ANALYSIS AND RESEARCH ON OPTIMAL ECONOMIC OPERATION OF COGENERATION MICRO-GRID BASED ON HEAT PUMP CONTROL

by

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When the micro-grid is connected to the grid, the influence of the load and the micropower supply's operating characteristics may cause the power exchange between the micro-grid and the large grid to cause unnecessary losses. The objective function of power supply satisfaction of large power grids. The article takes the cogeneration micro-grid as the research object. It proposes establishing an objective function including the satisfaction of micro-grid decision-makers, the satisfaction of social benefits, and the satisfaction of large-scale power supply using the analytic hierarchy process. After that, the article uses the particle swarm optimization algorithm combined with the typical dispatching strategy of the micro-grid to solve the aforementioned model with MATLAB as the primary tool, and obtains the 24 hour output optimization results of the micro-grid, and analyzes the results in detail. The calculation examples show that the model can achieve economic optimization based on satisfying the satisfaction of different groups, which verifies the scientificity and effectiveness of the proposed model.

Key words*: heat pump control, economic operation, cogeneration type, particle swarm optimization algorithm, micro-grid*

Introduction

The study found that the micro-grid formed by distributed power generation can make full use of local renewable energy, be green and environmentally friendly, and improve the reliability of traditional large power grids. Economic benefits are a crucial link in the design, construction, and operation of micro-grids and a key indicator to promote the rapid development of micro-grids.

The unsolved economic benefits of the micro-grid mainly focus on optimized configuration and economic dispatch. Some scholars have used the theory of the full life cycle and used calculation results to illustrate the advantages of hybrid isolated micro-grids over traditionally isolated grids. Some scholars have established a comprehensive benefit evaluation model for micro-grids, analyzed several types of typical micro-grid examples, and explained their respective advantages [1]. Some scholars mainly research methods for determining the capacity of energy storage devices in micro-grids, use the internal characteristics of batteries to model, establish several optimization schemes, and put forward suggestions for the optimal configu-

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ration of micro-grid energy storage devices. Some scholars have established a comprehensive benefit model that includes the most economical operation of micro-grid and the least carbon emission of micro-grid operation, and calculation examples illustrate the model's scientific validity. Some scholars have established a power generation system, including micro-grid and small hydro power, which illustrates this model's significance to improve power supply reliability and reduce power generation operating costs. Some scholars comprehensively consider three factors of economic cost, environmental cost, and health cost to establish a micro-grid economic dispatch model and use examples to illustrate the model [2]. Some scholars focus on photovoltaic (PV) power generation systems' economics and conduct cost/benefit analysis of several PV power generation systems. Some scholars focus on PV power generation systems' reliability and study the evaluation criteria of PV power generation system reliability. Some scholars proposed comprehensively considering sensitivity analysis and PV installation locations to conduct economic analysis on industrial PV micro-grids. Some scholars have developed a micro-grid dispatching controller used in the co-ordinated operation of the micro-grid and the leading network and proved that it could effectively solve the problem of power supply discontinuity caused by the intermittent distributed power supply. Some scholars took AC and DC micro-grid as the research object, studied the network structure design and control technology and strategy of AC and DC micro-grid, and discussed and prospected the future development trend of AC and DC micro-grid.

However, as aforementioned, the literature considers a single factor in the study of micro-grid's economic dispatch. None of them adds the power exchange between the micro-grid and the primary grid as a consideration standard to the objective function, making the final economic evaluation result lacking rigor. In this paper, the AHP analytic method from three different perspectives is used to establish an objective function that includes the satisfaction of micro-grid decision-makers, social benefit satisfaction, and the massive power grid's power supply satisfaction. Optimal scheduling solution and economic analysis of the results [3].

Model establishment

Objective function

Satisfaction of micro-grid decision-makers

This paper uses three indicators based on the micro-grid micropower fuel consumption cost, the micropower operation, maintenance cost, and the micro-grid and the large scale energy exchange cost to describe the economic cost of the micro-grid on the dispatch day and serve as the objective function [4]. The study found that the smaller the value of the objective function, the higher the satisfaction of micro-grid decision-makers:

$$f_1 = C_{\text{fuel}} + C_{o\&M} + C_{\text{ex}} \tag{1}$$

$$C_{\text{fuel}} = \sum_{t=1}^{24}\sum_{i=1}^{n}\left(\frac{P_i^t + W_i^t}{L\eta i}C_i\right) \tag{2}$$

$$C_{o\&M} = \sum_{t=1}^{24}\sum_{i=1}^{n}\left(P_i^1 K_{o\&M,i}\right) \tag{3}$$

$$C_{\text{ex}} = \sum_{t=1}^{24}\left(C_{\text{buy}}\frac{\left|P_{\text{ex}}^t\right| + P_{\text{ex}}^t}{2}\right) - C_{\text{sell}}\frac{\left|P_{\text{ex}}^t\right| + P_{\text{ex}}^t}{2} \tag{4}$$

where C_{fuel}, $C_{o\,\&M}$, and C_{ex} represent the fuel cost, operation, and maintenance cost, and energy exchange cost on the dispatch day, respectively, P^t_i – the active output power of the micropower source i at time t, W^t_i – the heat output of the micropower source i at time t (the fuel the battery does not provide heat), L – the net calorific value, η_i – the maximum total efficiency of the micropower source i, C_i – the fuel unit price required by the micropower source i, $K_{o\&M,i}$ – the operation and maintenance cost required by the micropower source, C_{sell} – the purchase electricity costs (real-time electricity prices) and electricity sales costs, and P^t_{ex} – the value of the active power exchange between the micro-grid and the large grid at time t, and it is stipulated that the purchase of electricity is positive and the sale of electricity is negative.

Satisfaction of social benefits

During operation, the micro-grid emits gases like CO, CO_2 polluting the local environment, and the environment is an essential part of social benefits. Therefore, this article uses the environmental cost during the operation of the micro-grid as the objective function. In principle, the lower the environmental cost, the higher the satisfaction of social benefits:

$$f_2 = C_D \tag{5}$$

$$C_D = \sum_{t=1}^{24}\sum_{k=1}^{M} 10^{-3}\beta_k\left(\sum_{i=1}^{n}\partial_{k,i}P_i^t\right) \tag{6}$$

where β_k is the treatment cost of the k pollutant and $a_{k,i}$ – the emission coefficient when the micropower source i is running to produce the k pollutant.

Satisfaction of massive power grid power supply

When the micro-grid is connected to the grid, due to the influence of the load and the micropower source's operating characteristics, the power exchange between the micro-grid and the large grid may be too frequent and cause unnecessary losses. This paper introduces the exchange power penalty cost C_{grid} as the objective function [5]:

$$f_3 = C_{\text{grid}} \tag{7}$$

This paper selects the total amount of power exchange between the micro-grid and the large grid $|P^t_{\text{ex}}|$, the peak-valley difference of power exchange $\Delta P_{\max}$, and the variance of the micro-grid purchased power exchange σ and assigns corresponding penalty factors to express the power supply satisfaction of the large grid:

$$C_{\text{grid}} = a_t\Delta P_{\max} + a_2\sum_{t=1}^{T}\left|P_{\text{ex}}^t\right| + a_3\sigma \tag{8}$$

among them

$$\sigma = \sum_{t=1}^{T}\left(P_{\text{buy}}^t - \frac{\sum_{t=1}^{T}P_{\text{buy}}^t}{24}\right)^2 \tag{9}$$

where P^t_{buy} is the power purchased from the micro-grid to the enormous power grid at time t and a_3 are the power exchange penalty factors of the enormous power grid, respectively.

Maximum objective function of comprehensive benefits

In this paper, the objective function comprehensively considers the previous three factors, namely, under the premise of satisfying power supply satisfaction and environmental satisfaction, realizing the economic operation of the micro-grid:

$$\min[f_1, f_2, f_3] \tag{10}$$

$$\min F_1 = A_1 f_1 + A_2 f_2 + A_3 f_3 \tag{11}$$

The formula represents the weight of the objective function, calculated according to the analytic hierarchy process introduced in the next section.

Constraints

The power balance constraint is shown in the following formula, where P_{load}^t is the load demand of the micro-grid system at time t:

$$\sum_{i=1}^{n}\left(P_i^t + P_{\text{ex}}^t = P_{\text{load}}^t\right) \tag{12}$$

The output power constraint of the micropower supply is shown in the following formula. In the formula: $P_{i,\min}$ and $P_{i,\max}$ represent the lower limit and upper limit of the active power output of the micropower supply, respectively:

$$P_{i,\min} \le P_i^t \le P_{i,\max} \tag{13}$$

The battery operation constraints are shown in the following formula. In the formula, $S_{BT}^{\max}$ represent the allowable value of the minimum and maximum remaining power of the battery, respectively:

$$S_{BT}^{\min} \le S_{BT}(t) \le S_{BT}^{\max} \tag{14}$$

The active power exchange constraint is shown in the following equation. The formula represents the lower limit and upper limit of the active power exchange between the large grid and the micro-grid:

$$P_{\text{ex},\min} \le P_{\text{ex}}^t \le P_{\text{ex},\max} \tag{15}$$

Model solving

Objective function weight determination

The objective function constructed in this paper contains three sub-objectives. The AHP method assigns different weights to each sub-objective, which is converted into a single objective solution [6, 7]. The paper uses the analytic hierarchy process to determine the weight of each objective function.

Building a judgment matrix

The judgment matrix is the degree of importance of the influence of the same level of factors on the upper level in the analytic hierarchy process. It can be obtained by the method of pairwise comparison:

$$A^{\bullet} = \begin{bmatrix} a_{11} & \cdots & a_{\text{ln}} \\ \vdots & \vdots & \vdots \\ a_{nl} & \cdots & a_{nn} \end{bmatrix} \tag{16}$$

The formula $a_{11} - a_{nn}$ is the represents the relative importance between elements of a particular factor level, which can be represented by numbers 1-9 and reciprocal.

Weight calculation steps

Let $\lambda_{\max}$ represent the maximum eigenvalue of the matrix, A^* represent the judgment matrix's consistency test index under different orders. The specific values are shown in tab. 1.

Table 1. Judgment matrix consistency test standards

1	2	3	4	5	6	7	8	9
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

If the eq. (17) is satisfied:

$$\frac{\lambda_{\max} - n}{(n-1)RI} < 0.10 \tag{17}$$

The previous results show that the aforementioned construction matrix can pass the final consistency test, and the weights obtained are available. Otherwise, the steps need to be repeated to recalculate the weights. In this section, 1, 3, and 5 are selected as the importance comparison scale of the judgment matrix, and the weight of $W = [0.637, 0.258, 0.105]^T$ in the actual calculation can be obtained corresponding to the size of A_1, A_2, A_3.

Optimal dispatch strategy for micro-grid

The power generation of PV and wind turbine (WT) is uncontrollable, but it does not consume fuel and pollute the environment. To improve the economy, we prioritize using the two to supply the micro-grid load. The micro-turbine (MT) works in the *heat-fixed power* mode, which can output active power to meet the needs of part of the while meeting the demand of the thermal load. To achieve energy cascade utilization and improve the operating efficiency of the power generation system, when the output of WT, PV, and MT meet the load requirements of the micro-grid on the day, that is, when the net load is negative, the excess can be charged to the battery or sold to the large grid, and if the cost of FC power generation is less than the price of electricity sold, it can also be used to send electricity to the large grid to maximize economic benefits. When the output of WT, PV, and MT cannot meet the load requirements of the day, that is, when the net load is positive, the battery status is detected. Within the allowable range of battery operation, priority is given to using the battery to generate electricity [8]. If there is still a load shortage, it will dynamically select fuel cell (FC) to generate electricity or purchase electricity from the large grid. If the micropower supply in the micro-grid cannot meet the power generation demand with the large grid, part of the load will be removed.

The granular group optimization method

This paper uses a particle swarm optimization algorithm to solve the optimal scheduling model. The basic algorithm flow is shown in fig. 1.

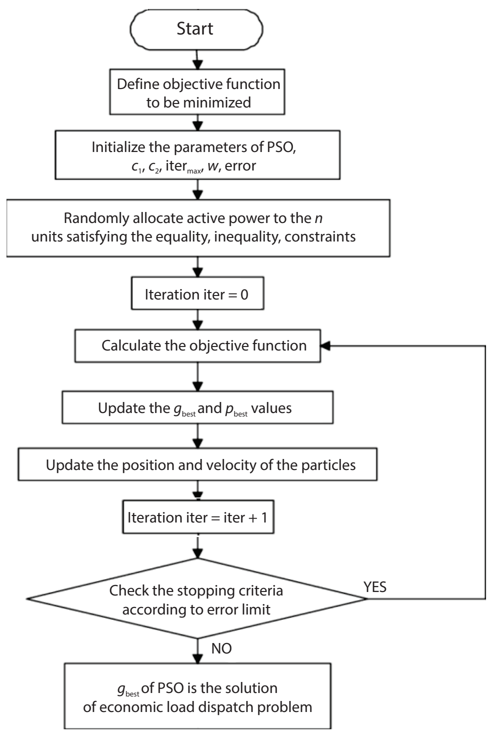

Figure 1. Flow chart of the particle swarm optimization algorithm

After testing, the maximum number of iterations is 300, and the number of particles is 600. To eliminate the particle swarm optimization algorithm's randomness as much as possible, the final calculation result is the average value after 50 iterations.

Case analysis

Basic data

This paper studies the economic dispatch of a micro-grid in grid-connected mode. Heating revenue is 0.1 Yuan per kWh, natural gas price is 2.5 Yuan per kWh, the upper and lower limits of active power exchange between the micro-grid and large power grid are 50 kW and –50 kW, and the power injected by micro-grid into the enormous power grid is negative, and *vice versa.* It is positive, the rated capacity of the battery is 450 kWh, and the maximum, minimum remaining capacity and initial capacity are, respectively: 65% S_{BTRC}, 20% S_{BTRC}, and 30% S_{BTRC}. The relevant information of each micropower supply is shown in tab. 2, the real-time electricity price is shown in fig. 2, MT output and heat and electric load are shown in fig. 3, and PV and WT output are shown in fig. 4.

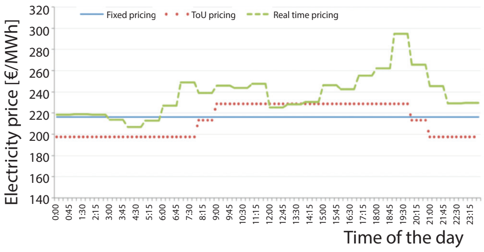

Figure 2. Real-time electricity price

Table 2. Characteristics of distributed power generation units in micro-grid

Power type	Maintenance cost Yuan per kWh	Investment cost Yuan per kWh	Life [year]	Power upper limit [kW]	Power lower limit [kW]
MT	0.070	10000	10	65	0
PV	0.035	20000	20	12	0
WT	0.035	12000	10	24	0
FC	0.070	28000	10	40	0
BT	0.070	667	10	60	–60

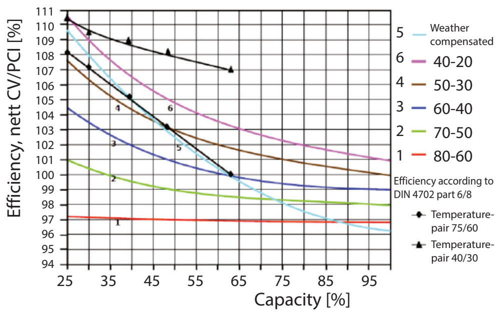

Figure 3. Known unit output and heat and electric load

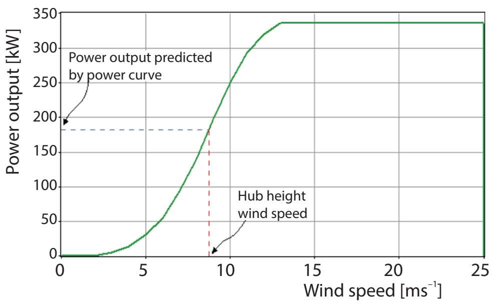

Figure 4. Output power prediction curve of photovoltaic cells and wind turbines

Result analysis

If the order of satisfaction is given as considerable grid power supply satisfaction > micro-grid decision-maker satisfaction > social benefit satisfaction, and this operation mode is named operation mode. At this time, the optimization results of the micro-grid's active power output are shown in fig. 5, and the change curve of the battery SOC is shown in fig. 6. Figures 5 and 6 show that there is almost no light during 01:00-07:00 a. m. and 21:00-24:00 p. m., and PV does not work, but the internal load demand of the micro-grid is not high. It can meet the micro-grid's internal load demand, that is, the internal net load of the micro-grid is negative. Therefore, during this period, the operation of the micro-grid reflects its benefit value. By matching the real-time electricity price, the internal micropower source generates electricity after meeting the load requirements, part of the battery is charged, and the remaining electricity is sold to the large grid to obtain higher economic benefits

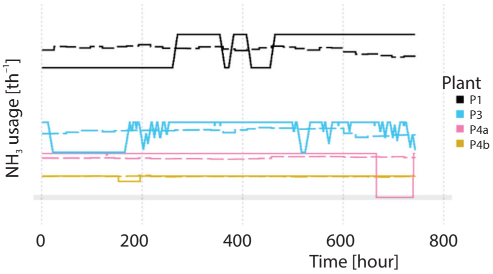

Figure 5. System optimization scheduling results in operating mode

During the period from 8:00 a. m. to 14:00 p. m., the WT output is at a relatively high level. Due to the sufficient light intensity, the PV output is more and reached the highest level of the dispatch day at 14:00 p. m., but the internal load demand of the micro-grid is at the highest stage of the dispatch day. The output of PV, WT, and MT alone cannot fully meet the load demand, that is, the net load inside the micro-grid is positive, and the load demand is still on the rise, reaching a peak at 14:00 p. m.. Therefore, in this period, we consider the micro-grid's operating economy, beneficiary travel (BT) gives priority to meet the load requirements, the FC output gradually increases, and BT, FC, and large grids co-ordinated to supply load. From 15:00 p. m. to 20:00 p. m., the output of WT is still relatively high, and the intensity of light is relatively sufficient but in a downward trend. The output of PV is gradually reduced and reduced to zero at 19:00, although the micro-grid's internal load demand is gradually decreasing. But it still needs more electricity to supply the load. The output of PV, WT, and MT alone cannot fully meet the load demand. That is, the internal net load of the micro-grid is positive. Therefore, in this period, we consider the economics of micro-grid operation. The BT gives priority to meet the load demand. The FC output shows a decreasing trend, BT, FC, and large grids co-ordinated to supply load. To ensure that the dispatch can be carried out generally on the next day, the battery's remaining power at the initial time and the end of the dispatch day must be equal [9]. From the aforementioned analysis, we can know that: we find that when the micro-grid is dispatched in different operating modes, the battery charge and discharge logic changes significantly. Because of the previous situation, the impact of battery capacity changes on the economics of micro-grid operation is studied. When the micro-grid is operated in two different operating modes and the battery rated capacity is gradually increased, the micro-grid's total daily operating costs (including daily operating costs and daily environmental penalty costs) change are shown in fig. 7.

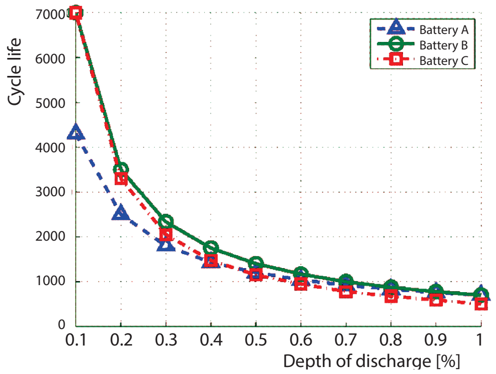

Figure 6. Optimal scheduling results of storage batteries in operating mode

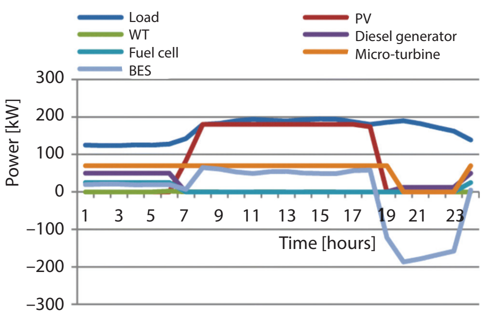

Figure 7. Impact of battery rated capacity change on the daily operating cost of microgrid

When the battery rated capacity changes from 450-900 kWh, the micro-grid's daily operating costs under the two operating modes show a downward trend. The daily operating cost of the micro-grid is reduced more significantly under the operating mode [10]. When the large grid power supply satisfaction objective function is introduced, the power exchange between the micro-grid and the large grid will be restricted. The micro-grid cannot be operated most economically. Still, to meet the micro-grid load demand, sufficient battery power will reduce the difficulty of economic dispatch, and the role of batteries is more pronounced.

It can be seen that as the grid satisfaction penalty gradually increases, the power exchange between the micro-grid and the large grid gradually decreases. The battery's efficient capacity is necessary to ensure the reliable and economic operation of the micro-grid power supply system. This also illustrates the importance of energy storage devices to the economic dispatch of the micro-grid. To usually meet the load demand, the battery charge and discharge depth must be increased. The frequency of battery charging and discharging or increasing the battery's rated capacity will also increase the operating cost and investment cost of energy storage. Therefore, the research of energy storage devices in micro-grid power generation systems and their charging and discharging strategies will be the direction and focus of further research.

Conclusion

Based on describing the micro-grid's traditional economic model, this paper introduces the objective function describing the power exchange between the micro-grid and the large grid, taking into account multiple benefits, and the research content is more practical. The paper explains the reasons for the micro-grid dispatch results under different operation modes, mainly the power exchange between the micro-grid and the large grid. It focuses on the crucial role of the battery in ensuring the micro-grid's economic operation when the operation mode changes and verifies the science of the proposed model. It also provides suggestions for the future development of micro-grid.

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