A Flexible Control Strategy of Air-Conditioning Cluster Participating in Primary Frequency Modulation

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Abstract. As renewable energy resources are gradually connected to the grid, demand response gradually develops and expands. As a response resource with a huge proportion of the load, the role of air-conditioning load is gradually being valued. The paper first describes the equivalent thermal parameter model of the air-conditioning load. Then, an air-conditioning cluster aggregation model is established based on Monte Carlo with uncertainties considered. Finally, the paper proposes a flexible trigger frequency setting method to provide a relatively consistent amount of adjustment in different situations. And the simulation proves the effectiveness of the method.

1. Introduction

With the increasing proportion of renewable energy resources in the power grid, the frequency regulation and power balance of the power grid are facing new challenges. It is difficult to deal with it only by the generation side, and the cost is also high. Therefore, the use of demand-side resources is a new way out[1]. The air-conditioning load accounts for a huge proportion of the load in the demand side. It is reported that the air-conditioning load in summer can account for 49.2% in Beijing. In addition, since the air-conditioning is a thermal energy storage load, a short-term shutdown will not have a big impact on user’s comfort[2]. Therefore, it is necessary and urgent to study how air-conditioning loads participate in grid interaction.

The first step is to establish air-conditioning models to measure the total amount of air-conditioning that can be adjusted. There have been some researches on the single model and aggregation model. Based on data-driven, linear regression is used to learn the data relationship for prediction in [3]. Through this method, the more accurate models are not needed to perform optimization. The SOC model of battery is used to simulate the air-conditioning cluster in [4], with the power limits and energy capacity expressed by SOC parameters and random exogenous. Reference [5] uses the state queueing (SQ) model to describe the aggregated thermostatically controlled loads considering the uncertainties. Based on the existed work, a new regulation capacity evaluation method is proposed in [6] with the air-conditioning switch cycle constraints considered.

Droop control is widely adopted for the air-conditionings to participate in the primary frequency modulation. Whether to act is determined by comparing the trigger frequency and monitoring the system frequency[7][8]. However, the traditional trigger frequency setting method is to set the trigger frequency...
once and keep it fixed. When the total power of the air-conditioning cluster fluctuates, the response amount provided is also different, which brings more uncertainties factors to grid dispatch.

The contribution of the paper is to evaluate the adjustable capacity of air-conditioning clusters through establishing an air-conditioning cluster aggregation model based on Monte Carlo and equivalent thermal parameter (ETP) model. And a flexible trigger frequency setting method is designed to provide a relatively consistent amount of adjustment in different situations.

The remainder of the paper is organized as follows. Chapter 2 describes the ETP model of a single air conditioner. Chapter 3 establishes the aggregation model based on Monte Carlo. Chapter 4 describes how to set the trigger frequency of the air-conditioning cluster. And Chapter 5 is the case study.

2. The equivalent thermal parameters (ETP) model

As shown in figure 1(a), the indoor temperature $T_{in}$ of the space where the air conditioner is located can be equivalently expressed by the thermal resistance $R$, the heat capacity $C$, and the outdoor temperature $T_{out}$ and the cooling power $P$. The change of $T_{in}$ can be expressed by (1)-(3), where $\Delta t$ is the interval of time $t$ and time $t+1$, $s$ indicates the ON/OFF status of the air conditioner[7].

\[
T_{in}^{t+1} = T_{out}^{t+1} - \eta PR - (T_{out}^{t+1} - \eta P R - T_{in}^{t}) \varepsilon, s = 1
\]

\[
T_{in}^{t+1} = T_{out}^{t+1} - (T_{out}^{t+1} - T_{in}^{t}) \varepsilon, s = 0
\]

\[
\varepsilon = e^{-\frac{R}{C}}
\]

According to the working principle of the air conditioner, it can be known that its ON/OFF status is constantly changing as shown in figure 1(b). When the air conditioner is ON, the indoor temperature drops and the power is equal to the rated power. When the air conditioner is OFF, the indoor temperature rises, and the power is equal to 0.

3. Air-conditioning cluster aggregation model based on Monte Carlo

3.1. Monte Carlo method

The operation of each air conditioner is an independent process. The parameters and initial state of each air conditioner are also independent and random, but there is a probability distribution about them. Based on this, this paper uses the Monte Carlo method to study the air-conditioning aggregation model. Monte Carlo method, also known as random sampling method, is a calculation method based on probability and statistics theory. The basic solution steps are as follows:

- Construct a parameter probability distribution model. If the problem studied is random, it only needs to accurately describe the random process; if the problem studied is deterministic, it needs to artificially construct a random process and probability distribution model.
• Sample based on parameter distribution. After constructing the parameter probability model, random variables are extracted from the known probability distribution, which is the basic method to realize the Monte Carlo method.

• Establish estimates. After constructing a probability model and sampling, a random variable must be determined as the solution to the problem studied.

3.2. The aggregation model of the air-conditioning cluster

Firstly, according to the ETP model of a single air conditioner described in Chapter 2, the parameters needed to establish the aggregation model are clearly defined. Secondly, the probability distribution of the above parameters is determined, and sampling is carried out according to the probability distribution. Each sampling result can act as the parameters of a single air conditioner. Finally, the operating conditions of each air conditioner are added together to obtain the aggregation characteristics of the air-conditioning cluster. For the air-conditioning cluster, its aggregate power and working status can be described by (4) and (5).

\[ s_c(t) = \frac{1}{M} \sum_{i=1}^{M} s_i(t) \]  
\[ P_{\text{con},\text{all}}(t) = \sum_{i=1}^{M} P_i(t) \cdot s_i(t) \]

where \( M \) is the number of air conditioners in the cluster, \( P_i(t) \) and \( s_i(t) \) are the rated power and ON/OFF status of air conditioner \( i \) respectively.

4. Flexible trigger frequency setting method

Suppose that the trigger frequency of the air conditioner is set to \( f_c \). That is, when the system frequency is less than trigger frequency, the air conditioner is turned off. The trigger frequency is evenly distributed in the range \([f_{c_{\text{min}}}, f_{c_{\text{max}}}]\). The upper limit is usually fixed according to frequency modulation rule. When the system frequency drops to \( f_{\text{system}} \), the air-conditioning load response is:

\[ P_{\text{response}} = P_{\text{con},\text{all}} \times \left( \frac{f_{c_{\text{max}}} - f_{\text{system}}}{f_{c_{\text{max}}} - f_{c_{\text{min}}}} \right) \]  

As shown in the figure 2, under different temperature and climatic conditions, the total amount of air-conditionings is different. If the response frequency is set between the same frequency response range, maybe it will lead to over-regulation or under-regulation. Therefore, the frequency response range must be set according to the total amount of air-conditioning to provide a relatively consistent response of the air-conditioning.

![Figure 2. Response Region](image-url)
In order to keep the air-conditioning load response consistent under various conditions, it can be obtained from (6):

\[(f_{c\text{ max}} - f_{c\text{ min}}) \propto P_{\text{con, all}}\]  

(7)

5. Case Study

5.1. Parameter setting

The parameter settings of the air-conditioning cluster are shown in table 1. In the simulation examples in this chapter, the parameters that have not been re-declared are set according to table 1.

| Parameter | Meaning | Description/Value |
|-----------|---------|-------------------|
| M         | Number of air conditioners | 10000 |
| \([T_{\text{min}}, T_{\text{max}}]\) | The upper and lower limits of indoor temperature set by the user | \([24^\circ\text{C}, 26^\circ\text{C}]\) |
| \(T_{\text{out}}\) | Outdoor temperature | 36°C |
| R         | Equivalent thermal resistance | N(3,0.2²) °C/kW |
| C         | Equivalent heat capacity | N(1.5,0.2²) kWh/°C |
| \(P_Y\)   | Rated power | N(3.5,0.2²) kW |

5.2. System frequency under different frequency response ranges

In this part, different air-conditioning load total power (p.u.) is used to characterize the different number of air-conditioning loads in working condition. The frequency response interval is set to 0.2Hz, 0.4Hz, 0.6Hz in the three scenes of air-conditioning load total power (p.u.) respectively 0.1p.u., 0.2p.u., and 0.3p.u. Simulations are performed in the three scenes respectively to demonstrate that different frequency response ranges should be set at different outdoor temperatures to obtain better frequency regulation effect. The simulation results are shown in Figure 3. Observation shows that:

- In the scene where the total power of the air-conditioning cluster is 0.1p.u., when the frequency response interval is set to 0.2Hz and 0.4Hz, the number of air-conditioning loads participating in the demand response is small, the system frequency drops significantly. When the frequency response interval is 0.6Hz, the air-conditioning loads participating in the response are the most, and the frequency modulation effect is the best.
In the scene where the total power of the air-conditioning cluster is 0.2p.u., the air-conditioning load is over-adjusted when the frequency response interval is set to 0.2Hz, and the system frequency overshoot is as high as 0.2Hz, which endangers the stability of the system. Compared with the frequency response interval of 0.4Hz, when it is 0.6Hz the overshoot is basically the same, the minimum system frequency is lower, and the air-condition load is under-adjusted. So the frequency response interval should be set to 0.4Hz.

In the scene where the total power of the air-conditioning cluster is 0.3p.u., there are too many air-conditioning loads in the open state at this time. As a result, the air-conditioning load is over-adjusted when the frequency response interval is set to 0.2Hz and 0.4Hz, and the overshoot of system frequency is large. So it should be set to 0.6 Hz.

6. Conclusion
The paper establishes a Monte Carlo-based aggregation model and proposes a trigger frequency setting method. Under different conditions of adjustable capacity, setting the trigger frequency according to the method proposed in the paper can provide a relatively consistent amount of adjustment. The simulation verifies that the method is more conducive to system frequency stability when air-conditioning cluster participates in primary frequency modulation. The paper conducts research on the cluster level. On the basis of the paper, how to set the trigger frequency of each air-conditioner in consideration of various factors will be the focus of the next stage.

Acknowledgments
This work was supported by the “Research and Demonstration Application of Key Technologies for Resource Assessment, Planning Operation, and Optimization Adjustment of Large-scale Adjustable Loads.” The program was funded by State Grid Zhejiang Electric Power Co., Ltd. under Grant 2021ZK52.
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