A Microgrid Management System Based on Metaheuristics Particle Swarm Optimization

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***Abstract*—Microgrid is playing an increasingly important role in making the utility grid more intelligent and efficient, since it can make better use of the renewable energy resources to simultaneously relieve the grid supply pressure and reduce carbon emissions. Innovations in electric technologies, information and communication technologies can facilitate better management of the power transmission and distribution in the microgrid. This paper proposes an optimization strategy, which considers distributed generations, photovoltaics and wind turbines, based on particle swarm optimization for the management of the microgrid. Simulation results demonstrate that with the optimal generation resources management and the effective use of demand side management in the microgrid, the proposed strategy can reduce electricity costs by 29.283% and 32.158% on weekdays and weekends, respectively.**

Keywords—microgrid, demand side management, optimization, photovoltaics, wind turbines

I. Introduction

Electricity is one of the fundamental components of our society. Today, with the development of the world, the demand for electricity is increasing, and the traditional power grid is more and more difficult to meet the needs of daily life and industrial use. Many specific problems such as unstable grid voltage, insufficient power supply, excessive carbon emissions, and insufficient self-healing ability have gradually emerged. Considering these issues, it is beneficial to promote microgrid technology, because it can make better use of renewable energy (such as solar energy, wind energy, etc.) by connecting distributed generation to the grid while ensuring the reliability of smart grids.

As an important part of smart grid [1], microgrid can make full use of small-scale distributed generation, which is dominated by renewable energy. The main working modes of the microgrid are grid-connected mode and island mode. These two modes allow the microgrid to operate in parallel with or independently of the grid, respectively, without grid support. Since the output of electricity generated using renewable energy depends mainly on natural conditions, its output fluctuates. Building an energy management system (EMS) for microgrids is one of the effective solutions [2]. The basic goals of microgrid EMS are voltage control and supply-demand balance. In particular, the method described below ensures that the load of the above two operating modes is below a threshold level.

In this paper, a specific EMS based on Particle swarm optimization (PSO) is implemented. In this system, operating cost and income of each part of the microgrid are considered. The main function of this EMS is to control the load shifting and peak clipping of the microgrid by controlling storage.

In the remainder of this paper, literature review is shown in Section II, principle and methodology are described in Section III, experiment and result analysis are presented in Section IV, and conclusion will be given in Section V.

II. Literature Review

A. Smart grid

According to [3], smart grid is a power network that can intelligently integrate the working of all connected users (generators, consumers, etc.) to provide electricity economically and efficiently. Microgrid is one of the important parts of smart grid, it can make contribution to the efficient work of the main grid. Harpreet Sharma & Gagandeep Kaur proposed an optimum solution of implementing a smart microgrid at I.K Gujral Punjab Technical University through Homer simulates in paper [4].

B. Demand Side Management

Demand side management (DSM) is of great significance to microgrid. DSM is an important part of the smart grid and the concept of DSM is to control the demand side consumption and reduce peak loads [5]. In papers [6]-[7], some methods of application of DSM in microgrid are given. In paper [6], a load shifting procedure was presented in a simulated environment of a residential infrastructure. Through predicting the future load patterns, various types of controllable devices were managed to reduce the peak demand of load. In paper [7], Chafaa Hamrouni *et al.* proposed a Microgrid Energy Management-Distributed Optimization Algorithm to enhance scalability of deployment, privacy and security in the smart microgrid.

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C. Optimization algorithm

As one of the most widely used microgrid optimization methods, mathematical algorithms show great value in microgrid optimization. These algorithms are designed to reduce operating costs and reduce carbon emissions by optimizing a given microgrid environment. These methods are used and analysed in paper [8]. This paper optimized a model considering the levelized cost of energy (LCOE) and renewable energy efficiency is proposed to solve the energy distribution optimization problem of grid-connected microgrids. The mathematical basis of the model is Differential Evolution-based Multi-Objective Mixed Multivariate Optimization (LDEMVO). At the same time, in order to reflect the superiority of LDEMVO in the application of the setting environment, the author also compared it with other four different algorithms (whale optimization algorithm, multi-section optimization algorithm, particle swarm optimization algorithm and gray wolf optimization algorithm). The conclusion is that using LDEMVO has advantages in terms of LCOE and discount rate, especially as storage capacity increases, the investment cost is higher.

D. Contributions

Compared to existing literatures, this paper focuses on verifying the feasibility of microgrid management by solving the multi-objective optimization problem of a grid-connected microgrid EMS in Shanghai area. The main contributions of this paper are:

- A microgrid EMS based on PSO is presented. This system adopts two typical theories (load shifting and peak clipping) in DSM and uses PSO as the core algorithm for optimization. This system is highly adaptable and practical.
- This paper verifies that PSO has better accuracy and faster convergence speed for power system problems.
- The results show that for the model set in this paper, the PSO algorithm has the ability to reduce electricity prices by 29.283% and 32.158% on weekday and weekend respectively.

III. PRINCIPLE AND METHODOLOGY

This section describes the basic principles of PSO. In addition, the experimental environment and ideal model of the paper, as well as the calculation formulas of power and cost of each part, and some power limits are also given.

A. Principle

PSO is an evolutionary computation technology. It is originated from the behavioural research on predation of flocks. The algorithm flow of PSO is shown in Fig. 1. In this figure, 'iterate *N* times' works as the end condition of the entire PSO algorithm, *N* is the number of iterations.

The particle updates its velocity and position by (1), (2) and (3):

$$V_{i+1} = \omega_i V_i + c_1 r_1 \left(P_{best_i} - X_i\right) + c_1 r_2 \left(G_{best_i} - X_i\right) \quad (1)$$

$$X_{i+1} = X_i + V_i \quad (2)$$

$$\omega_i = \frac{\omega_{max} - (\omega_{max} - \omega_{min}) \times i}{N} \quad (3)$$

where *i*= 1, 2, 3, …, *n*, *n* is the total number of particles. V_i is the velocity of the particle, it should be less than V_{max}, if $V_i > V_{max}$, then $V_i = V_{max}$. c_1 and c_2 are learning factors. P_{best} is the individual optimal and G_{bsest} is the global optimal. r_1 and r_2 are random numbers. X_i is the current location. ω is a non-negative number called the inertia factor. To balance the ability to find the optimal value globally and locally, the value of ω is given by the formula (3), both ω_{max} and ω_{min} use classic weight values.

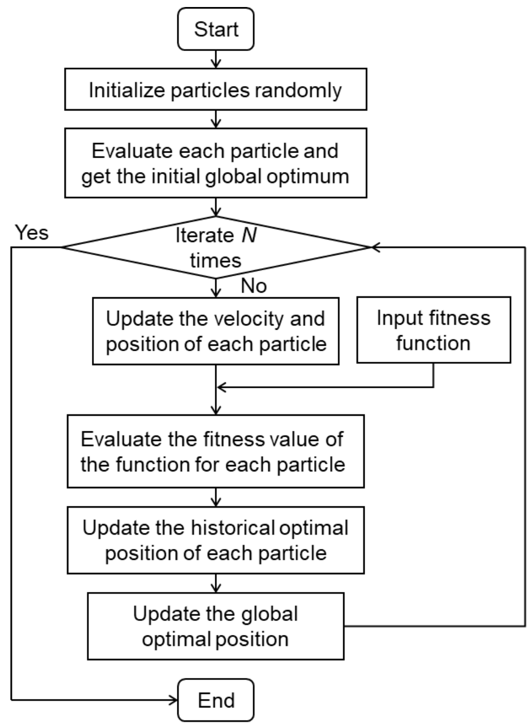

Fig. 1. Workflow of PSO

B. Methodology

(1) Design requirements

For a microgrid system, electricity can be exchanged bidirectionally between the grid and the microgrid. In order to reduce the comprehensive cost of the daily operation of the microgrid, when the electricity price of the external grid is low, the storage system does not discharge, and the microgrid purchases electricity from the grid to charge the storage. When the grid electricity price is high, the storage device is not charged, and the microgrid uses wind energy, solar energy and storage as much as possible to meet all the needs of the microgrid load, and sells the excess electricity to the grid, so as to achieve the goal of the lowest total operating cost. In order to better simulate the real situation, the construction and operation costs of WT, PV and storage are considered in this paper. Divide a day into 24 periods in hours, assuming that the microgrid meets the following conditions in each period: The load demand remains constant; The power output of wind power and photovoltaic is constant; The interaction power between the micro grid and the main grid is constant; The operating state of the battery is single, and its charge and discharge power remain constant.

(2) Structure of the simulation model

The simplified structure of grid-connected microgrid is shown in Fig. 2.

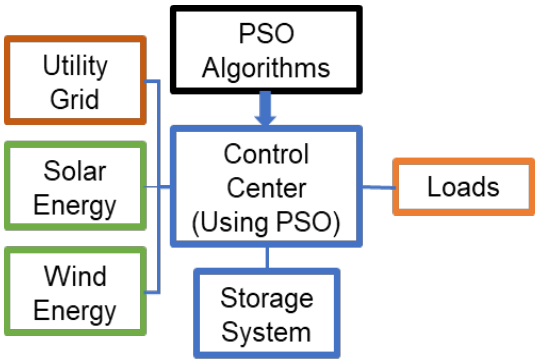

Fig. 2. Simplified model of microgrid in this paper

The fundamental purpose of this paper is to find out the daily lowest operating price and give the operation plan of each part of the microgrid through line graphs and tables based on the given microgrid configuration through a PSO program.

(3) Constraints and calculations:

The proposed microgrid management system is essentially an optimization problem. First, all the elements involved should be represented in mathematical equations so that they can be solved algorithmically.

① The total expenditure for daily microgrid operation is:

$$C_{S_{total}} = C_{buy} - I_{sell} + C_{S_{total}} - S_{PV} - S_{WT} - C_{PV} - C_{WT} \quad (4)$$

where C_{buy} is the total cost of purchasing electricity from the grid, I_{sell} is the income from selling electricity to the grid, $C_{S_{total}}$ is the operating cost of energy storage, S_{PV} and S_{WT} are the operating subsidies for PV and WT. $LCOE_{PV}$ is the power generation cost of PV, C_{WT} is the power generation cost of WT.

② For PV, the operating subsidy is:

$$S_{PV} = \sum_{t=1}^{24} P_{PV_t} \times C_{PVsub} \quad (5)$$

where P_{PV} is the total daily output of PV, and C_{PVsub} is the China's subsidy price for civilian distributed PV power generation.

The power generation cost of PV is quantified by LCOE:

$$C_{PV} = LCOE_{PV} = \frac{C_{buy} + C_{BOS} + C_{OM}}{E_{total}} \quad (6)$$

where C_{buy} is the cost of purchasing PV module, C_{BOS} is the cost of purchasing balance-of-system (BOS) components, C_{OM} is the cost of operation and maintenance and E_{total} is the total energy output over the lifetime of this PV.

③ For WT, the operating subsidy is:

$$S_{WT} = \sum_{t=1}^{24} P_{WT_t} \times C_{WTsub} \quad (7)$$

where P_{WT} is the total daily output of WT, and C_{WTsub} is the China's subsidy price for civilian distributed WT power generation.

④ For storage, because lead-acid batteries have the advantages of mature technology, low price and large energy storage capacity [9], so this paper uses lead-acid battery packs as energy storage devices. The constraint of the remaining capacity of the battery is evaluated by the State of charge (SOC):

$$S_{SOC_{min}} \le S_{SOC} \le S_{SOC_{max}} \quad (8)$$

where, S_{SOC} is the SOC of the storage, $S_{SOC_{min}}$ and $S_{SOC_{max}}$ are the minimum and maximum of SOC respectively.

The constraints of charge and discharge power of the storage respectively are:

$$\begin{cases} 0 \le P_{ch} \le P_{ch_{max}} \\ 0 \le P_{dch} \le P_{dch_{max}} \end{cases} \quad (9)$$

where $P_{ch_{max}}$ and $P_{dch_{max}}$ are the maximum of charge and discharge power.

The operating cost of storage is:

$$C_{S_{total}} = \sum_{t=1}^{24} \left(|P_{input}| + |P_{output}| \right) \times C_{storage} \quad (10)$$

where P_{input} and P_{output} are the total input power and output power in a certain hour, respectively. $C_{storage}$ is the operating cost per kWh of storage discharge and charge.

⑤ The power exchange constraints with the grid is:

$$0 \le |P_{tran}| \le P_{tran_{max}} \quad (11)$$

where $P_{tran_{max}} = 7\,kW$ is the maximum of transmission active power of the transmission line between the grid and the microgrid.

⑥ The total price of electricity purchased from the grid or sold to the grid on one day can be obtained by (11) and (12):

$$P_d = P_L - P_{PV} - P_{WT} - P_S \quad (12)$$

where P_L is the power required by the loads, P_{PV} is the total power provided by the PV, P_{WT} is the total power provided by the WT, and P_S is the power provided or absorbed by the storage.

The total electricity purchase cost and electricity sales revenue are:

$$\begin{aligned} C_{buy} &= \sum_{t=1}^{24} \left(|P_{d_t}| \times V_B \right) \\ I_{sell} &= \sum_{t=1}^{24} \left(|P_{d_t}| \times V_S \right) \end{aligned} \quad (13)$$

where V_B is the price per kWh of electricity purchased, and V_S is the price per kWh of electricity sold.

IV. EXPERIMENT AND RESULT ANALYSIS

This section gives the running steps of experimental procedure and result analysis.

A. Program structure

The whole structure of the program of this paper is divided into 5 parts and they are introduced in order below.

i. Data entering and parameter setting

Data of the main parts of this microgrid system and the parameters the PSO algorithm required are given, their specific values are as follows:

- The total number of particles *i* is set to 500.
- The number of iterations *N* is set to 500. This is an appropriate number of iterations for a microgrid with three optimization objects and a daily load not exceeding 50kW.
- The absolute value of the maximum and minimum motion velocities of the particles is set to 1.
- The learning factors c_1 and c_2 are both set to 2.
- The classic weight values $\omega_{max} = 0.9$ and $\omega_{min} = 0.4$. According to past research, using these two values can best balance the global search ability and local search ability of each particle.

ii. Scope limiting

Two important parts of the constraint: the upper limit of charge and discharge of the energy storage battery and the max transmission power between the main grid and this microgrid system are limited in this part.

For storage, the storage cap is 15 kW, to prolong the service life of the battery, its range is:

$$\begin{cases} S_{SOC_{max}} = 70\% \\ S_{SOC_{min}} = 15\% \end{cases} \quad (14)$$

And the SOC of the maximum battery output or input per hour is 30% [10].

iii. Loop of PSO algorithm

According to equations (1), (2) and (3), the main loop of the entire program is constructed. In this loop, in addition to the above equation, the fitness function is constructed using the formula listed in 3.2.3 as a criterion for evaluating the fitness of each particle.

After each evolution, it needs to be constrained by inequality group (9) and inequality (16) (all storage-related calculations will be quantified by SOC in the program).

iv. Calculate the cost of the unoptimized case

The daily electricity prices for the two unoptimized models are calculated and compared with the optimized results.

v. Output of result

After the main loop, the program results which include working schedule of the microgrid, daily electricity price and SOC of the storage is outputted.

B. Parameter settings

All the data sets needed for this paper are listed in Table II. The data in the table is the average of a household in Shanghai in summer (May-September, 153 days).

TABLE I. 24H WORKING DATA OF THE MICROGRID [11][12]

Period /h	Load/kW		PV power /kW	WT power /kW	Electricity price/yuan
	Weekdays	*Weekends*			
1	0.2	0.2	0	0.75	0.487
2	0.2	0.2	0	0.65	0.487
3	0.3	0.3	0	0.6	0.487
4	0.3	0.3	0	0.55	0.487
5	0.5	0.5	0	0.5	0.487
6	0.6	0.6	0.1	0.57	0.487
7	0.6	0.6	0.18	0.6	0.487
8	0.8	1	0.31	0.66	0.487
9	1	1	0.57	0.5	0.977
10	0.6	1.2	0.75	0.58	0.977
11	0.4	1.4	0.88	0.6	0.977
12	1.5	1.8	0.85	0.6	0.977
13	1.1	1.1	0.9	0.57	0.977
14	1.1	1.1	0.91	0.5	0.977
15	1.3	1,8	0.73	0.61	0.977
16	2.7	2.3	0.55	0.58	0.977
17	2.3	2.3	0.35	0.55	0.977
18	2.1	2.1	0.18	0.65	0.977
19	2	2	0.08	0.56	0.977
20	2.2	2.2	0	0.6	0.977
21	2	2	0	0.72	0.977
22	1	1	0	0.66	0.977
23	0.5	0.9	0	0.75	0.487
24	0.4	0.2	0	0.76	0.487

C. Result analysis

Based on the conditions provided above, PV and WT are determined by the natural working state, the external power grid has the ability to provide the full load demand to the microgrid ($P_{tran_{max}}$=70 kW , which is greater than the maximum hourly load), and the goal controlled directly by the control center is storage. All the results of simulation are obtained and all content is shown below:

(1) Situation in weekdays

Fig. 3 shows the daily working schedule of the whole microgrid system (external grid, storage, PV and WT) in weekdays.

Fig. 4 shows the optimization process of PSO in weekdays. At the beginning of this process, the fitness value (electricity cost) of a random particle is selected as the global optimum, and its value is 11.9647 yuan/day. As the program runs, as the program evaluates to 500 times, the global optimum tends to 8.4491 yuan/day. Total daily electricity cost reduces 3.5156 yuan/day and the reduction rate is 29.383%.

As for the case of using the external power grid completely, the electricity fee is 23.9325 yuan/day. Compared to this model that is not optimized by PSO algorithm, the daily electricity cost is reduced by 11.8678 yuan/day and the reduction rate is 49.589%. Compared to this model that is optimized by PSO algorithm, the daily electricity cost is reduced by 15.3834 yuan/day and the reduction rate is 64.278%.

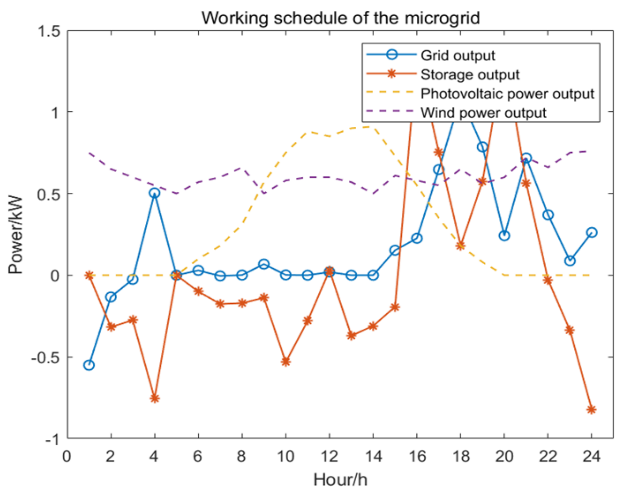

Fig. 3. Work schedule of microgrid (Weekdays)

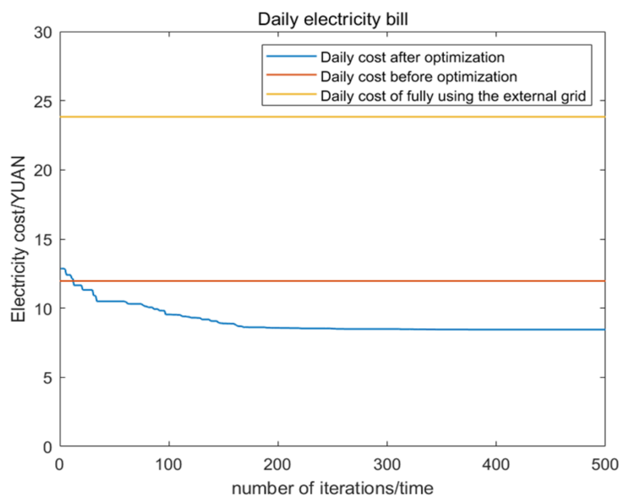

Fig. 4. PSO optimization curve and electricity cost (Weekdays)

(2) Situation on weekends

Fig. 5 shows the daily working schedule of the whole microgrid system (external grid, storage, PV and WT) in weekends.

Fig. 6 shows the optimization process of PSO in weekends. At the beginning of this process, the fitness value (electricity cost) of a random particle is selected as the global optimum, and its value is 12.8048 yuan/day. As the program runs, as the program evaluates to 500 times, the global optimum tends to 8.6870 yuan/day. Total daily electricity cost reduced 4.1178 yuan/ day. The reduction rate is 32.158%.

As for the case of using the external power grid completely, the electricity fee is 25.1017 yuan/day. Compared to this model that is not optimized by PSO algorithm, the daily electricity cost is reduced by 12.2969 yuan/day and the reduction rate is 49.988%. Compared to this model that is optimized by PSO algorithm, the daily electricity cost is reduced by 16.4317 yuan/day and the reduction rate is 65.392%.

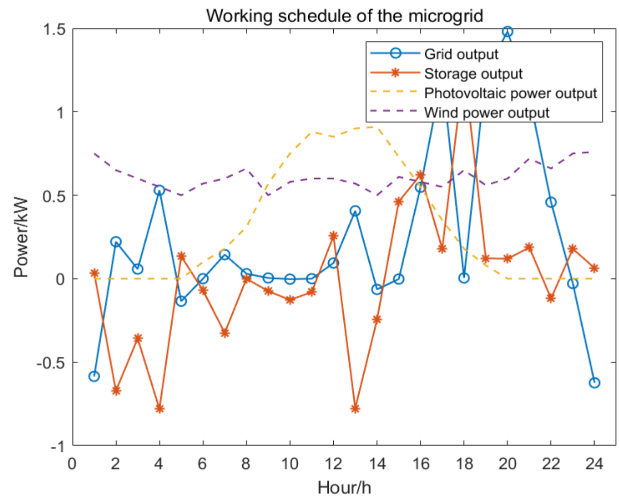

Fig. 5. Work schedule of microgrid (Weekends)

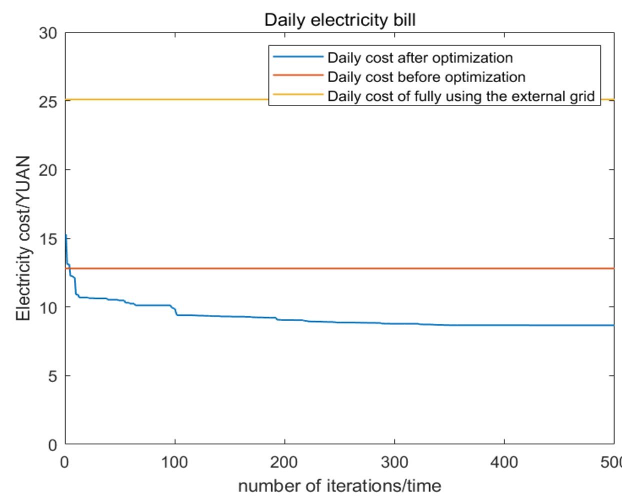

Fig. 6. PSO Optimization curve and electricity cost (weekends)

(3) Compare and analysis:

Based on the data gives above, a summary table Table II can be drawn.

TABLE II. SUMMARY OF ELECTRICTY COST

Comparing with the model of full using the external grid				
Period	*Kind of data*	*Operation status*		
		Full using of external grid	*Before optimization*	*After optimization*
Weekdays	*Electricity cost/yuan*	23.9325	11.9647	8.4491
	Reduction rate	N/A	49.589%	64.278%
Weekends	*Electricity cost/yuan*	25.1017	12.8048	8.6870
	Reduction rate	N/A	49.988%	65.492%
Comparison before and after optimization				
Period	*Kind of data*	*Operation status*		
		Before optimization	*After optimization*	
Weekdays	*Electricity cost/yuan*	11.9647	8.4491	

	Reduction rate	N/A	29.383%
Weekends	*Electricity cost/yuan*	12.8048	8.6870
	Reduction rate	N/A	32.158%

From Table II, it can be clearly shown that the electricity price drop rate of the microgrid load based on WT, PV and storage compared with the traditional grid-connected operation, and the optimization ability of PSO to the above microgrid model.

The applicability of the PSO algorithm to weekdays and weekends can also be obtained. In this experiment, the difference between weekday load and weekend load is how flat the daily load curve is in both cases. On weekdays, due to the large population mobility in residential areas and the large difference between day and night loads, the daily load curve has the characteristics of greater volatility. During the weekend, the population mobility is relatively low, the growth of the load is more gradual in the morning and afternoon, and the fluctuation of the daily load curve is less. The daily load of Weekends is 4.885% higher than the daily electricity bill of weekday. After optimization using PSO, the electricity price reduction rate of the former is 1.214% higher than that of the latter. This shows that PSO optimizes excellent stability when dealing with loads with different characteristics.

V. Conclusion

In this paper, an optimal configuration model including PV, WT and storage is established, which considers the economy and reliability of microgrid. In order to solve the optimization problem, the PSO algorithm is used to give the optimized daily power price and the operation plan of each part of the power grid. Finally, the practicability and rationality of this method are verified by MATLAB simulation results. The research results of this paper have reference value for the operation and optimal configuration of grid connected microgrid in East China.

For future work, some other optimization algorithms, e.g., genetic algorithm and imperial competition algorithm, will be considered. And the optimization results will be compared with those obtained by PSO to further summarize the characteristics and advantages of PSO.

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