Grid-connected microgrid operation strategy and aggregate load characteristics under differentiated power prices

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Abstract. In order to master the aggregated load characteristics of the grid-connected microgrid to serve the planning and operation of the distribution network, the operation strategies and aggregated load characteristics of the grid-connected microgrid under the differential power price are studied. This paper investigates the market mechanism of domestic and foreign microgrids and establishes power configuration modes for different types of microgrids. Under the current differentiated distributed power tariff, considering various power tariffs and generation costs, the output strategies and state change paths for different power scenarios are proposed. Based on this, a solution method based on adaptive immune particle swarm algorithm is presented. Through a large number of simulations, the aggregated load characteristics of the grid-connected microgrid are extracted, which provides a reference for the planning, operation and price mechanism of the microgrid and distribution network.

1. Introduction

With the depletion of fossil energy and the intensification of pollution problems, renewable energy has become one of the future development directions due to its clean and environmentally friendly characteristics. There are many types and large quantities of renewable energy, which will increase the complexity of the power grid and affect the power quality of the power grid. As a small power generation and distribution system, microgrid can integrate renewable energy, load, energy storage devices and so on, so as to improve the utilization rate of distributed energy and achieve effective distributed energy scheduling, which has gradually become the main means to solve the problem of grid connection of distributed generation. The operation mode of microgrid can be divided into island type and grid connected type. The island type needs to balance the fluctuation of frequency and voltage in real time, and it must be equipped with controllable energy or energy storage equipment with a certain capacity, which leads to high cost of the system. At present, it is difficult to promote the application. At present, the grid-connected microgrid is the main form of microgrid in China. In 2017, the National Development and Reform Commission officially issued the "Trial Measures for Promoting the Construction of Grid-connected Microgrid", which stipulates that when the grid-connected microgrid runs independently, it can guarantee continuous power supply for important loads for no less than 2 hours. Compared with the isolated island microgrid, it reduces the requirement for self-government of the microgrid. The construction and operation costs have been saved, and it has certain feasibility in our country at this stage. Because the grid-connected microgrid runs in parallel most of the time, it has a high degree of dependence on the power network. At the same time, the aggregated load characteristics of its grid-connected points present two-way uncertainty, which will also have some impact on the operation of the power network. Therefore, it is of great importance to study the operation strategy of microgrid and
the aggregated load characteristics of grid-connected points under the existing policy mechanism for the
planning, operation of distribution network at this stage and the adjustment of market mechanism in the
future.

For microgrid, its typical operation modes can be divided into three types: grid company operation
mode, user-independent operation mode and third-party operation mode, and grid-connected microgrid
is mostly the last two types. Grid-connected point aggregation load characteristic is to optimize the
exchange power between the controllable energy in the network and the distribution network according
to the changes of external electricity price mechanism, load and renewable energy. In the current
research, the objectives of microgrid economic dispatch can be divided into the least operating cost or
the most profitable. According to the structure and operation requirements of the grid-connected AC/DC
hybrid microgrid, a four-layer operation mode is proposed. Considering the daily operation costs,
including equipment maintenance costs, energy storage and converter loss costs, and purchase and sale
costs, an economic optimization model for AC/DC hybrid microgrid is established with the objective of
minimizing daily operation costs. Reference [1] considering the uncertainty of renewable energy and
load in the microgrid, a two-stage robust optimization model of Min-Max-Min structure is established.
The lowest operating cost scheduling scheme under the worst scenario is obtained, and the operating
cost increases the demand side response cost on the basis of reference [2]. Reference [3] establishes a
multi-objective optimal dispatch model considering both economic and environmental objectives, in
which the economy is the least operating cost and the depreciation cost of accumulator is also taken into
account compared with reference [4]. The environmental costs include the impact of carbon emissions
and other pollution gas emissions on the environment. In this paper, according to the current practical
power configuration of micro-grid, based on the current status of various types of distributed power
prices and operating costs, the power output strategies under different operation scenarios of grid-
connected micro-grid are studied, and through optimizing the operation data, the load characteristics of
grid-connected point aggregation are analyzed.

2. Power Composition and Power Supply Characteristics of Typical Microgrid

2.1. Internal Structure and Energy Configuration of Microgrid

2.1.1. Internal structure of microgrid
This paper chooses typical commercial microgrid for analysis. Microgrid relates to PCC of public
coupling point and substation in large power grid. The microgrid includes clean energy such as
photovoltaic power supply, gas turbine (GT) and energy storage equipment. The combined Cooling
Heating and Power (CCHP) system is composed of micro gas turbines, which can heat (cold) energy
and power simultaneously to users, thus improving energy efficiency.

2.1.2. Internal structure of microgrid
Photovoltaic arrays are composed of several photovoltaic modules through a certain connection, in
which the output power of a single photovoltaic module can be expressed as:

\[ p_s(G_s T) = p_s^N G \frac{G_s}{G_{Sr}} [1 + \eta_f (T_s - T_{Sr})] \]  

(1)

2.1.3. Energy storage battery
Energy storage can stabilize the power supply in the system and enhance the dispatch ability of
distributed power supply. The model of a storage battery is usually made up of a constant internal
resistance and a controllable voltage source \( E_b \) in series:

The controlled source \( E_b \) expression can be expressed as:
\[ E_h = E_0 - K \frac{Q}{Q - \int_0^t idt} + A \exp(-B \int_0^t idt) \]  

(2)

The above parameters can be calculated by the discharge characteristics of the energy storage battery.

2.1.4. Cogeneration of Cool, Heat and Power for Micro Gas Turbines

Based on the cogeneration system, the cogeneration system has been expanded and expanded in applications and scales. It works as shown in Figure 1.

![Figure 1 Working principle diagram of micro gas turbine](image)

Depending on the priority of demand, the system is usually divided into two operation modes, namely, heating for electricity and electricity for heat; heating for electricity means that the demand of heat load is taken as an index to meet the demand of heat first, while the demand of electricity load cannot be met, and can be supplemented by other means such as other power generating units or purchasing electricity from the power grid; Conversely, the "electrified heat" mode takes the power load demand as an index, and gives priority to meeting the power load demand, while the heat load demand cannot be met, which can be supplemented by the heat output equipment (such as boilers). The relationship between fuel consumption and output power for cogeneration units is as follows:

\[ Q_{GT} = \frac{p_e (1 - \eta_e - \eta_L)}{\eta_e} \]

(3)

\[ Q_{gr-co} = Q_{GT} \times COP_{co} \]

(4)

\[ Q_{gr-he} = Q_{GT} \times COP_{he} \]

(5)

\[ V_{GT} = \frac{\sum p_e \Delta l_i}{\eta_e \times LHV_{NG}} \]

(6)

3. Power Output Strategy and Micro electric Optimal Operation Model in Complex External Environment

Because microgrid contains users with a variety of energy needs and can operate on isolated islands, its dispatching operation must give priority to dispatching economy when parallel to the grid while meeting the internal load demand of the microgrid. In consideration of complex external market environment, microgrid economic dispatch problem not only optimizes the power dispatch strategy of distributed power microgrids inside microgrids, but also considers the impact of energy transactions with external grids on operational efficiency.

3.1. Power output strategy of typical microgrid in complex external environment

For photovoltaic batteries, there is no additional operating cost, so it is necessary to continue to exert as much power as possible to reduce the operating costs of other power sources, and overall operating costs will also be reduced. This paper assumes that photovoltaic cells do not consider abandoning light, and full power output. The operation strategy of energy storage batteries is low storage and high storage,
and the inequality constraints on the charging state of batteries should be considered. For cogeneration units, determine whether the operation can be profitable, that is, when the operation cost of cogeneration (7) is lower than that of electric heating/cooling, the unit will run, otherwise the output will stop.

\[ V_{GT}^t \lambda_{GT}^t \leq (p_{\text{heat}} + p_{\text{cool}}) \lambda_{g}^t \]  

(7)

Considering the unprofitable situation of the cogeneration system, if SOC < 80% and the current electricity price is lower than the cost of energy storage power generation, then the energy storage battery will be charged with the maximum charging power, corresponding to mode M1, when the sum of the load demand and the power consumption of the heating and cooling equipment (electric boilers, refrigerators, etc.) is less than the photovoltaic output, then the external characteristics of the microgrid and its power generation cost are as follows:

\[
\begin{align*}
    p_{eq}^i &= p_{PV}^i - p_{h-c}^i - p_{chm}^i \\
    C_{eq}^i &= \frac{1}{4} \lambda_{g}^i \cdot p_{eq}^i
\end{align*}
\]

(8)

At the same time, the cost of generating electricity from energy storage batteries increases to:

\[ \lambda_{ES}^i = \frac{1}{E_t} (\lambda_{ES}^{i-1} E_{e} + \frac{1}{4} p_{chm}^i \lambda_{g}^i) \]

(9)

Considering the unprofitable situation of the cogeneration system, if the sum of load demand and the power consumption of the cooling and heating equipment (electric boilers, refrigerators, etc.) is less than the photovoltaic output, the current electricity price is higher than the cost of energy storage power generation if the SOC is less than 80%. If there is still a margin of photovoltaic power generation in addition to meeting the power consumption requirements, this margin is used for the charging of energy storage batteries, corresponding to mode M2, in which the characteristics outside the microgrid and the cost of power generation are:

\[
\begin{align*}
    p_{eq}^i &= p_{PV}^i - p_{l}^i - \min \{p_{chm}^i, p_{PV}^i - p_{l}^i\} \\
    C_{eq}^i &= \frac{1}{4} \lambda_{g}^i \cdot p_{eq}^i
\end{align*}
\]

(10)

3.2. Optimal dispatch model for microgrid
The types of power supply in commercial microgrid mainly include photovoltaic power supply, thermoelectric cogeneration unit and energy storage device. Essentially, its optimal dispatch is to control the output of different power sources in the microgrid, to achieve the maximum benefits of the microgrid, for each moment:

\[
\begin{align*}
    \min C &= C_{co} - C_{pr} \\
    C_{co} &= \frac{1}{4} (\lambda_{ES} p_{PV}^t + \lambda_{PV} p_{PV}^t + \lambda_{GT} V_{GT}^t) \\
    C_{pr} &= \frac{1}{4} \lambda_{g}^i (p_{PV}^t + V_{GT}^t - L_{g}^t)
\end{align*}
\]

(11)

3.3. Model Solution Based on Adaptive Immune Particle Swarm Optimization
Based on the above analysis, the microgrid optimal dispatch model contains non-linear problems, and there are many dispatch operation modes, which makes it more difficult to solve the model. In order to solve complex nonlinear problems, the adaptive immune particle swarm optimization algorithm proposed in [5] is used in this paper. The algorithm is based on the evolutionary model of particle swarm optimization and uses the artificial immune mechanism as an auxiliary regulation. The introduction of immune mechanism into standard particle swarm optimization can make the population more diverse
and improve the calculation accuracy of the algorithm. In this algorithm, the optimal solution is antigen, particle is antibody, affinity is the similarity between antigen and antibody, which is optimized by immune regulation mechanism and concentration regulation mechanism.

4. Case study

4.1. Typical microgrid parameters
In this paper, a microgrid design case in Shanxi Province of China is selected to simulate and analyze the example. Typical daily load data are calculated for different weather in each season. In parallel mode, the charging and discharging of batteries are not affected by external conditions except their own performance factors, so it can be assumed that the charging and discharging of batteries are the same in different seasons and weather conditions. Among them, the load parameters and power capacity configurations of commercial microgrid are shown in Table 1.

| Table 1 Load and power capacity of commercial microgrid |
|---------------------------------------------------------|
| Electric load (MW) | Heating load (MW) | Photovoltaic capacity (MW) | Energy storage capacity (MWh/MW) | Installed capacity of CCHP (MW) |
| 3 | 1.5 | 3 | 4.8/1 | 1.5 |

Various power supply parameters are shown in Table 2, typical solar output curve of photovoltaic batteries per unit capacity is shown in Figure 2, typical daily load curve of microgrid is shown in Figure 3, and typical daily cooling and heat load curve of microgrid is shown in Figure 4. Other related data are shown in Table 2.

| Table 2 Other relevant parameters |
|----------------------------------|
| Parameter type                  | Basic data           |
| SOC constraints of energy storage battery | 20%-80% |
| Charge discharge efficiency     | 80%                  |
| Generation efficiency of gas turbine | 27%          |
| Heat loss coefficient of gas turbine | 3%          |
| Refrigeration coefficient of bromine refrigerator | 0.7 |
| Heating coefficient of bromine cooler | 0.8          |
| Heating coefficient of electric boiler | 0.8          |
| Refrigeration coefficient of electric refrigerator | 3 |
| Minimum operation time of diesel generator/h | 4           |
| Start stop cost of diesel generator/yuan | 500          |

Figure 2 Typical daily output curve of unit capacity photovoltaic cells
The example in this paper considers the time-sharing price policy, time period division and corresponding price as shown in Table 3. Table 4 is the microgrid power supply parameters in the example.

Table 3 Time of use tariff division

| Time   | Time interval | Electricity price |
|--------|---------------|-------------------|
| Peak   | 10:00-15:00   | 0.6               |
|        | 19:00-21:00   |                   |
|        | 8:00-10:00    |                   |
| Usual  | 16:00-18:00   | 0.5               |
|        | 22:00-23:00   |                   |
| Valley | 0:00-7:00     | 0.35              |

Table 4 Power supply parameters of microgrid

| Type of power supply | Installed capacity/MW | Generation cost | construction cost | Failure rate | Repair rate |
|----------------------|------------------------|-----------------|-------------------|--------------|-------------|
| Photovoltaic cell    | 3                      | 0               | 2400              | 5.0          | 24          |
4.2. Grid-connected Indicators for Microgrid
The concurrency of microgrid will bring some new features to the load characteristics of the power network, and at the same time, the planning and operation of the power network are also facing new problems. A good analysis of load characteristics of microgrid will provide decision-making basis for rational power network planning, optimal operation of power network, and optimal allocation of resources. The following are the load characteristic indicators that are often used in power network planning and operation.

Load Upper and Lower Limits: Refers to the upper and lower limits of loads that occur in a certain statistical period (such as the year, month, day, etc.) for power grids, power plants, users or electrical equipment, which can also be referred to as the upper and lower limits of loads for a statistical period. Based on the statistical cycle, it is generally divided into the upper and lower limits of annual load, the upper and lower limits of monthly load and the upper and lower limits of daily load.

Average load: The average load of a power network, power plant, user, or electrical equipment in a statistical period (e.g., month, day, etc.) that can be divided by 24 hours based on daily energy. According to different statistical periods, it can be generally divided into annual average load, monthly average load and daily average load.

Peak-valley difference: The difference between the maximum and minimum daily loads.

Typical daily load curve: represents the change trend of daily load over time in this region, can more accurately reflect the demand for power of the society, to a certain extent, can more fully reflect the characteristics of daily load in this region.

These indicators are closely related to the planning and operation of distribution network, so it is very important to select the methods to obtain these indicators.

5. Conclusion
Based on the existing power and load models, this paper takes into account the factors such as the power price on the grid, the cost of various types of power supply, the cost of charging and discharging of energy storage devices, and the operating characteristics of each distributed energy source. To maximize the daily income of microgrid, the dispatch and operation strategies of commercial microgrid are optimized. Combined with photovoltaic solar output curve and typical daily load curve, the out-of-load characteristic curves of typical microgrid under different weather conditions are obtained. On this basis, the simulation results are analyzed, and several external characteristics indicators of typical micro-grid are obtained. Finally, the influence of power price on the output external characteristics and energy output of micro-grid is analyzed, which provides data basis and theoretical support for the planning and operation of micro-grid parallel operation, and has certain application reference value.

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