13]

The maximum positive and negative reserves provided by conventional units are as follows
\[
\begin{align*}
R_{\text{up}} &= \sum_{i=1}^{N} P_{\text{ini}} - \sum_{i=1}^{N} P_{\text{init}} \quad \text{max}, \\
R_{\text{down}} &= \sum_{i=1}^{N} P_{\text{init}} - \sum_{i=1}^{N} P_{\text{ini}} \quad \text{min}, \\
R_{\text{up}}^c &= \sum_{i=1}^{N} P_{\text{ini}} - \sum_{i=1}^{N} P_{\text{init}} \quad \text{max}, \\
R_{\text{down}}^c &= \sum_{i=1}^{N} P_{\text{init}} - \sum_{i=1}^{N} P_{\text{ini}} \quad \text{min},
\end{align*}
\]

where, \( N \) is the total number of conventional units; \( P_{\text{i}} \) is the real-time output of conventional unit \( i \), whose upper and lower limit are \( P_{\text{max}} \) and \( P_{\text{min}} \).

The opportunity constraints of rotation reserve are shown as
\[
\begin{align*}
P_{\text{up}}(R_{\text{up}}^c + P_{\text{bat}}^c) &\leq R_{\text{up}} \leq (R_{\text{up}}^c + P_{\text{bat}}^c), \\
R_{\text{down}} &= \Delta P_{\text{up}} + \Delta P_{\text{bat}} + \Delta P_{\text{bat}}.
\end{align*}
\]

where, \( R_{\text{up}} \) is the rotating reserve capacity required in \( t \) period; \( P_{\text{bat}}^c \) and \( P_{\text{bat}}^d \) are respectively the maximum charge and discharge power of the energy storage device; \( P_{\text{up}} \) is the probability of satisfying the condition with the confidence level \( \alpha \). \( \Delta P_{\text{up}}, \Delta P_{\text{bat}} \) and \( \Delta P_{\text{bat}} \) are the actual prediction errors of load power, wind power output and photovoltaic output in \( t \) period respectively, which are generally assumed to follow the normal distribution.

(2) Power balance constraint
\[
P_{\text{it}} = \sum_{i=1}^{N} P_{\text{ini}} + P_{\text{bat}} + P_{\text{bat}}\quad (7)
\]

where, \( P_{\text{it}} \) is the actual output of conventional unit \( i \) in period \( t \); \( P_{\text{bat}} \) is the actual charge and discharge power of the lithium battery in \( t \) period (when it is positive, it means discharge; when it is negative, it means charge). \( P_{\text{it}}, P_{\text{bat}}, P_{\text{bat}} \) are the real-time predicted values of load, wind power output and photovoltaic output in \( t \) period.

(3) Lithium battery constraints
\[
\begin{align*}
P_{\text{bat}}^c, \Delta t &\leq 0.25E_{\text{bat}} \quad (8) \\
P_{\text{bat}}^d, \Delta t &\leq 0.25E_{\text{bat}} \\
S_{\text{cmin}} &\leq S_{\text{cmax}}(t) \leq S_{\text{cmax}} \quad (9)
\end{align*}
\]

where, \( E_{\text{bat}} \) is the capacity of lithium battery; \( S_{\text{c}}(t) \) is the residual capacity of lithium battery in \( t \) period; \( S_{\text{cmin}} \) and \( S_{\text{cmax}} \) are the minimum and maximum residual capacity limits of lithium battery respectively.

2.3. Optimal Economic Operation Model of Grid-Connected Microgrid

There are two main goals in the economic operation of grid-connected microgrid, namely, to achieve the optimal economic operation of microgrid and to participate in the peak load reduction and valley filling of large grid. Next, a multi-objective optimization model is established to minimize the total operation cost of microgrid and maximize the peak load and valley load effect of interconnection line in a specific period of time[14].

2.3.1. Objective function. The objective functions are shown in equations (10) and (11)
\[
f_1 = \min \left( \sum_{i=1}^{T} \sum_{t=1}^{N} u_{it} C_{\text{op},i} + \sum_{t=1}^{N} C_{\text{eq}} (1-u_{it}) u_{it} + C_{\text{bat},i} P_{\text{bat},i} + C_{\text{bat},i} - C_{\text{sell},i} P_{\text{sell},i} + C_{\text{pen}} \right)
\]
\[
f_2 = \max \left( \sum_{i=1}^{T} P_{\text{buy},i} + \sum_{i=1}^{T} P_{\text{sell},i} \right)
\]

where, \( f_1 \) and \( f_2 \) are the optimal economy and the maximum effect of peak shaving and valley filling respectively; \( C_{\text{buy},i} \) and \( C_{\text{sell},i} \) are the price of purchasing and selling electricity from the main
network in \( t \) period respectively; \( P_{buy,t} \) and \( P_{sell,t} \) are the power purchased and sold from the main network in \( t \) period respectively.

2.3.2. Constraints. The constraints of grid connected operation of microgrid are basically the same as those of island operation. The following only introduces the inconsistent parts.

(1) Power balance constraints

\[
P_{t} = \sum_{i=1}^{N} P_{i,t} = P_{buy,t} + P_{sell,t} + P_{i,t} + P_{line,t}
\]

where, \( P_{line,t} \) is the transmission power of the link \( t \) period.

(2) Tie-line transmission power constraints

\[
0 \leq P_{buy,t} \leq P_{line,max} \quad 0 \leq P_{sell,t} \leq P_{line,max}
\]

where \( P_{line,max} \) is the maximum transmission power of the tie line.

(3) Rotation alternate constraint

The positive reserve and the negative reserve provided by tie lines are shown as follows

\[
R_{up}^{line} = \begin{cases} P_{line,max} - P_{buy,t} & P_{buy,t} \geq 0 \\ P_{sell,t} & P_{sell,t} > 0 \end{cases}
\]

\[
R_{down}^{line} = \begin{cases} P_{buy,t} & P_{buy,t} > 0 \\ P_{line,max} - P_{sell,t} & P_{sell,t} \leq 0 \end{cases}
\]

For grid-connected microgrid, the probability constraints of the rotating reserve capacity taking into account the capacity provided by the tie lines can be calculated by

\[
P \left( -R_{down}^{line} + P_{bat}^{up} + R_{up}^{line} \right) \leq R_{c} \leq R_{up}^{bat} + P_{bat}^{down} + R_{up}^{line} \geq \alpha
\]

3. Solving the Optimal Economic Operation Model of Microgrid

3.1. Multiobjective Programming Solving Algorithms

Based on the traditional linear weighting method to solve multi-objective programming, a multi-objective programming calculation method based on weight feedback correction is proposed. First, the initial weight of each target is set by Delphi method. Then each target is given a benchmark value, and the unit weight of each target relative to its benchmark value is obtained by calculation. Finally, the weight of each target is optimized by the proportion of the unit weight of each target to the sum of all target normalization results. The weight correction and the objective function expressions are shown in expressions (17) and (18), respectively.

\[
\Delta w_{i} = \lambda \left[ \frac{x_{i}}{\sum_{r} x_{r}} - \frac{1}{n} \right]
\]

\[
w_{i}' = w_{i} + \Delta w_{i}
\]

\[
f = \min \left( \sum_{i=1}^{n} w_{i} \left( \frac{x}{x_{i}} \right)^{2} \right)
\]

\[
\sum_{i=1}^{n} w_{i} = 1
\]

where, \( n \) is the number of targets; \( w_{i} \) is the initial weight; \( \Delta w_{i} \) is the weight correction for the \( i \) th target; \( w_{i}' \) is the corrected value of the \( i \) th target weight; \( \lambda \) is the depth of adjustment; \( f \) is the optimal solution for multiobjective programming.
3.2. Particle Swarm Optimization

In Particle Swarm Optimization (PSO), each iteration updates the speed and position of the particle through formulas (19) and (20) [15].

\[ v_{i}^{k+1} = w v_{i}^{k} + c_1 r_1 (p_i^k - x_{i}^{k}) + c_2 r_2 (g_d^k - x_{i}^{k}) \]  
\[ x_{i}^{k+1} = v_{i}^{k+1} + x_{i}^{k} \]

where, \( v_{i}^{k+1} \) and \( x_{i}^{k+1} \) are the velocity and the position of the \( i \)th particle after \( k+1 \) iterations, respectively; \( w \in [0.1, 0.9] \) is the inertial weight factor; \( c_1 \) and \( c_2 \) are acceleration coefficients, which are generally 2; \( r_1, r_2 \in [0, 1] \) are uniformly distributed random numbers. \( p_i \) and \( g_d \) are the individual optimal position and the global optimal position after \( k+1 \) iterations respectively. In this paper, PSO algorithm is combined with multi-objective planning, and the weight of each objective is optimized through the calculation results of each PSO iteration to solve the economic operation optimization problem of microgrid. The solution process is shown in Figure 3.

**Figure 3.** Flow chart of the algorithm for the economic operation of the microgrid.
4. Example Analysis

4.1. Example Analysis of Island Microgrid

This example chooses the data of a microgrid in Henan Province to calculate. The microgrid contains three micro-engines, two wind turbines, a set of photovoltaic batteries and one energy storage device. The specific parameters of each micro-power source are shown in Table 1-3, respectively.

| Table 1. Microturbine parameters |
|----------------------------------|
| Type   | Number | Lower power limit | Upper power limit |
|--------|--------|-------------------|-------------------|
| MT1    | 1      | 12                | 65                |
| MT2    | 1      | 10                | 50                |
| MT3    | 1      | 6                 | 30                |

| Table 2. Wind turbine parameters |
|----------------------------------|
| Single unit capacity /kW | Quantity / set | Cut in wind speed / m/s | Rated wind speed / m/s | Cut off wind speed / m/s |
| 50                       | 2             | 4                         | 15                     | 25                      |

| Table 3. Lithium Battery Parameters |
|--------------------------------------|
| Maximum state of charge/kW·h | Minimum state of charge/kW·h | Maximum charging power/kW |
| 160                           | 48                               | 40                         |

| Minimum discharging power /kW | Charging efficiency | Discharge efficiency |
| 40                             | 0.95                           | 0.95                      |

PSO and the multi-objective programming algorithm are used to solve the optimal economic operation model of microgrid. The PSO particle number is 100 and the maximum number of iterations is 200. The load power, wind power output and photovoltaic output data for next dispatch cycle are predicted as shown in Figure 4, based on historical data. The prediction error coefficient of wind power and photovoltaic output is 0.12, and the load power prediction error coefficient is 0.1. The initial capacity of the battery is 48 kW.h.

When the reserve capacity provided by the system does not meet the requirements, the penalty fee is 10 yuan per kilowatt, from which the operating costs of the island microgrid under different confidence levels are obtained as shown in Figure 5. After considering the penalty of insufficient reserve, the operation cost of microgrid in a scheduling cycle decreases first and then increases with the increase of $\alpha$. When $\alpha=0.95$, the operation cost of the system is the lowest. Therefore, the confidence level of rotating reserve for microgrid operation is set as 0.95. At this time, the operating cost of microgrid is 1659.5 yuan, and the output of each power supply is as shown in Figure 6. Without considering the charge and discharge loss cost of lithium battery and the start-up cost of micro gas turbine, when $a$, the operation cost of micro grid is 1416.2 yuan, as shown in Figure 7.
Figure 6. Microgrid Economic Operation Considering Battery Charge Discharge Loss and Micro-fuel Engine Startup Cost.

Figure 7. Microgrid Economic Operation Excluding Battery Charge Discharge Loss and Micro-fuel Engine Startup Cost.

Compared with Fig.6 and Fig.7, on the one hand, whether to consider the battery charge and discharge loss has a great impact on the operation mode of the energy storage device. When the loss is taken into account, the cycle times of battery charge and discharge are only 4 times, and the depth of each charge and discharge is very low; when the loss is not taken into account, the number of charge and discharge cycles is 12, and the depth of each charge and discharge is very high, which will greatly shorten the service life of the battery; on the other hand, whether the start-up cost of the micro gas turbine is taken into account also has a great impact on the operation mode of the micro gas turbine. When the start-up cost is taken into account, in order to reduce the start-up cost, the micro gas turbine chooses to maintain its start-up state by charging the energy storage device with a lower power at a low load, so as to reduce the number of switching on and off; when the start-up cost is not included, the conventional unit will frequently start and shut down, which will greatly increase the maintenance cost of the micro combustion engine. Therefore, in the process of micro grid operation, considering the charge and discharge loss of energy storage and the start-up cost of conventional units, making a reasonable operation strategy will greatly improve the use of energy storage times and the utilization efficiency of micro gas turbine.

4.2. Example Analysis of Grid Connected Microgrid

When the microgrid in 4.1 is connected to the grid, the maximum transmission power between the microgrid and the main grid is assumed to be 50KW. The electricity purchase and sale price of the microgrid in one day can be divided into three types: peak time price, valley time price and normal time price, as shown in Table 4.

| Time                        | Electricity purchase price | Electricity sale price |
|-----------------------------|----------------------------|------------------------|
| Peak(10:00~12:00;18:00~21:00) | 1.1                        | 0.85                   |
| Valley (0:00~7:00)          | 0.5                        | 0.3                    |
| Normal(8:00~9:00;13:00~17:00;22:00~23:00) | 0.8                        | 0.65                   |

For the grid connected microgrid, two operation schemes are considered in this example.

Scheme 1: The objective function is to minimize the total cost of microgrid operation. Under the confidence level determined in 3.1, considering the charge and discharge loss of lithium battery and the start-up cost of conventional units, the output of microgrid in a dispatching cycle is optimized. The optimization result is shown in Figure 8, and the total operation cost of the system is 1243.6 yuan.

Scheme 2: At the same time of realizing the optimal economy of microgrid, the efficiency of peak load shedding and valley filling of microgrid auxiliary large grid is considered. By using the multi-objective planning method proposed in this paper, the operation cost of microgrid in a scheduling cycle is calculated to be 1372.4 yuan, and the optimization results are shown in Figure 9.
Compared with the above two schemes, scheme 1 makes full use of the time-sharing electricity price to realize the economic operation of the microgrid itself, so the number of cycles of energy storage charging and discharging is more, and the depth of charging and discharging is also larger; scheme 2 helps the grid to cut the peak and fill the Valley while realizing the economic operation, so the operation cost of the microgrid increases by 11.9%, but it is still lower than the island operation mode. And it helps the large power grid to realize 387kw·h peak load and valley load electricity, that is, the cost of peak load and valley load is only 0.38 yuan / kWh, which realizes the economic operation of the main network and the micro network.

5. Conclusions

Based on the consideration of the energy storage charge and discharge loss and the start-up cost of conventional units, the optimization models of microgrid under different operation modes are established respectively in this paper. And the model is solved by the multi-objective programming method based on the weight optimization feedback and particle swarm optimization algorithm.

(1) For islanding operation mode, this paper analyzes the influence of charge and discharge loss of energy storage device and startup cost of conventional unit on the economic operation of micro grid. The results show that considering charge and discharge loss and startup cost in operation can effectively improve the service life of energy storage and utilization efficiency of micro gas turbine, although the operation cost has increased.

(2) For the grid connected operation mode, through the comparison of the two operation schemes, the calculation and analysis results that scheme 2 can make full use of the coordination and mutual assistance characteristics of the micro grid and the large grid, which can not only improve the economy and operation reliability of the micro grid itself, but also help the large grid to cut the peak and fill the valley, reduce the peak regulation pressure of the grid, and realize the efficient utilization of resources.

The model established in this paper can provide some reference for the microgrid to make the day ahead dispatching plan.

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