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A Day-Ahead Energy Optimal Configuration of Islanded Microgrid

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Abstract. Microgrid can effectively utilize renewable resources and reduce fossil fuel exploitation and environmental pollution. By setting the microgrid of renewable energy sources as the research object, this paper proposes a day-ahead energy optimization method under island mode. Overall management is realized for electric energy generated by multiple renewable energy sources. Moreover, by combining with energy storage devices and power generation equipment, economic configuration of operation optimization is completed for microgrid system on the basis of particle swarm optimization algorithm under MATLAB environment.

Keywords: distributed power, economic optimization, energy management, microgrid, particle swarm optimization algorithm

1 Introduction

Energy is the important material source for human survival and continuous social progress; meanwhile, it is also the important economic pillar in the development process of national economy. Owing to the energy waste caused by large power grid and drawbacks brought about by power supply reliability, human beings have turned their eyes on microgrid. As an independent small electric power system, microgrid connects new distributed powers like wind turbine generator and photovoltaic array, traditional distributed powers like diesel generator, energy storage devices and loads; it either independently operates under island mode or runs under grid-connected mode; it is connected to a large power grid for power exchange through one or several exits [1]. Energy optimization management for microgrid is the key to microgrid studies. The main task of microgrid energy management is to reasonably dispatch various distributed powers, energy storage devices, and different kinds of loads inside the microgrid on the premise of satisfying load demand and power quality in the grid, so as to guarantee economic, safe and stable operation of the microgrid [2]. Particle swarm optimization algorithm is adopted in this paper by taking an independent microgrid structure as an example. The calculation results verify the effectiveness and practicability of microgrid model proposed in this paper and its energy optimization configurations [3].

2 Microgrid Energy and Economic Model

Microgrid energy optimization configuration is the core issue of microgrid studies. Compared with traditional thermal power, hydroelectricity and nuclear power, renewable energy sources in microgrid have characteristics like randomness, intermittency and uncontrollability. Thus it is hard to predict its output. Especially for microgrid in island operation, the system capacity is small and the ability to resist the output fluctuation of renewable energy sources is poor, so a higher requirement is raised for energy management [4].

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2.1 Output Models of Equipment Units

2.1.1 Wind turbine Generator

This paper establishes a model for wind turbine generator from the angle of energy optimization and management. The key point is to study the output power variation characteristic curve of wind turbine generator rather than its hardware structure. Common parameters of wind turbine generator include: cut-in wind speed, rated wind speed, cut-out wind speed and rated power. In this paper, a model is established for the output of wind turbine generator according to formula (1):

$$P_{WT}\begin{cases}0, v \le v_{ci} \\ av(t)^3 - bP_r, v_{ci} \le v_r \\ P_r, v_r < v < v_{co} \\ 0, v > v_{co}\end{cases} \tag{1}$$

In the formula: P_{WT} : output power; v_{ci} : cut-in speed, m/s; v_{co} : cut-out speed, m/s; v_r: rated wind speed, m/s; P_r : rated output power, kW; $a = \frac{P_r}{v_r^3 - v_{ci}^3}$ and $a = \frac{v_{ci}^3}{v_r^3 - v_{ci}^3}$.

Constraint condition: The minimum actual output power of wind turbine generator is 0 and the maximum output power is the maximum allowable output power under the corresponding wind speed.

2.1.2 Photovoltaic Array

In order to maximize the use ratio of photovoltaic array, the photovoltaic array operates at the maximum power point when maximum power point tracking technology is applied. The power characteristic can be expressed with formula (2):

$$P_{PV} = \frac{P_{STC}G_{AC}[1 + k(T_C - T_r)]}{G_{STC}} \tag{2}$$

In the formula: P_{PV} : output power; P_{STC} : the maximum test power under standard test condition (the incident intensity of solar energy is 1 kW/m2 and the environment temperature is 298.15 K); G_{AC} : illumination intensity; G_{STC} : illumination intensity under standard test condition, 1 kW/m2; k: power-to-temperature coefficient, -0.47%/K; T_C : the actual working temperature of photovoltaic array; T_r : reference temperature, 298.15 K.

2.1.3 Lead-acid Battery

The relation between the charging power P_c and discharging power P_d of lead-acid battery and state of charge can be expressed with formula (3) and formula (4) respectively [5]:

$$SOC(t) = (1-\delta)SOC(t-1) + \frac{P_c \Delta t \eta_c}{E_c} \tag{3}$$

$$SOC(t) = (1-\delta)SOC(t-1) - \frac{P_d \Delta t}{E_c \eta_d} \tag{4}$$

In the formula: $SOC(t)$: the state of charge of storage battery at the end of time frame t; $SOC(t-1)$: the state of charge of storage battery at the end of time frame t-1; δ : the self-discharging efficiency of storage battery, 0.01%/h; P_c and P_d : the charging and discharging powers of storage battery, kW; η_c and η_d : the charging and discharging efficiency of storage battery, 90%; Δt : the charging and discharging time of storage battery, h; E_c : the rated capacity of storage battery, kW·h.

Constraint condition: The maximum charge capacity and the maximum discharge capacity of lead-acid battery in each hour should not exceed 0.2 times of the rated capacity of storage battery, i.e. $-0.2E_c \le P_{Bat} \cdot 1h \le 0.2E_c$.

In order to guarantee that the storage battery has enough electric quantity used for real-time scheduling, the depth of discharge of microgrid should not be too large during optimization in advance. Therefore, the maximum depth of discharge during optimization in advance is set to 0.6. In another word, the minimum state of charge should not be lower than 0.4, i.e. $SOC \ge 0.4$.

2.1.4 Diesel Generator

Diesel generator is composed of two parts which are diesel engine and electric generator. Due to the restriction of machinery and heat, the output power of diesel generator is restrained by multiple aspects. The rated power of diesel generator refers to the maximum allowable output power of diesel engine under continuous running for 12 h, i.e. the common rated power. In addition, diesel generator has continuous power, i.e. the maximum power allowing continuous operation for a long time. Generally speaking, it is less than 80% of the rated power.

The fuel characteristic of diesel generator in the microgrid of this paper can be expressed with formula (5) [6]:

$$P_{DG} = C_1 Diesel + C_2 P_{DG-rated} \tag{5}$$

In the formula: P_{DG}: the output power of diesel generator, kW; Diesel: the oil consumption of diesel generator, L; $P_{DG-rated}$: the rated power of diesel generator, kW; C_1 and C_2: coefficients.
Constraint condition: The maximum output power during the operation of diesel generator should not exceed the rated power, i.e. $0.3P_{DG-rated} \le P_{DG} \le P_{DG-rated}$. .

2.2 Cost Models of Equipment Units

2.1.1 Fixed Investment

The initial fixed investment of microgrid is presented in Table 1.

Table 1. Initial fixed investment of microgrid (10,000 Yuan)

Designation	*Wind turbine generator*	*Photovoltaic array*	*Diesel generator*	*total*
initial outlay	100	44	6	150

The initial investment cost of distributed powers in microgrid is high, especially the investment in wind turbine generator and photovoltaic array. Generally speaking, bank loans or other financing modes are required to purchase the above devices. The fixed investment cost of every day in bank loans after conversion is:

$$Cost_{Day-invest} = \frac{1}{365} Cost_{sum} \frac{r(1+r)^Y}{(1+r)^Y - 1} \tag{6}$$

In the formula: $Cost_{sum}$: the total investment cost of power generation equipment; Y: the predicted lifetime of equipment, 13 years; r: a value related to bank loan interest rate, return on equity and debt ratio, 6.7%. By substituting data in Table 2-1 into formula (6), the fixed investment cost of every day can be gained: $Cost_{invest} = 483.4\,Yuan$.

2.1.2 Operation and Maintenance Cost of Equipment

Operation and maintenance cost exists in the operation process, and it can be expressed with formula (7).

$$M_i = K_i \cdot P_i \tag{7}$$

In the formula: M_i: the maintenance cost of equipment i, Yuan; K_i: the maintenance cost coefficient of equipment i, Yuan/kW; P_i: the output power of equipment i, kW; for storage battery, discharging power should be considered and there is no need to consider charging power.

Table 2 shows the maintenance cost coefficients of different types of equipment.

Table 2. Maintenance coefficients of different types of equipment (Yuan/kW)

Different types of equipment	Diesel generator	Wind turbine generator	Photovoltaic array	Accumulator battery
Maintenance coefficients	0.0946	0.0296	0.0096	0.0832

2.1.3 Operation and Maintenance Cost of Equipment

Fuel cost. Among all the devices, only diesel generator has fuel cost, and the fuel cost of diesel generator is as follows [7].

$$C_{DG} = \frac{k}{C_1} P_{DG} - \frac{k}{C_1} C_2 P_{DG-rated} \tag{8}$$

In the formula: C_{DG} : the fuel cost of diesel generator; k: the price of diesel oil per liter.

Environmental cost. Many distributed powers exist in microgrid. Besides fuel cost, diesel generator will also produce environmental cost. Environmental cost is composed of two parts: 1. environmental loss caused by the consumption of environmental resources; 2. penalty for pollutant emission.

$$Enviro = \sum_{i=1}^{n} (V_i + V_{pi}) \cdot Q_i \tag{9}$$

In the formula: V_i : environmental value of pollutant i, Yuan/kg; V_{pi} : penalty for the emission of pollutant i, Yuan/kg; Q_i : the emission quantity of pollutant i; n: the type of pollutant.

3 Day-ahead Optimization Mechanism

From the angle of day-ahead time, the intra-day distributed energy resource output and load are predicted. Based on this, by directing at operating cost minimization for independent microgrid, and considering technical characteristics of various generation units, optimized dispatching is realized for the intra-day starting and stopping state of diesel generator and the operating state of energy storage devices.

Optimization objective for distributed powers: Within the maximum allowable output scope of renewable energy sources, more energy should be output, the output of diesel generator must be reduced as far as possible, and the use ratio of renewable energy sources should be improved, so as to realize resource conservation and environmental protection. Optimization objective for storage battery: When the output of renewable energy sources is greater than load demand, the storage battery has enough space for energy storage to store electric quantity; when the output of distributed powers is insufficient, the storage battery should be able to supply to the load in time, the operation of diesel generator should be reduced or stopped, and insufficient utilization of storage battery must be avoided [8].

The detailed information about day-ahead optimization of microgrid is presented in Fig. 1.

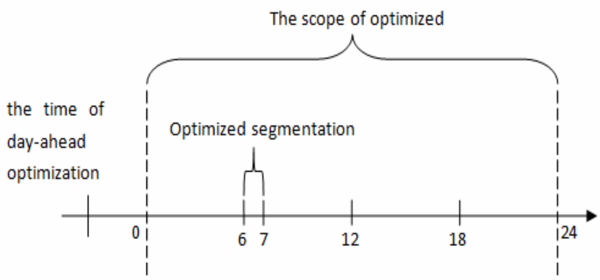

Fig. 1. Chart for day-ahead optimization of microgrid

Specifically speaking, day-ahead optimization means to divide the future day into 24 time frames (with each time frame including 1 hour) and to plan the energy dispatching situations of various equipment units in the 24 time frames. A day-ahead plan will be formulated according to the predictions about wind driven turbine, photovoltaic array and load in microgrid, so as to realize economic efficiency, environmental benefit and load satisfaction during microgrid operation.

4 Study on Day-ahead Optimization Algorithm

4.1 Particle Swarm Optimization Algorithm

The research problem about economic optimization of microgrid energy management system (i.e. the problem of economic optimization for scheduling) belongs to dynamic and multidimensional multi-input nonlinear function optimization problem. Solution of such problem has requirements in two aspects. Firstly, the global optimal solution should be searched; and secondly, a relatively high convergence rate is needed. As a multi-agent algorithm, particle swarm optimization algorithm has presented many advantages, such as strong searching ability for complex nonlinear problems, simple application, easy implementation, high accuracy, high convergence rate, and strong robustness. Therefore, it shows very strong superiority in the process of solving practical problems [9].

4.2 Analysis on Day-ahead Optimization Examples

The research content in this paper is microgrid in island operation facing renewable energy sources, and the specific structure is shown in Fig. 2.

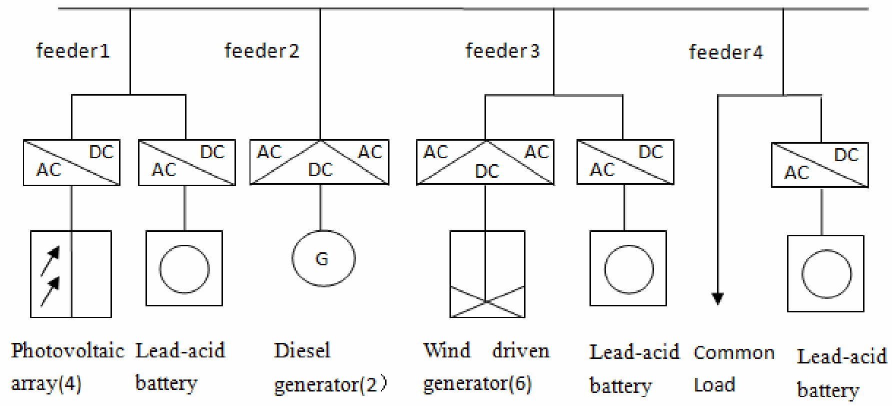

Fig. 2. Microgrid structure chart of the analysis example

4.2.1 Optimization Principle

At present, one objective will be considered in optimization: minimizing the total cost. By setting hour as the unit, the time span of optimization is 24 h.

Objective function: to minimize the operating cost

$$Fit1 = Cost_{Day-invest} + Cost_{WT} + Cost_{PV} + Cost_{DG} + Cost_{Bat} \quad \textbf{(10)}$$

In the formula, $Cost_{Day-invest}$: the everyday cost after converting the initial investment cost of generation units in microgrid; $Cost_{WT}$: the total operating cost of wind turbine generator; $Cost_{PV}$: the total operating cost of wind turbine generator; $Cost_{DG}$: the total operating cost of diesel generator; $Cost_{Bat}$: the total operating cost of storage battery.

4.2.2 Optimization Flow

The day-ahead optimization flow is as follows:

(1)Enter the predicted data about temperature, illumination intensity, wind speed and total load of the future day as well as the rated powers of diesel generators;

(2)Calculate the maximum allowable output of photovoltaic array and wind turbine generator on the future day;

(3)Enter the objective function and constraint conditions;

(4)Search results satisfying the conditions via particle swarm optimization algorithm.

4.2.3 Analysis Example

Data about temperature, illumination intensity, wind speed and total load of the future day are entered; meanwhile, the rated powers of two diesel generators (30 kW and 40 kW) are entered respectively. Fig. 3 shows the prediction curves for temperature, illumination intensity, wind speed and total load of the independent microgrid on the future day.

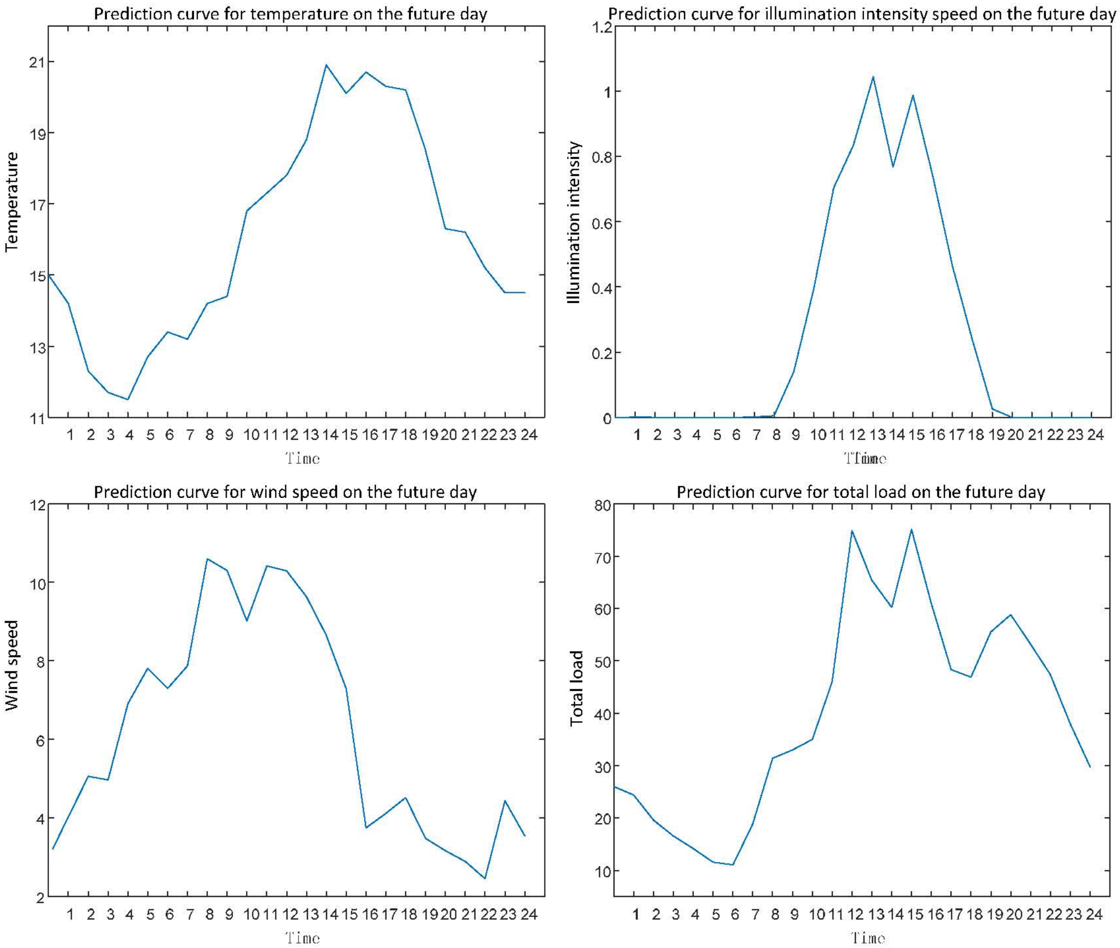

Fig. 3. Prediction curves for temperature, wind speed, illumination intensity and total load of the independent microgrid on the future day

According to temperature, illumination intensity and wind speed situations as well as photovoltaic array and wind turbine generator models, the maximum allowable outputs of photovoltaic array and wind turbine generator under corresponding conditions are calculated. Via MATLAB tool, according to the formulas, it can be gained that the daily maximum electric output of wind turbine generator is 413.61 kWh, the daily maximum electric output of photovoltaic array is 263.76 kWh, and the daily maximum allowable electric output of renewable energy sources is 677.37 kWh. The curves for daily maximum allowable output of renewable energy sources are presented in Fig. 4.

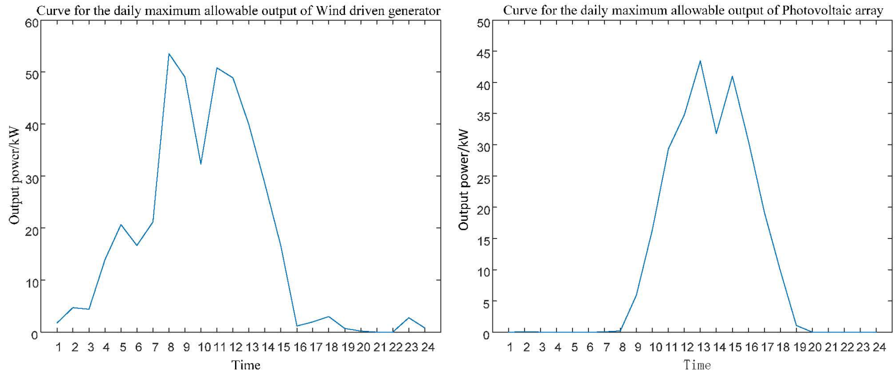

Fig. 4. Curves for the daily maximum allowable output of renewable energy sources

The objective function and constraint conditions are entered. The optimization variables of objective function are output of wind turbine generator, output of photovoltaic array, output of 2 diesel generators, power of supply load, and output of storage battery. The upper limit and lower limit of constraint are shown in Table 3.

Table 3. Constraint of various equipment units

different types of equipment	upper limit of constraint	lower limit of constraint
Wind turbine generator	Maximum allowable output power under corresponding conditions	0
Photovoltaic array	Maximum allowable output power under corresponding conditions	0
Diesel generator	rated power	0
output of storage battery	0.2 times rated capacity	-0.2 times rated capacity
remaining battery capacity	rated capacity	0.4 times rated capacity

This paper is based on the particle swarm optimization algorithm routine under MATLAB environment: a group of random particles are initialized in PSO; the optimal solution is found through continuous iteration and searching. In this paper, the number of particles is set to 50, and the global optimal solution is searched through iterative operation.

4.3 Optimization Results

In conclusion, according to the output models and cost models of various equipment units in microgrid system introduced in the above chapters, the output power configurations of various distributed generation units, energy storage devices and diesel generators in microgrid system can be gained from day-ahead optimization. The specific narration is as follows:

Charts for optimized output power of renewable energy sources are presented in Fig. 5.

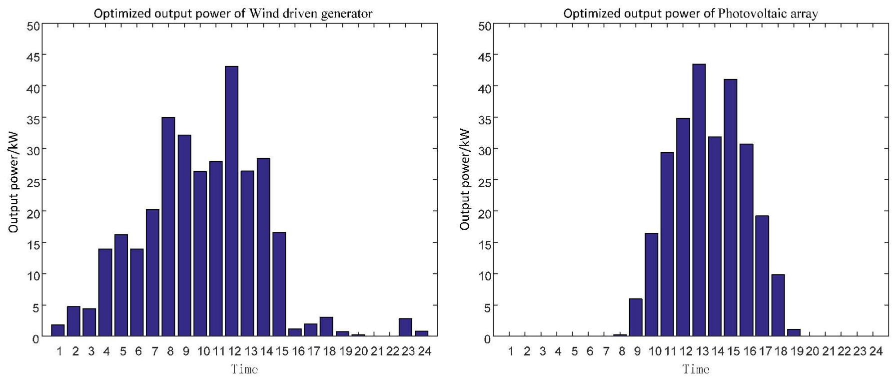

Fig. 5. Charts for optimized output power of renewable energy sources

Charts for optimized output power of renewable energy sources are presented in Fig. 6.

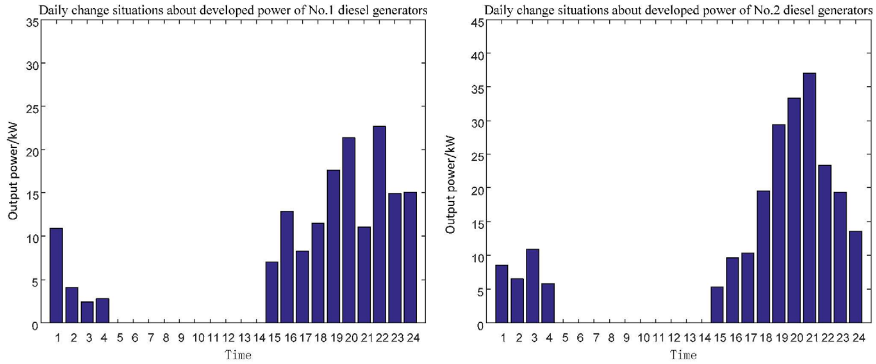

Fig. 6. Charts for daily change situations about developed power of diesel generators

Chart for charging and discharging powers of storage batteries is presented in Fig. 7.

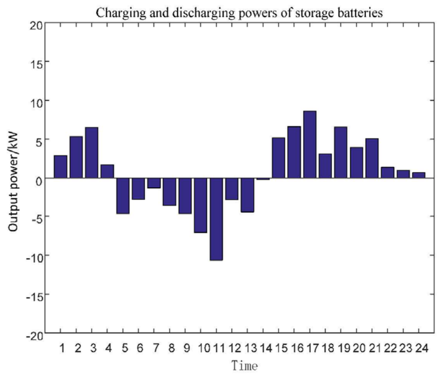

Fig. 7. Chart for charging and discharging powers of storage batteries

Chart for daily change situations about optimized output power and maximum allowable output power of wind turbine generator is presented in Fig. 8.

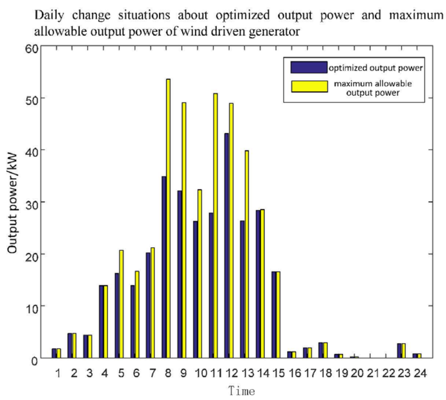

Fig. 8. Chart for daily change situations about optimized output power and maximum allowable output power of wind turbine generator

Chart for daily change situations about optimized output power and maximum allowable output power of photovoltaic array is presented in Fig. 9.

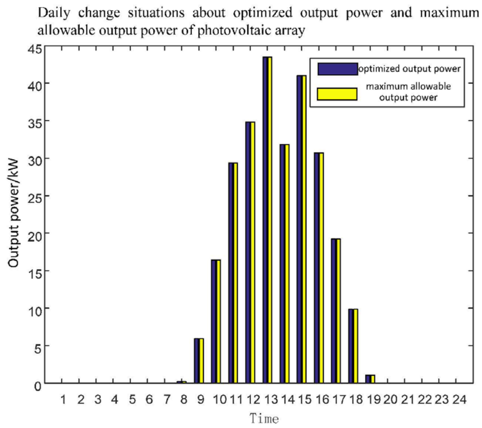

Fig. 9. Chart for daily change situations about optimized output power and maximum allowable output power of photovoltaic array

Chart for daily change situations about developed power of each diesel generator is presented in Fig. 10.

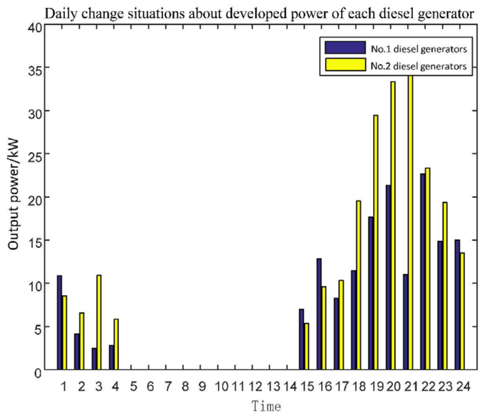

Fig. 10. Chart for daily change situations about developed power of each diesel generator

Chart for daily change situations about total output power of diesel generator is presented in Fig. 11.

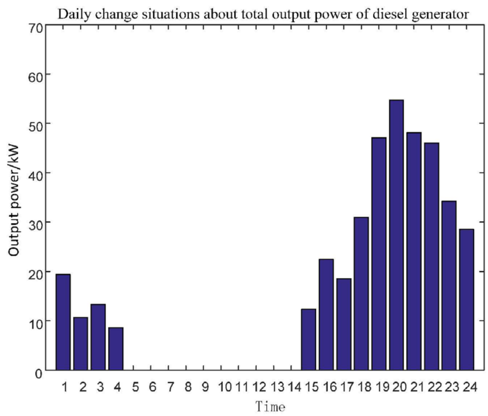

Fig. 11. Chart for daily change situations about total output power of diesel generator

Chart for daily change situations about charging and discharging powers as well as residual energy of storage battery is presented in Fig. 12.

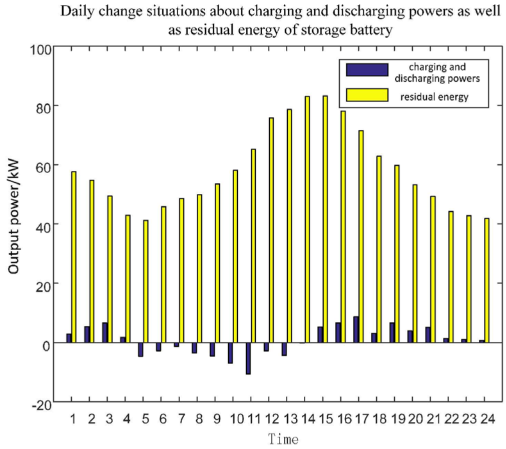

Fig. 12. Chart for daily change situations about charging and discharging powers as well as residual energy of storage battery

According to Fig. 8 and Fig. 9, from the 5th hour to the 14th hour, wind curtailment happens to wind turbine generator, and the optimized output of photovoltaic array occupies 100% of the maximum allowable output. According to the equipment models, the operating cost of photovoltaic array is lower than that of wind turbine generator. Therefore, when a choice needs to be made between wind curtailment and light curtailment, wind curtailment should be selected, so as to fully utilize photovoltaic array and reduce the operating cost.

Based on the economic optimization of implementation algorithm, the output of renewable energy sources is limited. According to Fig. 10 and Fig. 11, diesel generator cooperates with storage battery in output from the 1st hour to the 4th hour and from the 15th hour to the 24th hour, so as to meet the load demand. The powers of diesel generators are set at two grades, so as to increase the satisfaction of power load to the largest extent.

According to Fig. 7 and Fig. 12, the residual energy of storage battery approaches the lower limit at the 4th hour and 24th hour, but it does not exceed the lower limit; moreover, it reaches the peak value at the 15th hour, and there is surplus capacity in capacity limitation. Therefore, the setting of battery capacity is reasonable and it will not affect the energy storage of renewable energy sources. Besides, it will not be lower than the constraint limit and make output impossible.

Through specific examples, the author has obtained the final day-ahead optimal energy configuration results by applying particle swarm optimization algorithm. The configuration results are true, reliable and consistent with the practical situations. The optimization of microgrid energy will not only help to reduce the operating cost of microgrid but also efficiently deploy resources. This paper just starts the discussion. The author hopes to make more peers pay attention to optimal configuration of energy resources, and to promote the development of microgrid research field.

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