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MULTI-OBJECTIVE OPTIMAL SCHEDULING OF GRID-CONNECTED MICROGRID CONSIDERING ENERGY STORAGE AND LOAD MANAGEMENT

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ABSTRACT

This paper focuses on the optimal dispatching of microgrid with photovoltaic and energy storage. Firstly, considering the constraints of energy storage, interruptible load and transferable load, a multi-objective optimization model of grid-connected microgrid under time-sharing price and demand response is established, aiming at minimizing the operation cost, environmental cost and tie-line power fluctuation of microgrid. Then, aiming at the multi-objective, multi-constraint and non-linear characteristics of the model, an optimization solution method based on non-dominated sorting genetic algorithm-II (NSGA-II) is proposed. Finally, the article simulates the case based on MATLAB and OPENDSS joint simulation platform. The results of the example prove the validity and rationality of the model.

Keywords: microgrid, multi-objective optimization, demand response, NSGA-II

1. INTRODUCTION

With the increasing depletion of traditional energy and the increasingly serious environmental pollution, the development of renewable energy has become the consensus of all countries in the world [1]. However, renewable energy generation such as wind power generation and photovoltaic power generation in micro-grid has the characteristics of intermittent, randomness and uncertainty. The grid-connected operation of micro-grid will bring adverse effects on the safe and stable operation of the distribution network[2-3]. Therefore, how to utilize the resources of energy storage and demand side controllable loads to realize the multi-coordinated dispatch of microgrid while ensuring economic and environmental friendliness has become one of the research hotspots nowadays.

At present, many research scholars have carried out research on microgrid optimal dispatch and made some research progress. Literature [4] treats interruptible load as a dispatchable resource that actively participates in the operation of microgrid, and establishes the multi-objective dispatching models for peak-shaving and valley-filling of tie-line and minimum fluctuation of tie-line respectively. Considering the transferable load on demand side and aiming at minimizing the total operation cost of energy storage cycle, reference [5] establishes a unified optimal dispatching model for photovoltaic micro-grid which is suitable for island and grid-connected operation modes.

2. MULTI-OBJECTIVE OPTIMIZATION MODEL

In this paper, the objective function of optimal dispatching model of microgrid is constructed from three aspects: operation cost of microgrid, environmental cost and power fluctuation of tie-line between the microgrid and the distribution network.

2.1 Optimizing goal 1

This paper focuses on the operation optimization of microgrid, so it does not consider the investment cost of photovoltaic and energy storage equipment, but only includes the cost of electricity purchase, energy storage operation, compensation for interruptible load and transferable load in demand side when participating in dispatching. Therefore, the operation cost of microgrid is as follows:

$$f_1 = C_{grid} + C_{ES} + C_{IL} + C_{TL} \tag{1}$$

2.1.1 Electricity purchasing cost

The cost of purchasing electricity considering time-of-use price is as follows:

$$C_{grid} = \sum_{t}^{T} (c_t^{grid} P_t^{grid}) \tag{2}$$

where P_t^{grid} is the power that microgrid purchase from the distribution network at *t* time; c_t^{grid} is the price of electricity purchased at *t* time; *T* is the number of time periods of dispatching cycle. This paper studies the day-ahead dispatching, taking T = 24.

2.1.2 Energy storage operation cost

$$C_{ES} = \sum_{t=1}^{T} c_{ES,price} \left| P_{ES,t} \right| \Delta t \tag{3}$$

where $c_{ES,price}$ is the unit operating cost of the energy storage system, $P_{ES,t}$ is the charging and discharging power of the energy storage at t time.

2.1.3 Interruptible load compensation cost

$$C_{IL} = \sum_{n=1}^{N} \sum_{t=1}^{T} c_{IL,price} P_{t,IL}^{n} \Delta t \tag{4}$$

where $c_{IL,price}$ is the compensation cost of unit interruption power, $P_{t,IL}^{n}$ is the interruption power of user *n* at *t* time, and *N* is the number of users with interruptible load.

2.1.4 Transferable load compensation cost

$$C_{TL} = \sum_{n=1}^{N} \sum_{t=1}^{T} c_{TL,price} P_{t,TL}^{n} \Delta t \tag{5}$$

where $c_{TL,price}$ is the compensation cost of unit transfer power, $P_{t,TL}^{n}$ is the transfer power of user n at t time, and N is the number of users with transferable load.

2.2 Optimizing goal 2

At present, coal-fired power generation still occupies a large proportion in the grid side. In order to reduce the environmental pollution caused by coal-fired power generation, the second objective function is to minimize the environmental cost which is given as follows:

$$f_2 = \sum_{t}^{T} \omega_e p_t^{grid} \tag{6}$$

Where ω_e is the baseline carbon emission factor for coal-fired power generation, taking $798g/kW \cdot h$; p_t^{grid} is the purchase of power of micro-grid at *t* time.

2.3 Optimizing goal 3

$$f_3 = \sum_{t=1}^{T-1} \left(P_{t+1}^{grid} - P_t^{grid} \right) \tag{7}$$

where P_{t+1}^{grid} and P_t^{grid} are respectively the power of the link line at *t*+1 and *t* time.

2.4 Optimization variables

$$X = \left(P_{ES,t}, P_{IL,t}^{n}, T_{IL}(n), P_{TL,t}^{n}, T_{TL}(n) \right) \tag{8}$$

where $P_{ES,t}$, $P_{IL,t}^{n}$, $T_{IL}(n)$, $P_{TL,t}^{n}$ and $T_{TL}(n)$ are respectively the charging and discharging power of energy storage, the interruption power of interruptible load, the interruption duration of user *n*, the transfer power of transferable load and the transfer time of user *n*.

2.5 Constraint condition

2.5.1 Relevant constraints of energy storage system

$$\begin{cases} 0 \le P_{ES,C}^{\min} \le P_{ES,t} \le P_{ES,C}^{\max} \\ P_{ES,D}^{\min} \le P_{ES,t} \le P_{ES,D}^{\max} \le 0 \end{cases} \tag{9}$$

where $P_{ES,C}^{\min}$ and $P_{ES,C}^{\max}$ are respectively the minimum and maximum charging power of the energy storage system. $P_{ES,D}^{\min}$ and $P_{ES,D}^{\max}$ are the minimum and maximum discharge power of the energy storage system.

The current state of the energy storage system is derived from the following formula:

$$E_{ES,t} = (1-g)E_{ES,t-1} + P_{ES,t}\Delta T \tag{10}$$

Where g is the self-loss coefficient of the energy storage system, $E_{ES,t-1}$ is the energy storage capacity of the energy storage system at one moment, $P_{ES,t}$ is the charging and discharging power at t time, ΔT is the unit time length.

SOC is defined as the state of charge of the energy storage system:

$$SOC_t = \frac{E_{ES,t}}{E_{ES}^{rated}} \tag{11}$$

where E_{ES}^{rated} is the rated capacity of the energy storage system.

The state of charge should satisfy the constraint as follows:

$$SOC_{\min} \le SOC \le SOC_{\max} \tag{12}$$

where $SOC_{\max}$ and $SOC_{\min}$ are upper and lower limit constraints of SOC in the actual operation of ESS.

2.5.2 Relevant constraints of interruptible load

$$P_{n,IL,\min} \le P_{IL,t}^{n} \le P_{n,IL,\max} \tag{13}$$

$$T_{IL}(n) \le T_{IL,\max}(n) \tag{14}$$

where $P_{n,IL,\min}$ is the minimum interrupt power of user *n* $P_{n,IL,\max}$ is the maximum interrupt power of user *n*. $T_{IL,\max}(n)$ is the upper limit of allowable interrupt duration for user *n*.

2.5.3 Relevant constraints of transferable load

$$P_{n,TL,\min} \le P_{TL,t}^{n} \le P_{n,TL,\max} \tag{15}$$

$$\sum_{t=1}^{T} P_{TL,t}^{n} = 0 \tag{16}$$

where $P_{n,TL,\min}$ is the minimum interrupt power of user n , $P_{n,TL,\max}$ is the maximum interrupt power of user n. Formula (16) denotes that the total power consumption of user n remains unchanged in a cycle (especially in a working day).

2.6 Selection of the optimal solution

This paper uses the method of fuzzy decision to select the optimal solution from Pareto frontier. The membership function u_{ij} of the *j*-th objective function of the *i*-th Pareto solution is

$$u_{ij} = \frac{f_{j,\max} - f_{ij}}{f_{j,\max} - f_{j,\min}}, j = 1,2,3 \tag{17}$$

where f_{ij} is the j-th objective function value of the i-th Pareto solution. For the i-th Pareto solution, the normalized membership function u_i is as follows:

$$u_i = \frac{\sum_{j=1}^{M} u_{ij}}{\sum_{i=1}^{I}\sum_{j=1}^{M} u_{ij}} \tag{18}$$

where I is the number of Pareto solutions, M is the number of objective functions.

3. EXAMPLE ANALYSIS

3.1 Basic data

The EPRI microgrid is adopted in this example[6]. The structure of EPRI microgrid is shown in Fig.2. The photovoltaic output and total load curve in the microgrid are shown in Fig.3. The time-sharing price is shown in Fig.4. The rated capacity of the energy storage system is 1000kWh. The charging and discharging efficiency is 0.9, and the upper and lower limits of SOC are 0.9 and 0.3, respectively. Related data on interruptible and transferable loads are shown in Table 1.

3.2 Simulation and analysis

Based on MATLAB platform and OPENDSS, the optimization model is solved by NSGA-II algorithm. The population size is set at 500, the maximum number of iterations is 100, the crossover rate is 0.9, and the mutation rate is 0.1.

In the case of complete photovoltaic absorption, the obtained Pareto frontier is shown in Fig. 5. The size of the fuzzy membership function obtained by the decision maker according to the actual focus is shown in Table 2. In this paper, the largest value of the membership function is chosen as the optimal solution.

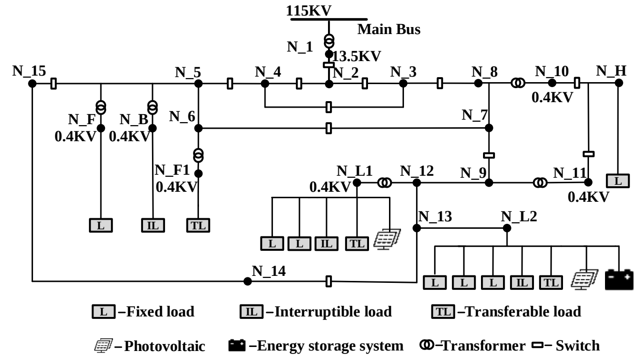

Fig. 2. EPRI microgrid structure

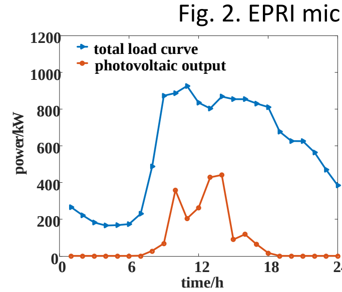

Fig. 3. Photovoltaic and Load Curves

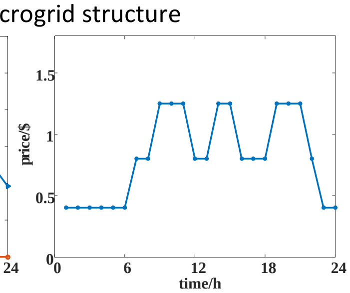

Fig. 4. TOU price

Table 1. Interruptible and Transferable Load Related Data

	Class I Load	Class I Load	Class I Load
Interruption compensation cost/$	0.3	0.2	0.25
Interruption times	2	2	4
Interruption duration/h	2	2	4
Transfer compensation cost/$	0.08	0.06	0.07

Table 2. The value of membership function

Operation cost of micro grid/$	Environmental cost/$	Tie-line power fluctuation/kW	The value of membership function(u)
13482	12496	1542	0.0177
13474	12468	1580	0.0348
13426	12460	1620	0.0335

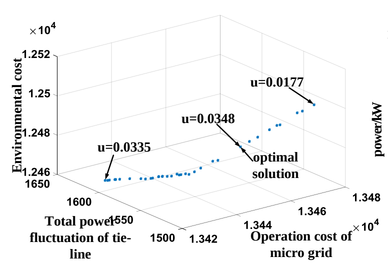

Fig. 5. Pareto frontier

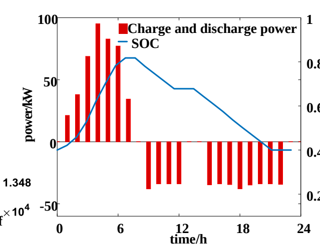

Fig. 6. Charge and discharge power and SOC curve

Following is the further analysis of typical photovoltaic microgrid. The optimized charging and discharging power and charging state of the energy storage system are shown in Fig.6. It can be seen that the energy storage system charges when the load is low and discharges during peak-to-peak period when the load is concentrated.

Fig.7 shows the curves of interruptible load and transferable load before and after optimization. It can be seen that the load consumption in peak period can be reduced and the load consumption in valley period can be increased by adjusting the flexible load on demand side.

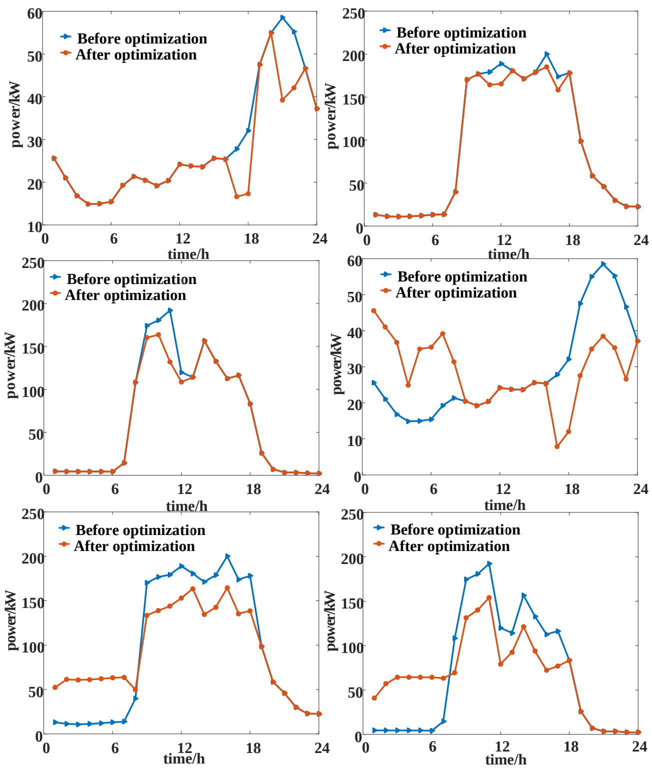

Fig. 7. Interruptible load and transferable load curve before and after optimization

Fig.8 shows the power and probability density curves of tied-lines before and after optimization. From the probability density curve, it can be seen that the power fluctuation of tie-line after optimization is obviously smaller than that before optimization.

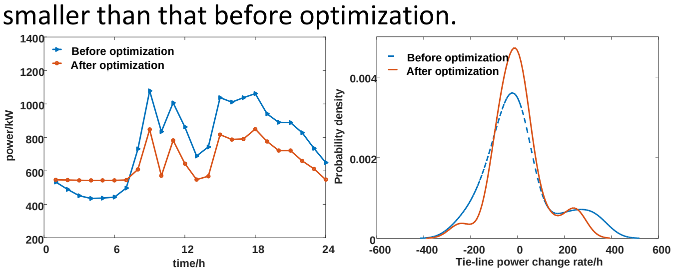

Fig. 8. The-line power and probability density curve before and after optimization

The relevant index values of objective function before and after optimization are calculated. The results are shown in Table 3. It can be seen that the operation cost, environmental cost and total fluctuation of tie-line power have been significantly improved after optimization, and the economic benefits of microgrid have been improved.

Table 3. Relevant index values of objective function before and after optimization

Index	Operation cost of micro grid/$	Environmental cost/$	Tie-line power fluctuation/kW
Before optimization	14309	12649	2314
After optimization	13474	12468	1580

4. CONCLUSIONS

Considering the flexible load of energy storage system and demand side as scheduling resources, this paper proposes a multi-objective optimal scheduling model with minimal microgrid operation cost, environmental cost and tie-line power fluctuation under time-sharing price. The multi-objective genetic algorithm is used to solve the proposed model. The simulation results show that the energy storage system and flexible load can be incorporated into the operation scheduling of microgrid. Through the cooperative optimization of "source-storage-load", the operation cost of micro grid, environmental cost and power fluctuation of tie-line can be effectively reduced, and the system can operate safely and reliably.

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