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Genetic Algorithm Based Temperature-Queuing Method for Aggregated IAC Load Control

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Abstract: In recent years, demand response (DR) has played an increasingly important role in maintaining the safety, stability and economic operation of power grid. Due to the continuous running state and extremely fast speed of response, the aggregated inverter air conditioning (IAC) load is considered as the latest and most ideal object for DR. However, it is easy to cause load rebound when the aggregated IAC load participates in DR. Existing methods for controlling air conditioners to participate in DR cannot meet the following three requirements at the same time: basic DR target, load rebound suppression, and users’ comfort. Therefore, this paper has proposed a genetic algorithm based temperature-queuing control method for aggregated IAC load control, which could suppress load rebound under the premise of ensuring the DR target and take users’ comfort into account. Firstly, the model of the aggregated IAC load is established by the Monte Carlo method. Then the start and end time of DR are selected as the main solution variables. A genetic algorithm is used as the solving tool. The simulation results show that the proposed strategy shows better performance in suppressing load rebound. In the specific application scenario of adjusting the frequency fluctuation of the microgrid, the results of the case show that this strategy can effectively control the frequency fluctuation of the microgrid. The effectiveness of the strategy is verified.

Keywords: demand response; power system; smart grid; microgrid

1. Introduction

The dynamic balance between power generation and electricity consumption is critical to the safety, stability and economic operation of the power grid [1]. This is traditionally accomplished by adjusting the supply to meet the demand. Recently, there has been a growing interest in addressing these issues on the demand side by using existing resources more efficiently rather than building more supply infrastructure; this is known as demand response (DR) [2]. Moreover, interest in DR will increase as smart grids evolve into so-called energy-hub conglomerates that combine generation, storage and consumption [3]. DR refers to the behavior of power users in response to the power supply to change their inherent habitual power consumption mode to reduce or transfer the electrical load within a certain period of time. Through reasonable regulation, not only can the load peak pressure be reduced quickly, but also a variety of auxiliary services can be provided to ensure the efficiency of the power grid [4]. Compared with the construction of a power plant, the investment cost of DR is low and it has good social benefits, as well as economic benefits [5].

With the continuous development of inverter air conditioning (IAC) technology in recent years, the proportion of IAC load is gradually increasing [6]. The aggregated IAC load has heat storage capacity, which can convert electric energy into heat energy for storage within a certain time, and has no obvious impact on the human body within a certain temperature range. With the controllability, stability and continuity of operation, it has a better application prospect than other traditional loads in terms of DR. The main control
method for the aggregated IAC load to participate in DR is the direct load control (DLC) [7]. DLC is a control mode that changes the operating state of IAC by directly adjusting the setting temperature of each IAC. However, if the control strategy of the aggregated IAC load cannot be properly set, the phenomenon of load rebound will occur, which will cause a huge impact on the power grid and threaten the safe and stable operation of the power grid [8]. Therefore, it is necessary to conduct in-depth research on the control method of the aggregated IAC load.

In recent years, there have been some researches on the control strategy for air conditioning loads that participate in DR. Reference [9] focused on the compensation allocation of user participating in DR with different temperature settings, but the control method of specific users and the impact of control on power were not involved. The users’ comfort was considered in [10], but the target of DR and the impact of the load rebound were not considered. A temperature setting strategy based on NTAC (Normalized Temperature Adjustable Capacity) was proposed in [11], which could reduce power without generating rebound power. However, this method does not consider the load recovery after the end of the DR period and the users’ comfort. A DR strategy for air-conditioning to suppress load rebound was proposed in [12], but the distribution of initial temperature settings is not considered in the temperature adjustment, and the target of DR cannot be quantitatively controlled. Reference [13] proposed a VSOC (Virtual State of Charge) prioritized virtual-energy storage control strategy, which could achieve a controllable and stable power response in a short time. However, the long-term control could not be optimized. Reference [14] proposed a control strategy considering load reduction and rebound suppression based on a state-queuing model of air conditioner. However, the state-queuing model needs to recognize the real-time operating state of air conditioning. The requirements for the identification accuracy of temperature change and the delay of data transmission are too high to realize in practical application. It can be seen that these works do not consider the following issues at the same time: (1) the basic DR target; (2) the suppression of load rebound; and (3) the comfort of users’ participating in DR.

Therefore, a genetic algorithm based temperature-queuing method for aggregated IAC load control is proposed in this paper, which could suppress load rebound under the premise of ensuring the DR target, and take users’ comfort into account. A genetic algorithm is chosen as the solution tool. The contributions of this paper can be summarized as follows:

(1) It is pointed out that the start and end time of DR and the setting temperature are the main control variables. In this case, real-time monitoring of the intermediate process is no longer required during control.

(2) Under the premise of DR target, the load rebound is suppressed by staggered arrangement of the aggregated IAC load.

(3) In the algorithm optimization process, the adjustment range of setting temperature is ensured to be the smallest, and the users’ comfort is guaranteed.

The structure of this paper is shown in Figure 1. The rest of this paper is organized as follows. Section 2 introduces the model of aggregated IAC load. Section 3 establishes the temperature-queuing method and algorithm to optimize is discussed in detail. In Section 4, two case studies are shown: a basic DR scenario and a special microgrid scenario. Section 5 concludes the paper.
2. Modeling of Aggregated IAC Load

In order to study the control strategy for aggregated IAC load participating in DR, it is necessary to model the aggregated IAC load firstly. Based on the model, the further control strategy in Section 3 can be analyzed.

For individual IAC, the common modeling method is to use the equivalent thermal parameter (ETP) model [15]. Ignoring the difference of temperature between the inner and outer walls, and the difference of temperature between indoor air and solid, the first-order ETP model of the building is chosen, which is shown in Figure 2.

Thus, the indoor temperature can be represented by:

\[
T_i(t_{k+1}) = (1 - e^{-\frac{\Delta t}{C}}) \cdot (T_o(t_k) - R \cdot Q(t_k)) + e^{-\frac{\Delta t}{C}} \cdot T_i(t_k)
\]

(1)

where \(R\) is the equivalent thermal resistance, \(C\) is the equivalent thermal capacity, \(Q\) is the cooling capacity, \(t_k\) is the time \(k\), \(\Delta t\) is the simulation time step, \(T_o\) is the outdoor temperature, and \(T_i\) is the indoor temperature.

For IAC, its active power \(P\) and frequency of the compressor \(f\) are in a linear function relationship approximately, and its cooling capacity \(Q\) and frequency of the compressor \(f\) are, approximately, in a quadratic function relationship [16]:

\[
\begin{align*}
P(t_k) &= m f(t_k) + n \\
Q(t_k) &= a f^2(t_k) + b f(t_k) + c
\end{align*}
\]

(2)

where \(m\) and \(n\) are power-frequency coefficient, and \(a\), \(b\) and \(c\) are cooling capacity-frequency coefficient.

The relationship between the real-time operating frequency of the compressor and the indoor temperature is shown in the following formula [17]:

\[
f(t_k) = \begin{cases} 
  f_{\text{min}} + \frac{f_{\text{max}} - f_{\text{min}}}{2 \Delta T} \cdot (T_{\text{in}} - T_{\text{set}} + \Delta T) & T_{\text{in}} \geq T_{\text{set}} + \Delta T \\
  f_{\text{min}} & T_{\text{set}} - \Delta T \leq T_{\text{in}} < T_{\text{set}} + \Delta T \\
  0 & T_{\text{set}} - T_{\text{co}} \leq T_{\text{in}} < T_{\text{set}} - \Delta T \\
  T_{\text{in}} < T_{\text{set}} - T_{\text{co}} 
\end{cases}
\]

(3)
where $T_{\text{set}}$ is the setting temperature, $\Delta T$ is the deadband temperature, $T_{\text{co}}$ is the cut-out temperature, and $f_{\text{max}}$ and $f_{\text{min}}$ are respectively the maximum and minimum frequencies of the compressor. When the indoor temperature is too high, the compressor runs at the maximum frequency. When the indoor temperature is within the deadband of the setting temperature, the compressor frequency changes linearly with the indoor temperature. When the indoor temperature is lower than the lower limit of the deadband temperature, the compressor runs at the minimum frequency. When the indoor temperature is further lower than the cut-out temperature, the compressor stops running. The above content constitutes an individual IAC model.

For the model of aggregated IAC load, the Monte Carlo method of one-time aggregated is usually adopted. The method of one-time aggregated directly classifies the individual IACs with similar parameters in the same area (having the same outdoor temperature) into one group. The flow chart of the model of the aggregated IAC load is shown in Figure 3. First, simulate each single IAC in chronological order, and then sum the power of each IAC to obtain the aggregate power. This constitutes a complete model of the aggregated IAC load. Through this model, the DLC strategy can be given, and the reason for load rebound can be further analyzed.

Figure 3. The flow chart of the model of aggregated IAC load.

### 3. DLC Strategy of Aggregated IAC Load

#### 3.1. Analysis of Power Characteristics of Aggregated IAC Load in DR

Figure 4 shows a schematic diagram of the load rebound. The black line is the load baseline. The red line shows the load as load rebound occurs. In order to participate in a DR project at noon in summer, the setting temperature of all IACs shall be raised uniformly at the beginning of a peak load in a day ($t_2$). After the DR task is completed, the setting temperature shall be uniformly set back at the end of the peak load ($t_2$). The frequency of each compressor is increased and the total power will rise instantly.

Therefore, it can be seen that the total power of the aggregated IAC load is closely related to the setting temperature. The operating status of the aggregated IAC load is aggregated by the operating status of individual IACs, which are directly affected by the setting temperature sequence. The setting temperature sequence of the aggregated IAC load can be represented by a matrix $T$ of the following form:
where the initial operating frequency of the DR project. The initial operating frequency of the IAC compressor is increased and the total power will rise instantly.

The initial operating frequency of the i-th IAC at time j. For the i-th IAC, when not participating in the DR project, the setting temperature is kept constant while in operation, that is:

\[ T_{i,s_j} = T_{i,e_j+1} = \cdots = T_{i,e_j} = T_{i,\text{set}} \]  

where \( s_j \) and \( e_j \) are the start and end time of operation respectively, and \( T_{i,\text{set}} \) is the original setting temperature.

When participating in the DR project, the setting temperature should be increased to meet the demand of load reduction, that is:

\[ T_{i,p_i} = T_{i,p_{i+1}} = \cdots = T_{i,e_{i}} = T_{i,\text{DR}} \]  

where \( p_i \) and \( q_i \) are the start and end time of DR respectively, \( T_{i,\text{DR}} \) is the setting temperature of DR.

As can be seen from the above, the direct cause of the load rebound is the unreasonable setting of \( p_i \) and \( q_i \), while \( T_{i,\text{DR}} \) only determines the load reduction. Therefore, the determination of the DLC strategy includes two aspects. First of all, the setting temperature of each IAC in the DR period should be determined according to the specific load reduction requirements. Then, the reasonable control of \( p_i \) and \( q_i \) is considered to suppress load rebound.

3.2. Determination of the Setting Temperature

It is assumed that each IAC has entered a steady state operation state before the DR project. The initial operating frequency of the i-th IAC compressor \( f_{i,\text{set}} \) is determined by its original setting temperature \( T_{i,\text{set}} \). The initial active power can be given by:

\[ P_{i,\text{set}} = m_i f_{i,\text{set}} + n_i \]  

When participating in DR, the active power can be given by:

\[ P_{i,\text{DR}} = m_i f_{i,\text{DR}} + n_i \]  

where \( f_{i,\text{DR}} \) is the frequency of the compressor when participating in DR, which is directly determined by \( T_{i,\text{DR}} \).

The load reduction of the aggregated IAC load can be given by:

\[ \Delta P = \sum_{i=1}^{N} (P_{i,\text{set}} - P_{i,\text{DR}}) = \sum_{i=1}^{N} m_i \cdot (f_{i,\text{set}} - f_{i,\text{DR}}) \]  

Figure 4. Schematic diagram of load rebound.
where \( N \) is the number of individual IAC. Set \( \Delta P \) equal to the DR target to obtain a set of indefinite equations about \( T_{i,DR} \). In order to consider users’ comfort, each temperature setting adjustment should be as small as possible, that is, to minimize the variance of the adjustment of the setting temperature. The variance of the adjustment of the setting temperature can be given by:

\[
S^2 = \frac{\sum_{i=1}^{N} |T_{i,\text{set}} - T_{i,\text{DR}}| - \frac{\sum_{i=1}^{N} |T_{i,\text{set}} - T_{i,\text{DR}}|}{N}}{(N - 1)} \tag{10}
\]

The optimal solution of each \( T_{i,DR} \) can be obtained by minimizing \( S^2 \). The \( T_{i,DR} \) thus obtained can be used to adjust the setting temperature in a minimum range to ensure users’ comfort while ensuring the DR target.

### 3.3. A Temperature-Queuing Method to Suppress Load Rebound

After determining the DR target, DLC can be used to directly adjust the setting temperature of the aggregated IAC load to achieve load reduction. However, the general DLC method can easily cause load rebound. Therefore, it is of great significance to deeply study the control methods to suppress load rebound under the premise of ensuring the DR target.

The method of loose control for users is generally considered. In a given period of time, users can freely control their own \( p_i \) and \( q_i \), so that the DR items of each IAC are staggered in the form of random distribution. However, the problem is that the load aggregator weakens its ability to control the IAC load. The intelligent control terminal of IAC will no longer play the original control function, and may be unable to achieve the DR target as expected.

For this reason, using the temperature-queuing method should be considered to ensure that each \( p_i \) and \( q_i \) are staggered. Figure 5 shows a schematic diagram of the simplest equally spaced queuing method. The start and end times of each IAC are equidistantly arranged in a later order, so as to avoid load rebound. However, it is difficult to obtain the optimal solution of the total power curve in this way. Thus, it is necessary to adopt intelligent algorithms to solve the optimal solution of the final staggered arrangement of \( p_i \) and \( q_i \). The genetic algorithm is used to solve the problem.

A genetic algorithm mainly includes several steps of population initialization, fitness function calculation, selection, crossover and mutation. The optimization process is shown in Figure 6. The main parameters of the genetic algorithm used in this paper are shown in Table 1.
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![Figure 6. Optimization process of genetic algorithm.](image)

| Parameter           | Value |
|---------------------|-------|
| Chromosome size     | 1000  |
| Size of population  | 80    |
| Probability of crossing | 0.7  |
| Probability of mutation | 0.05 |  

It is worth noting that a large maximum number of iterations is set to ensure that a convergent optimal solution is obtained. The ETP model is used to model the IAC load which ensures that the steady-state operation process fluctuates within the dead zone temperature. The above guarantees the stability of the proposed model.

For the aggregated IAC load containing \(m\) individual IAC, the solution variables are \(p_i\) and \(q_i\) \((i = 1, 2, 3 \cdots m)\), and a chromosome can then be coded as:

\[
x = (p_1, q_1, p_2, q_2 \cdots p_m, q_m)
\]  

(11)

When setting the code value in the genetic algorithm, each \(p_i\) and \(q_i\) need to be constrained so that the DR project can be carried out within the specified time interval, which is:

\[
\begin{align*}
& \frac{\Delta P}{\Delta t} \leq k_{st} \quad (t_{st1} \leq t \leq t_{st2}) \\
& \frac{\Delta P}{\Delta t} \leq k_{ed} \quad (t_{ed1} \leq t \leq t_{ed2})
\end{align*}
\]

(12)

where \(t_{st1}\) and \(t_{st2}\) are the earliest and latest moments when DR starts, and \(t_{ed1}\) and \(t_{ed2}\) are the earliest and latest moments when DR ends.

For the final total power curve, it is expected to meet the following two basic requirements:

1. The total power should change at a certain rate at the start and end of the DR period instead of instantly dropping to the total standby power or rising to the total cooling power, corresponding to time \(t_1\) and \(t_2\) in Figure 4, which can be represented by:

\[
\begin{align*}
& \frac{\Delta P}{\Delta t} \leq k_{st} \quad (t_{st1} \leq t \leq t_{st2}) \\
& \frac{\Delta P}{\Delta t} \leq k_{ed} \quad (t_{ed1} \leq t \leq t_{ed2})
\end{align*}
\]

(13)
where $P$ is the final total power, $k_{st}$ and $k_{ed}$ are the maximum rate of change of the total power respectively at the start and end of the DR period.

2. The total power should be as close as possible to the baseline load after the end of the DR period, corresponding to the period $t_2$ to $t_3$ in Figure 4, which can be represented by:

$$\left|\frac{P(t) - P_0(t)}{P_0(t)}\right| \leq \eta (t \geq t_{ed})$$

(14)

where $P_0$ is the baseline load, $\eta$ is the rebound limit coefficient.

Fitness value is the basis for selection. The higher the fitness, the more likely the individual is to survive. The second requirement is then selected as the main fitness function of the genetic algorithm, and the first requirement is selected as the constraint.

The main function of the fitness function considering the requirement $b$ can be represented by:

$$f_1(x) = \left|\frac{P_0(t)}{P(t) - P_0(t)}\right|$$

(15)

The penalty function considering the first requirement can be represented by:

$$f_2(x) = \begin{cases} -f_1(x) & (x \in \Omega) \\ \sum \frac{\Delta t}{\Delta P} & (x \not\in \Omega) \end{cases}$$

(16)

where $\Omega$ is the range that meets the requirements.

The fitness function can be finally represented by:

$$f(x) = f_1(x) + f_2(x)$$

(17)

All of the above constitute a complete DLC strategy of aggregated IAC load to regulate the frequency of the microgrid. It can be seen from the above content that, compared with the strategy in [14], the biggest advantage of the strategy proposed in this paper is that it avoids precise identification of the operating state space. This strategy only needs to read the setting temperature data, which greatly improves the feasibility.

4. Case Study

The purpose of this section is to test the whole strategy. All models are fully implemented and simulated in MATLAB/Simulink (The MathWorks Inc., Natick, MA, USA).

4.1. Basic DR Analysis of Aggregated IAC Load

Firstly, in order to verify the basic DR strategy, the model of aggregated IAC load containing 1000 individual IACs is built. The main parameters of each IAC of the aggregated IAC load are shown in Table 2.

Table 2. Main parameters of the aggregated IAC load.

| Parameter | Description                                      | Value     |
|-----------|--------------------------------------------------|-----------|
| $R$       | Equivalent thermal resistance                    | 3.0–8.0 °C/kW |
| $C$       | Equivalent thermal capacity                      | 2500–3500 kJ/°C |
| $f_{max}$ | Maximum compressor operating frequency          | 1–10 Hz   |
| $f_{min}$ | Minimum compressor operating frequency          | 100–120 Hz |
| $P_{max}$ | Active power at $f_{max}$                        | 1.0–5.0 kW |
| $P_{min}$ | Active power at $f_{min}$                        | 10–20 W   |
| $Q_{max}$ | Cooling capacity at $f_{max}$                    | 6.0–8.5 kW |
| $Q_{min}$ | Cooling capacity at $f_{min}$                    | 30–70 W   |
| $\Delta T$| Deadband temperature                             | 0.5–0.8 °C |

A typical summer day is chosen as the date of the case. The application scenario is a typical commercial building. Assume that all IACs are used in the following scenarios:
8:30 a.m. to 9:30 a.m. is the time to start work, and each IAC is turned on randomly during this period; the off-work time is from 9:30 p.m. to 10:30 p.m., and each IAC is turned off randomly during this period. The total power of the aggregated IAC load and the outdoor temperature for that day is shown in Figure 7. This total power will be used as the load baseline. It can be seen from Figure 7 that the total power rises at a high speed in the morning, which is caused by the centralized turning on of ACs. After stable operation, the total power is positively correlated with the outdoor temperature.

![Figure 7. Total power baseline of aggregated IAC load and outdoor temperature.](image)

Consider the basic DR scenario that 800 kW of load reduction power is required at 11 a.m. After determining the DR target, the setting temperature of each IAC is determined by using the method proposed in Section 3.2. The distribution of the setting temperature before and during DR is shown in Figure 8, which is the solution with the smallest variance of change. It can be seen that the overall setting temperature increases. After calculation, the average setting temperature of each individual IAC has increased by 0.367 °C.

![Figure 8. Distribution of the setting temperature.](image)

After determining the setting temperature of each IAC, DLC can be used to directly adjust the setting temperature of each IAC to achieve load reduction. Consider using three methods for DLC to compare and analyze the control results. The first method is centralized control, that is, all IACs adjust the setting temperature at 11:00 a.m. and call back at 12:00 a.m. The second method is the equally spaced queuing method, as shown in Figure 5. The start and end times of each IAC to participate in DR are equidistantly arranged in a later order. The third method is to use the temperature-queuing method proposed in this article. Its relevant parameters are shown in Table 3. The total power curves of these three control methods in the DR period are shown in Figure 9.
Consider the basic DR scenario that 800 kW of load reduction power is required at 11 a.m. After determining the setting temperature of each IAC, DLC can be used to directly realize the DR target. The following indicators are defined:

- Maximum rebound power $P_{re}$: The maximum power above the baseline after the end of DR.
- Ratio of rebound $K_{re}$: The ratio of the maximum rebound power to the baseline at that time. The expression can be written as follows:

$$K_{re} = \frac{P_{re}}{P_0} \quad (18)$$

- Duration of rebound $T_{re}$: The duration of the rebound power exceeding the baseline.
- Duration of over-limit rebound $T_{re}$: The duration of the rebound power exceeding the rebound limit coefficient $\eta$.

After calculation, the above indicators of load curves obtained by each method are shown in Table 4. It can be seen from the indexes that the indicators of centralized control are the worst among them. Compared with the equally spaced queuing method, $P_{re}$, $K_{re}$ and $T_{re}$ under the control of the temperature-queuing method proposed in this paper are reduced by 9%, 8% and 18%, respectively. Due to the constraint function of the genetic algorithm, the power curve obtained by the temperature-queuing method does not exceed the rebound limit $\eta$.

Therefore, the DLC strategy proposed in this paper obviously suppresses load rebound on the premise of the basic DR target. In general, the effectiveness of the strategy is proved. Next, select the microgrid as a specific application scenario. Analyze the implementation effect of the strategy in the special application scenario.

### Table 3. Main parameters of the temperature-queuing method.

| Parameter | Description | Value |
|-----------|-------------|-------|
| $t_{st1}$ | Earliest moment when DR starts | 10:30 a.m. |
| $t_{st2}$ | Latest moment when DR starts | 11:30 a.m. |
| $t_{ed1}$ | Earliest moment when DR ends | 1:30 p.m. |
| $t_{ed2}$ | Latest moment when DR ends | 2:30 p.m. |
| $k_{st}$ | Power change constraint when DR starts | 30 kW/min |
| $k_{ed}$ | Power change constraint when DR ends | 30 kW/min |
| $\eta$ | Rebound limit coefficient | 0.4 |

**Figure 9.** Total power of aggregated IAC load of different methods.
Table 4. Indicators of load curves obtained by each method.

| Parameter                  | Centralized Control Method | Equally Spaced Queuing Method | Temperature-Queuing Method |
|----------------------------|----------------------------|-------------------------------|----------------------------|
| $P_c$(kW)                 | 3779                       | 1898                         | 1725                       |
| $K_{re}$                   | 2.92                       | 1.43                         | 1.32                       |
| $T_1$(min)                 | 51                         | 88                           | 72                         |
| $T_2$(min)                 | 13                         | 11                           | 0                          |

4.2. Specific Application Scenario: Microgrid Frequency Regulation

As a new form of energy organization, microgrid effectively integrates distributed power sources, energy conversion devices, loads, and monitoring and protection devices. However, due to the fluctuation and unpredictability of the output power of renewable energy and the instability of the operation of energy storage devices such as electric vehicles, the frequency fluctuation problem of the microgrid in the island operation is still very serious [18]. Therefore, adjusting the frequency fluctuation of the microgrid is considered as a specific analysis scenario.

4.2.1. Analysis of Microgrid Structure and Its Normal State Operation

The architecture of the microgrid selected for the case is shown in Figure 10. When in the island operation mode, the switch is off and the microgrid is not connected to the main grid. The microgrid is mainly composed of the wind power system, photovoltaic system, energy storage batteries and load. Each distributed power source is connected to the bus through respective power electronic converters, which are simplified and omitted in Figure 10. The load is divided into controllable load and uncontrollable load according to whether it can participate in DR. In this case, the controllable load refers to the aggregated IAC load.

![Figure 10](image_url)

Figure 10. The architecture of microgrid under the island operation mode.

This paper focuses on the control strategy of the aggregated IAC load. Therefore, in order to simplify the analysis, only wind power is selected as the representative of distributed power sources to explore the influence of wind power operation volatility on the frequency fluctuation of the microgrid. The output power of the wind power system is closely related to the wind speed. The relationship between the output power of the wind power system and the wind speed can be expressed by the following formula:

$$P_{wt} = \begin{cases} 
0 & \text{if } v < v_{ci} \\
\frac{v - v_{ci}}{v_r - v_{ci}} & \text{if } v_{ci} \leq v < v_r \\
P_r & \text{if } v_r \leq v < v_{co} \\
0 & \text{if } v \geq v_{co}
\end{cases}$$  (19)
where \( v_{ci} \) is the cut-in wind speed, \( v_r \) is the rated wind speed, and \( v_{co} \) is the cut-out wind speed. Based on these, a complete wind power system is constructed.

The number of individual IACs in the microgrid is still set to 1000, and the parameters are the same as in Section 4.1, which are shown in Table 4. The main parameters of the microgrid, except the aggregated IAC load, are shown in Table 5.

| Component                          | Parameter | Description                     | Value       |
|------------------------------------|-----------|---------------------------------|-------------|
| Wind Power System                  | \( P_{rw} \) | Rated output power of wind power system | 1700 kW     |
|                                    | \( v_{ci} \) | Cut-in wind speed               | 4 m/s       |
|                                    | \( v_r \)   | Rated wind speed                | 12 m/s      |
|                                    | \( v_{co} \) | Cut-out wind speed              | 25 m/s      |
| PV System                          | \( P_{pv} \) | Rated output power of PV system | 1000 kW     |
| Battery System                     | \( W_b \)   | Capacity of the energy storage battery | 2000 kWh   |
| Uncontrollable Load                | \( P_{L1} \) | Output of the uncontrollable load 1 | 1500 kW     |
|                                    | \( P_{L2} \) | Output of the uncontrollable load 2 | 1500 kW     |

The frequency of the microgrid mainly depends on the balance of active power in the system. Influenced by the external environment, the output of distributed power sources may fluctuate. Taking wind power as an example, load fluctuation is generally slow under normal conditions. Therefore, the frequency of the microgrid will not change significantly under normal operating conditions, and almost maintained at 50 Hz.

However, when the distributed generation device fails, or extreme weather conditions, such as a sudden change in wind speed occur, the output of the distributed power drops rapidly. At this time, it is difficult for the microgrid to quickly respond to frequency fluctuation. The microgrid may be in danger of losing stability at this time. Therefore, fast-response loads, such as the aggregated IAC load, are required to participate in DR to balance the fluctuation.

4.2.2. Determination of DR Target When Frequency Fluctuating

Suppose the case that the wind speed drops suddenly from 13 m/s to 9.5 m/s at 12 o’clock in the morning. After the simulation analysis, the wind power output instantly drops from 1700 kW to 862 kW at 12 o’clock. When there is no DR intervention, due to the power shortage on the power generation side, the system frequency first drops, and then the system frequency is restored to stability according to the droop control adjustment method. The frequency of microgrid fluctuates, as shown in Figure 11. In Figure 11, time zero represents the wind fluctuation point, which is 12 p.m. As can be seen from Figure 11, due to the shortage of wind power, the system frequency drops first, and after 16.44 s, the system frequency reaches a stable level (defined as the frequency in the range of 50 ± 0.001 Hz). The error between the system frequency and the rated frequency is up to 0.131 Hz.

![Figure 11. Frequency of microgrid when wind speed drops.](image-url)
Next, consider controlling the frequency of the microgrid through the DR of the aggregated IAC load. The first thing that needs to be done is to determine the DR target. Therefore, a hierarchical secondary control method for the aggregated IAC load participation in DR is adopted to determine the DR target. The control block diagram of the strategy is shown in Figure 12.

![Figure 12. The control block diagram of the hierarchical secondary control method.](image)

The primary control adopts the droop control method. It simulates the primary frequency regulation strategy of a traditional generator set. It is mainly used to suppress impulsive fluctuation components with a small change range and short period. Due to the advantages of a fast response and power compensation, the aggregated IAC load can quickly suppress system frequency fluctuations and improve the stability of the system. Compare the frequency of the microgrid output by the phase-locked loop with the rated frequency, and the active power can be calculated through the proportional link. Therefore, the active power output by the primary control can be expressed as:

$$\Delta P_1 = K_f(f_N - f)$$  \hspace{1cm} (20)

where $K_f$ is the coefficient of droop control, $f_N$ is the rated frequency of the microgrid, $f$ is the real-time measurement of microgrid frequency, and $\Delta P_1$ is the DR target of the primary control of the aggregated IAC load.

The secondary control simulates the frequency modulation method of the traditional generator set. The integral regulator is used for PI control in the secondary control link. It is mainly used to suppress impulsive fluctuation components with a large change range and long period. It can restore the large frequency deviation to the reference frequency or its vicinity. The active power output by the primary control can be expressed as:

$$\Delta P_2 = \frac{(f_N - f)}{sT_f}$$  \hspace{1cm} (21)

where $T_f$ is the coefficient of integral regulator.

Therefore, the total DR target of the aggregated IAC load can be expressed as:

$$\Delta P = \Delta P_1 + \Delta P_2 = K_f(f_N - f) + \frac{(f_N - f)}{sT_f}$$  \hspace{1cm} (22)

Through this method, the final DR target is calculated as 834.36 kW.

4.2.3. DR Implementation and Its Effect Analysis

After the frequency of the microgrid fluctuates, the hierarchical secondary control of the aggregated IAC load is started. After determining the DR target, DLC is used to control the aggregated IAC load and return the setting temperature to the initial temperature through the temperature-queuing method after a period of time. During this period, each
single IAC adjusts its running state respectively; Figure 13 shows the power changes of 10 IACs. The total power obtained by aggregating all 1000 IACs is shown in Figure 14.

![Power changes of 10 IACs of aggregated IAC load](image)

**Figure 13.** The power changes of 10 IACs of aggregated IAC load.

![Total power of aggregated IAC load](image)

**Figure 14.** Total power of aggregated IAC load.

Based on this, the frequency change of the microgrid is shown in Figure 15. By contrast, the adjustment result of the state-queuing method based on [14] is also shown in Figure 15.

![Frequency of microgrid under different control methods](image)

**Figure 15.** Frequency of microgrid under different control methods.

The frequency fluctuation of the microgrid and the time to stabilize in different control scenarios are shown in Table 6.

| Control Method          | Frequency Fluctuation | Time to Stabilize |
|-------------------------|-----------------------|-------------------|
| Without DR              | 0.131 Hz              | 16.4 s            |
| State-queuing method    | 0.075 Hz              | 8.24 s            |
| Temperature-queuing method | 0.056 Hz          | 7.23 s            |

**Table 6.** Parameter statistics under different control methods.
After calculation, compared with not introducing DR, the frequency fluctuation amplitude under the temperature-queuing method has been reduced by 57%, and the time to stabilize has been shortened by 56%. Compared with the state-queuing method, the frequency fluctuation amplitude and the time to stabilize are also reduced by 25% and 12% respectively, which shows that the temperature-queuing method has better performance. This proves the practicability of the method proposed in this article.

5. Conclusions

This paper proposes a temperature-queuing control method for the aggregated IAC load participating in DR. This control method can effectively suppress the load rebound on the premise of ensuring the basic DR target and take users’ comfort into account. A genetic algorithm is chosen as the solution tool. In the case study, compared with the equally spaced queuing method, the maximum rebound power, ratio and duration of the rebound controlled by the new method have reduced by 9%, 8% and 18%, respectively. The result shows that the method can more effectively reduce the impact of load rebound on the power curve. When it is applied to adjust the frequency fluctuation of the microgrid, the temperature-queuing method has also shown better performance. Compared with the state-queuing method, the frequency fluctuation amplitude and the time to stabilize are reduced by 25% and 12% respectively, which shows that the temperature-queuing method can effectively reduce the duration and amplitude of microgrid frequency fluctuation.

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