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Multi-Time Scale Energy Management and Optimal Dispatch Scheme for Islanded DC Microgrid Operation

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Abstract. DC microgrid has outstanding advantages in accepting new energy generation system and DC load, etc. This paper takes the islanded DC microgrid as the research object, and proposes a multi-time scale optimization scheduling scheme for the islanded DC microgrid. On the basis of satisfying the power balance of the DC bus and considering the factors of economy and environmental protection, this scheme realizes the optimized operation of the DC micro-grid under the isolated island mode. The optimization scheme consists of two stages: day-ahead scheduling and intraday scheduling. According to the short-term forecast data in advance, the day-ahead dispatching takes economic and environmental protection as the target to dispatch controllable unit. In this paper, intraday scheduling maintains the power of the battery energy storage and interruptible loads determined by day-ahead scheduling. Taking ultra-short-term prediction data as the premise, intraday scheduling takes the minimum deviation between the output power of controllable power supply and the corresponding value of day-ahead scheduling as the target to formulate scheduling scheme. Finally, an example is given to verify the feasibility of the optimized scheduling scheme by simulating the proposed program on MATLAB.

1. Introduction

In recent years, the permeability of photovoltaic (PV) and wind turbine (WT) and other new energy sources in the micro-grid has gradually increased, and the power load has diversified, so the DC micro-grid has significant advantages [1]. In many cases, the microgrid is isolated island mode, for example, the power supply in remote mountainous areas is inconvenient, the main network is disconnected due to climate reasons, and the main network is scheduled for power outage, etc. Therefore, it is very necessary to optimize the energy scheduling under isolated island operation.

At present, some references have studied the energy management of isolated island operation of micro-grid. Reference [2-4] aimed at the micro-grid system under isolated island operation mode, established the operation optimization model of isolated island micro-grid with the lowest total operation cost that can be achieved within the system dispatching cycle as the optimization goal.

Reference [5] took the variation of energy storage as a reference and cut the load according to the importance degree to ensure the reliable operation of the system. Reference [6] combined the GOSSIP distributed algorithm with the cost function of the system, and proposed the optimal scheduling method of distributed economy. References [7-8] studied the uncertainty of renewable energy forecast data. Reference [7] adopted random variables to simulate the uncertainty of forecast data. Reference [8] proposed a two-step optimal scheduling method based on power supply classification, which is based on dividing the power supply into two types: base-load power supply and frequency-modulated power supply. The above references are all about the system operation cost as the target, and more influencing factors are not considered when the system is running.

There are also some references that takes environmental factors into account. References [9-11] studied the economic cost and environmental cost of micro-grid. Reference [9] used fitting functions for wind and light energy output and load power to obtain data. Reference [10] adopted the interactive multi-objective optimization method of evaluation function. Reference [11] optimized load distribution. Reference [12] studied the energy efficiency of the cold, heat and power connection system in the isolated island operation. References [13-15] comprehensively considered the output power cost, demand side management cost and environmental governance cost of the power supply. Reference [14] studied the planned island operation mode and took the charging and discharging power of the battery as an optimization variable. Reference [15] took the minimum of flexibility insufficiency rate and operating cost as the target. Although the above references have considered the economy and environmental protection of isolated island operation of micro-grid, they have not studied the uncertainty of forecast data.

To this end, this paper proposes a multi-time scale optimal dispatch scheme for the isolated island mode of DC microgrid. Firstly, the structure of DC microgrid and the modeling of each unit are introduced. Secondly, the energy management method of system operation is introduced. It includes day-ahead scheduling and intraday scheduling. Day-ahead scheduling aims at system economy and environmental protection to schedule the operation of controllable units. Based on the day-ahead scheduling to determine the interruptible load and energy storage state, intraday scheduling aims to minimize the deviation between the output power of each controllable power source and the corresponding value of day-ahead scheduling. Finally, using the yalmip toolbox of MATLAB and calling cplex for simulation, the rationality and effectiveness of the proposed scheduling method in this paper are verified.

2. System Structure and Unit Modeling

2.1. System Structure

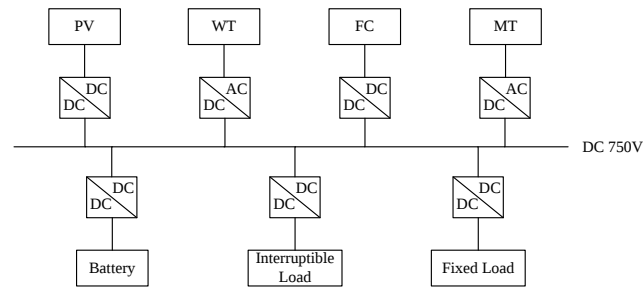


Figure 1. Structure of DC microgrid under isolated island

Figure 1 is a structure of the DC microgrid under the isolated island built in this paper. Distributed power supply is relatively rich. PV and fuel cell (FC) are connected to DC bus through DC/DC converter, WT and micro-gas turbines (MT) are connected to DC bus through AC/DC converter, and batteries are connected to DC bus through DC/DC converter. Total load (TL) includes interruptible load (IL) and fixed load (FL). The system maximizes the consumption of electricity generated by

renewable energy sources, and MT and FC serve as stable and controllable distributed power supply load.

2.2. Unit Modeling

2.2.1. PV unit model. In this paper, the PHOTOVOLTAIC power generation system works in the maximum power point tracking mode. According to the PV maximum output power under standard test conditions provided by the manufacturer, taking solar radiation intensity S and environmental temperature T as input variables, the output power of the photovoltaic power generation system is calculated as follows:

$$P_{PV} = P_m \frac{S}{S_{ref}} [1 + k_{PV}(T - T_{ref})] \quad (1)$$

P_{PV} is the actual output power of photovoltaic cells, P_m is the maximum output power of photovoltaic cells under standard test conditions, S is the actual solar radiation intensity, S_{ref} is the solar radiation intensity under standard test conditions, T is the actual battery temperature, T_{ref} is the battery temperature under standard test conditions, and k_{PV} is the power temperature coefficient.

2.2.2. WT unit model. The output power of wind power system is mainly determined by wind speed and wind energy utilization coefficient. In this paper, the generator set adopts the variable pitch control mode, and the relationship between the power and wind speed of the wind turbine is as follows:

$$P(v) = \begin{cases} 0 & v < v_{ci} \text{ or } v > v_{co} \\ \frac{P_r}{v_r^3 - v_{ci}^3} (v^3 - v_{ci}^3) & v_{ci} < v < v_r \\ P_r & v_r < v < v_{co} \end{cases} \quad (2)$$

$P(v)$ is the actual output power of wind turbine, v is the actual wind speed, v_{ci} is the input wind speed, v_r is the rated wind speed, v_{co} is the cut out wind speed, P_r is the rated output power of wind turbine.

2.2.3. FC unit model. FC adopts natural gas fuel cell. Its active power output is proportional to fuel input. The relationship between fuel cost and output power is as follows:

$$C_{fc} = \frac{C_{fuel}}{L} \sum_t \frac{P_{fc}}{\eta_{fc}} \quad (3)$$

C_{fc} is the cost of fuel cell, C_{fuel} is the price of fuel, L fuel is the low calorific value, P_{fc} is the output power of fuel cell, and η_{fc} is the power generation efficiency of the FC.

2.2.4. MT unit model. MT uses natural gas fuel for power generation, and determines the power generated by the micro-turbine according to the fuel volume. The relationship between fuel cost and output power of micro gas turbine is as follows:

$$C_{mt} = \frac{C_{fuel}}{L} \sum_t \frac{P_{mt}}{\eta_{mt}} \quad (4)$$

C_{mt} is the fuel cost of the micro-turbine, C_{fuel} is the fuel price, P_{mt} is the power produced by the micro-turbine, and η_{mt} is the power efficiency of the MT.

2.2.5. Energy storage unit model. Battery is selected as the energy storage equipment in this paper. The state of charge (SOC) of battery is as follows:

$$SOC = \frac{C_r(t)}{C_N} \times 100\% \quad (5)$$

C_r is the remaining capacity in the battery at time t , and C_N is the capacity when the battery is fully charged.

$$P_{\text{bat}}(t) = P_{\text{dis}}(t)I_{\text{dis}}(t) - P_{\text{ch}}(t)I_{\text{ch}}(t) \quad (6)$$

$P_{\text{bat}}(t)$ is the charging and discharging power of the battery at time t . $P_{\text{dis}}(t)$ is the discharge power. $I_{\text{dis}}(t)$ is an integer variable of 0-1, indicating the discharge state, 0 means no discharge, 1 means discharging. $P_{\text{ch}}(t)$ is the discharge power. $I_{\text{ch}}(t)$ is an integer variable of 0-1, indicating the charging state, 0 means no charging, and 1 means charging.

$$C_r(t) = C_r(t-1) + P_{\text{bat}}(t)\Delta t \quad (7)$$

Δt is the unit of time.

3. Energy Management Scheme of DC Microgrid under Isolated Island

The scheme includes two stages: day-ahead scheduling and intraday scheduling. According to the short-term forecast data, the operation and maintenance costs and environmental protection costs are taken as objective functions to schedule controllable units. During the intraday phase, the interruptible load and energy storage state determined the previous day remain unchanged. In combination with the ultra-short-term prediction data, the daily planned power deviation of each controllable unit is taken as the target dispatching controllable unit.

3.1. Day-ahead scheduling

3.1.1. The objective function. Taking system economy (including interruption compensation cost of interruptible load, system operation and maintenance cost) and environmental protection as the objective function, the formula is as follows:

$$\min F = \sum_{t=1}^T \left(\sum_{i=1}^N (C_i(P_i(t)) + k_i P_i(t)) + \sum_{j=1}^M (1 - I_j(t)) C_{\text{IL}j} P_{\text{IL}j}(t) + \sum_{i=1}^N \sum_{j=1}^L \alpha_j A_{ij} P_i(t) \right) \quad (8)$$

T is the scheduling cycle of the day-ahead scheduling plan, taking 1 hour as the unit time period, where $T=24$. N is the type of distributed power supply. P_i is the power generated by a distributed power supply. $C_i(P_i)$ is the fuel cost of distributed energy. k_i is the operation and maintenance cost coefficient of distributed power supply. M is the number of interruptible loads. I_j is the running state of interruptible load, with 1 for run and 0 for interrupt. $C_{\text{IL}j}$ is the compensation cost of interruptible load. $P_{\text{IL}j}$ is the predicted consumption power of interruptible load. L is the type of pollutant. α_j is the conversion coefficient of the j th pollutant. A_{ij} is the unit emission of the i th pollutant from the j th distributed power supply.

3.1.2. The constraint. The stable operation of the system needs to meet some constraints.

Power balance of the system is as follows:

$$\sum_{i=1}^N P_i(t) = P_{\text{FL}}(t) + \sum_{j=1}^M I_j(t) P_{\text{IL}j}(t) \quad (9)$$

P_{FL} is the power consumed by fixed load.

Output constraints of the controllable unit are as follows:

$$P_{\text{imin}} \leq P_i \leq (1 - E_r) P_{\text{imax}} \quad (10)$$

$$E_r = \frac{\sum_{i=1}^n \Delta P_{i,\text{max}} + \Delta P_{\text{load, max}}}{\sum_{i=1}^n P_{i,\text{max}} + P_{\text{load, max}}} \quad (11)$$

P_{imin} is the minimum output of a distributed power supply. P_{imax} is the maximum output of a distributed power supply. E_r is the error coefficient, which is determined according to short-term and ultra-short-term prediction errors of load and renewable energy. $\Delta P_{i,\text{max}}$ is the maximum difference

between short-term and ultra-short-term forecast data of renewable energy output at the same time. $P_{i,\max}$ is the maximum short-term forecast of renewable energy output. $\Delta P_{\text{load},\max}$ is the maximum difference between short-term and super-short-term forecast data of important loads at the same time. $P_{\text{load},\max}$ is the maximum value of short-term forecast of important loads.

The climbing constraints of controllable unit output are as follows:

$$|P_i(t) - P_i(t-1)| \leq \Delta P_i^{\max} \quad (12)$$

$\Delta P_i^{\max}$ is controlled unit climbing power limitation of the maximum value.

Reliability constraints of interruptible loads are as follows:

$$\sum_{t=1}^T I_j(t) P_{ILj}(t) \geq P_{ILj,\min} \quad (13)$$

$P_{ILj,\min}$ is the minimum operating power for the jth interruptible load.

The operating constraints of the energy storage unit are as follows:

$$P_{\text{bat},\min} \leq P_{\text{bat}}(t) \leq P_{\text{bat},\max} \quad (14)$$

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \quad (15)$$

$P_{\text{bat},\max}$ and $P_{\text{bat},\min}$ are the upper and lower limits of energy storage charging and discharging power respectively. $SOC_{\min}$ and $SOC_{\max}$ are the minimum and maximum values of charged state respectively.

3.2. Intraday scheduling

3.2.1. The objective function. The intraday scheduling plan keeps the interruptible load and the storage battery state determined by the day-ahead scheduling plan unchanged. According to the ultra-short-term prediction data of renewable energy and load, the intraday scheduling plan aims to minimize the deviation of output power of each controllable unit from the day-ahead scheduling. The objective function is as follows:

$$\min D = \sum_{t=1}^H \left[\left(\frac{P_{\text{fc}}(t) - P_{\text{fc}}(h)}{P_{\text{fc}}(h)} \right)^2 + \left(\frac{P_{\text{mt}}(t) - P_{\text{mt}}(h)}{P_{\text{mt}}(h)} \right)^2 \right] \quad (16)$$

Intraday scheduling takes 15min as the unit time period, where $H=96$. refers to the intraday output of fuel cell and micro gas turbine in time period T, while $P_{\text{FC}}(H)P_{\text{MT}}(h)$ refers to the day-ahead scheduling plan of fuel cell and micro gas turbine in the hour h. $P_{\text{fc}}(t)$ and $P_{\text{mt}}(t)$ are the intraday output of FC and MT in time period t, while $P_{\text{fc}}(h)$ and $P_{\text{mt}}(h)$ are the day-ahead scheduling plan of FC and MT in hour h.

3.2.2. The constraint. The stable operation of the system needs to meet some constraints.

$$P_{\text{fc}}(t) + P_{\text{mt}}(t) + P_{\text{pv}}(t) + P_{\text{wt}}(t) + P_{\text{bat}}(h) = P_{\text{FL}}(t) + \sum_{j=1}^M I_j(h) P_{ILj}(h) \quad (17)$$

$P_{\text{pv}}(t)$, $P_{\text{wt}}(t)$ and $P_{\text{FL}}(t)$ are ultra-short-term data of PV, WT and FL at time t respectively. $P_{\text{bat}}(h)$ is the charging and discharging power of the battery in the day-ahead scheduling plan. $I_j(h)$ and $P_{ILj}(h)$ are respectively the operation state and power of the interruptible load in the day-ahead scheduling plan at h hours.

$$P_{i,\min} \leq P_i(t) \leq P_{i,\max} \quad (18)$$

$$|P_i(t) - P_i(t-1)| \leq \Delta P_{i,\max} \quad (19)$$

4. The Example Analysis

The structure shown in Figure1 is used in this example. The installed photovoltaic capacity is 100kW. The installed capacity of the fan is 180kW. The charging and discharging efficiency of the battery is 90%. Relevant configuration parameters of DC micro grid are shown in Table 1-3.

Table 1. Distributed power supply parameters in the example

Distributed power supply	Upper limit of output power (kW)	Lower limit of output power (kW)	Operation and maintenance cost (yuan /kWh)
PV	100	0	0.0096
WT	180	0	0.0296
FC	120	15	0.0293
MT	200	15	0.0419
Battery	40	-40	0.0274

The compensation factor of IL1 is 0.55/kWh. The compensation factor of IL2 is 0.45/kWh. The short-term forecast data are shown in Figure 2-3.

Table 2. Parameter setting of controllable unit in the example

controlled units	Gas price (Yuan/m ³)	Low calorific value of gas (kWh/m ³)	Power generation efficiency
FC	2.05	9.7	40%
MT	2.05	9.7	28%

Table 3. Emission coefficient and translation cost of each micro-source

Pollutant type	CO ₂	SO ₂	NO _x
Cost of pollution control (Yuan/kg)	0.21	14.842	62.964
Emission factor of pollutants (g/kWh)	FC 489	0.003	0.014
	MT 724	0.0036	0.20

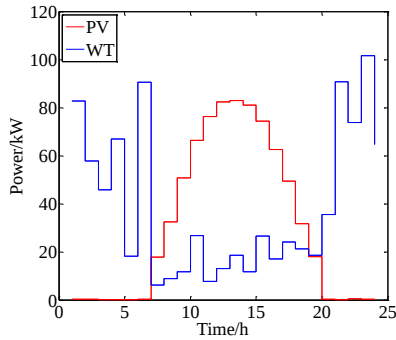


Figure 2. Short-term forecast data for PV and WT

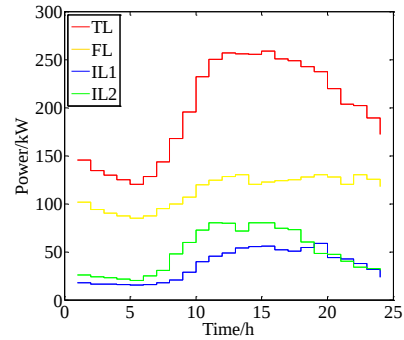


Figure 3. Short-term forecast data for FL, IL and TL

When IL participates in system operation scheduling as FL, the scheduling results of the system are shown in Figure 4-5.

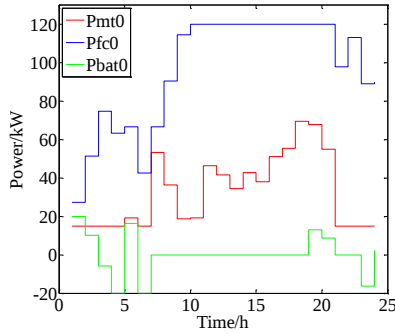


Figure 4. Scheduling results of FC, MT and battery

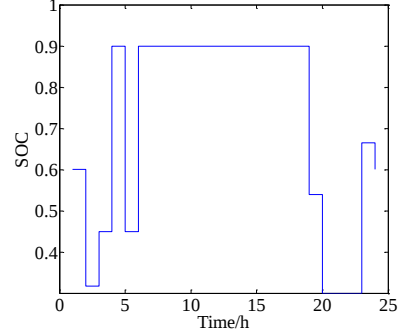


Figure 5. The state of charge of the battery

The total cost of the system is 2316.22 yuan/day, of which the economic cost is 1948.31 yuan/day and the environmental cost is 367.91 yuan/day. It can be seen from Figure 3 that the power generation of FC accounts for a large proportion, which is related to the power generation efficiency and pollution control costs of micro-sources. When the load is light, the accumulator, FC and MT jointly maintain the load demand. During the peak load period, the FC generates electricity with full capacity, and the battery neither charges nor discharges, so the MT recharges the remaining power required by the load.

After adopting the method described in the paper, the scheduling results are as follows:

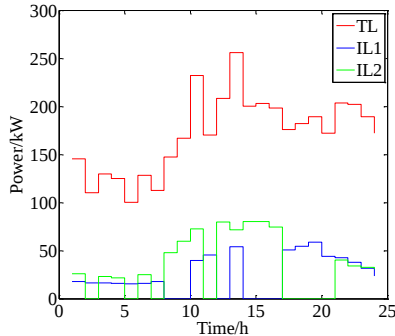


Figure 6. The IL and TL results of day-ahead scheduling

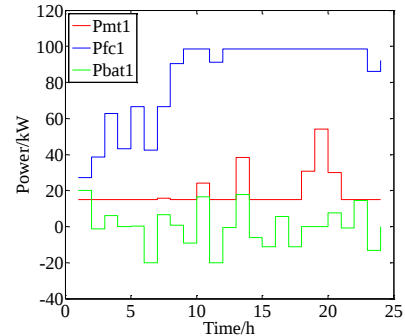


Figure 7. The FC, MT and battery results of day-ahead scheduling

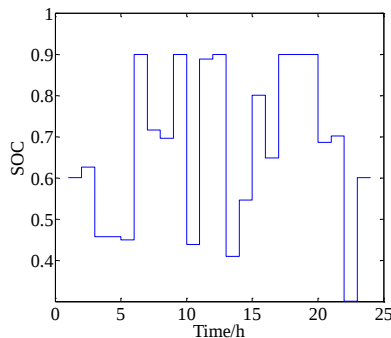


Figure 8. The state of charge of the battery of day-ahead scheduling

The day-ahead dispatching cost is 2115.22 yuan/day, among which the operation and maintenance cost is 1833.18 yuan/day and the environmental protection cost is 282.03 yuan/day. When interruptible load participates in scheduling, the operation and maintenance cost and environmental protection cost of the system are significantly reduced. The output of micro sources such as FC and MT is significantly reduced, and the battery plays a greater role in the power balance of the regulation system.

The ultra-short-term prediction data are shown in Figure 9.

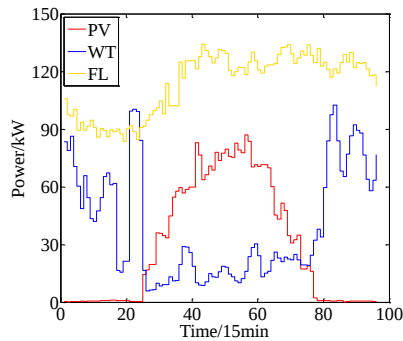


Figure 9. Ultra-short-term forecast data of microgrid

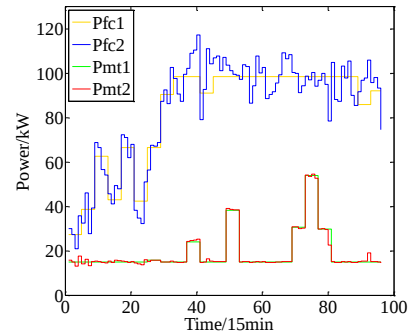


Figure 10. Comparison of the power of FC and MT during intraday scheduling and day-ahead scheduling

It can be seen from Figure 10 that the scheduling results of FC and MT of day-ahead scheduling and intraday scheduling are compared. It can be seen from Figure 10 that the fuel cell is mainly responsible for the intraday power adjustment. Due to the impact of the efficiency and pollution control cost of the micro-turbine, it assumes auxiliary functions for power fluctuation. The sample difference of power fluctuation of intraday dispatching controllable unit is 1.37. The total operating cost of the system is 2,128.99 Yuan/ day. The result of system operation shows that the scheme proposed in this paper not only improves the economy of system operation, but also increases the environmental protection.

5. Conclusion

This paper first introduces the optimal dispatch of dc microgrid under isolated island, and proposes a multi-time scale optimal dispatch scheme of DC microgrid under isolated island mode. The scheme is studied from two stages: day-ahead scheduling and intraday scheduling. The purpose of day-ahead scheduling is to optimize the operation of the system economically and environmentally. The goal of intraday scheduling is to minimize the deviation from the day-ahead scheduling plan. These two stages cooperate to achieve the goal of environmental protection and economic optimization. A numerical example verifies the feasibility and effectiveness of the proposed method.

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