Secondary frequency modulation control strategy of household air-conditioning Load participating system based on K-Means clustering algorithm

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Abstract. Compared with traditional frequency modulation methods, if a reasonable control method can be adopted, load-side frequency modulation has the advantage of low cost. Air conditioning is a typical high-power household temperature-controlled load. The huge number and outstanding energy storage characteristics make it an important part of demand response and power system frequency modulation. This paper proposes a clustering and equivalent replacement method for air-conditioning load based on K-Means clustering algorithm. Based on the classification algorithm of air-conditioning load, a control strategy based on K-Means clustering algorithm for air-conditioning load participation in secondary frequency modulation of the system was proposed. Aiming at the phenomenon of "secondary peak load" in the process of load recovery in traditional control strategies, the time-sharing grouped frequency modulation control strategy is proposed. The simulation proves the effectiveness of this control strategy in eliminating the "secondary peak load" phenomenon.

1. introduction

Air conditioning is a typical high-power household temperature-controlled load. The huge number and outstanding energy storage characteristics make it an important part of demand response and power system frequency modulation[1]. However, a single air conditioner has the problems of scattered distribution and small independent response capacity. Therefore, it is necessary to establish an aggregate model of the air conditioning load group to determine the FM reserve capacity that the air conditioning load can provide in response to the system frequency modulation. Establishing a simple and effective aggregation model can also improve the efficiency of air conditioning load when participating in the system's secondary frequency modulation.

In this paper, based on the first-order air conditioning model, Monte Carlo method is used to establish air conditioning aggregation models. The control strategy of simultaneous frequency control of air conditioners with different characteristic parameters is complicated and unsuitable for implementation, and problems such as "secondary peak load" and "lack of load richness" are likely to occur when participating in system frequency modulation[2-4]. Therefore, this paper adopts K-Means clustering algorithm to reasonably cluster and equivalently substitute air conditioning load, and puts forward a frequency modulation control strategy by distinguishing the air conditioning load working state and changing the temperature setting value.
2. Physical model of single household air conditioner load

As shown in Figure 1, in this paper, the air conditioning load model uses a simplified equivalent thermal parameter model [5-6].

\[ \frac{d}{dt} C_a (T_{in}(t) - T_{out}(t)) = \frac{1}{R_1} (T_{in}(t) - T_{out}(t)) - \frac{1}{R_2} (T_{in}(t) - T_m(t)) + \eta P \]  

\[ \frac{d}{dt} C_m (T_m(t) - T_m) = \frac{1}{R_2} (T_m(t) - T_m) \]

In Formula (1) and Formula (2): \( P(kW) \): air conditioning unit power; \( \eta \): energy efficiency ratio of electric heat pump; \( \eta P \): heating/cooling power of air-conditioning unit.

The start-stop control model of a single air conditioner mainly simulates the start-stop law of the air conditioner in order to maintain a specific indoor temperature. The indoor temperature is not always at the user's temperature set point \( T_{set} \), but in the temperature range \([T_{min}, T_{max}]\) with the user's temperature set point \( T_{set} \) as the median. Only when the real-time indoor temperature \( T_{in} \) is lower than the lower limit of the indoor temperature \( T_{min} \) or higher than the upper limit of the indoor temperature \( T_{max} \), the air conditioner changes its working state, as shown in Figure 2. The indoor temperature limit \([T_{min}, T_{max}]\) expressed by \( \theta \) can be calculated as shown in the Formula (5):

\[ T_{min} = T_{set} - \frac{\theta}{2} \quad T_{max} = T_{set} + \frac{\theta}{2} \]  

In Formula (3), \( T_{min} \): lower limit of indoor temperature; \( T_{max} \): upper limit of indoor temperature; \( T_{set} \): user's temperature set point.

3. Cluster analysis of air-conditioning load based on K-Means clustering algorithm

3.1. Basic principle of K-Means clustering algorithm

Clustering algorithm is an ideal multivariate statistical technique, which mainly uses the similarity of target data objects and then classifies them. K-Means, as a representative of unsupervised clustering algorithm, has simple and effective algorithm and wide application fields features. The key characteristic parameters of the air-conditioning load can describe the temperature change law of the air-conditioning load. According to the key characteristic parameters of the air-conditioning load, random numbers are generated according to their parameter distribution, and then cluster analysis is performed. The specific clustering steps are as follows:
Step 1: Use the elbow method to determine the $k$ value of the cluster number. The core index of the elbow method is the sum of squared errors $SSE$. Calculate the $SSE$ of the load sample according to Formula (4). When the $k$ value is less than the true cluster, the value of $SSE$ will drop greatly due to the increase of $k$, and when the value of $k$ reaches the true value, the decrease of $SSE$ will suddenly decrease. As the value of $k$ increases, the sample division will become more accurate. The aggregation level of each aggregation group is higher, and the value of the sum of squared errors will gradually flatten.

$$SSE = \sum_{i=1}^{k} \sum_{j \in p \in C_i} |p - m_i|^2$$  \hspace{1cm} (4)

Step 2: When the error square sum $SSE$ of the load sample is stable, observe the $SSE-k$ curve, and the $k$ value corresponding to the point with the largest curvature is the optimal clustering number.

Step 3: Randomly select a load sample from the load sample group as the first clustering center.

Step 4: Use the standardized Euclidean distance method to calculate the distance between each load sample and the current cluster center, that is, the distance from the nearest cluster center. Assuming that the $n$-dimensional vector expression of the air-conditioning load characteristic parameters is $\left[ x_{a1}, x_{a2}, \cdots, x_{an} \right]$, then use Formula (5) to standardize the load characteristic parameters. Then use Formula (6) to calculate the distance between two feature parameter vectors.

$$x_j^* = \frac{x_{ij} - x_{ij,\text{min}}}{x_{ij,\text{max}} - x_{ij,\text{min}}}$$  \hspace{1cm} (5)

$$d_{ab} = \sqrt{\sum_{j=1}^{n} (x_{aj}^* - x_{bj}^*)^2}$$  \hspace{1cm} (6)

Step 5: Calculate the probability value that each sample point is selected as the next cluster center, and select the next cluster center through the roulette method.

Step 6: Repeat step 4 and 5 until $k$ cluster centers are selected.

Step 7: Calculate the distance between the remaining $n-k$ samples in the air-conditioning sample and the cluster center, and divide it into the cluster with the smallest distance.

Step 8: After all the samples are divided, Calculate the average value of each group of load samples again and obtain a new cluster center.

3.2. Example analysis.

Use K-Means clustering algorithm analyses on air-conditioning load. Assuming the air-conditioning load in a certain region in winter needs to participate in power system frequency modulation at 10:00-11:00 in the morning, load aggregator is required to cluster 5000 air conditioning loads in advance. Distribution of characteristic parameters of air conditioners are shown in Table 1. The air conditioner temperature setting of the agreement is 21 °C, and the outdoor temperature detected is 0 °C. The initial temperature of each air conditioner is randomly generated within the range of $[20 \ °C , \ 21 \ °C]$.

| Parameter | Parameter Description | Value |
|-----------|-----------------------|-------|
| $R$       | Equivalent thermal resistance | —— |
| $P$       | Rated power            | —— |
| $C$       | Equivalent heat capacity | —— |
| $k_R$     | $R$ bimodal normal distribution probability coefficient | 0.3 |
| $k_P$     | $P$ bimodal normal distribution probability coefficient | 0.5 |
| $\mu_R$  | $R$ bimodal normal distribution mean | $5.5^\circ C/kW$ |
\[ \mu_R, \mu_P, \mu_P, \mu_C \] 

\[ \mu_R \] \text{ bimodal normal distribution mean} \quad \text{3.5°C/kW}

\[ \mu_P \] \text{ bimodal normal distribution mean} \quad \text{2.5kW}

\[ \mu_P \] \text{ bimodal normal distribution mean} \quad \text{4.5kW}

\[ \mu_C \] \text{ lognormal distribution mean} \quad \text{0.18kWh/°C}

\[ \sigma \] \quad \sigma_R, \sigma_P, \sigma_C \quad \text{0.2}

According to the clustering step, first determine the size of the \( k \) value of the cluster center, as shown in Figure 2, which is the \( SSE-k \) curve. It can be seen from the figure that when the clustering center \( k=3 \), the curvature is the largest.

![SSE-k curve](image)

When \( k=3 \), 5000 air conditioners are divided into three groups by clustering algorithm. Then the air conditioners of each group are aggregated again, the average power of each aggregated air conditioner group is simulated. Analyze the effect of clustering and. Figure 3 shows the average power chart of the air conditioning of the cluster group.

![Average power of clustering group when \( k=3 \)](image)

In the following research content of this paper, the frequency modulation control strategy is implemented for the air conditioning load with the same or similar characteristic parameters, and the effect of frequency modulation is verified by simulation. In order to facilitate the analysis of the FM control strategy described later, as well as to better simulate and verify the FM effect, this paper proposes a method of using the characteristic parameter values of typical cluster centers to replace the characteristic parameter values of all air conditioners in the group. As the load power curve of each air conditioning load group using the equivalent substitution method has the same change trend, take the first group of temperature control load as an example, and Figure 4 is a comparison diagram of using the equivalent substitution method and not using the equivalent substitution method.
According to the analysis of Figure 5, after using the equivalent substitution method, the trend of the average power change of the clustering group is the same, and the average power value has little difference. Therefore, the air conditioning load represented by cluster center $k$ calculated by K-means algorithm can replace the air conditioning of its group. In the next chapter of the simulation of air conditioning load participating in power system frequency control strategy, substitution method can be used to analyze the control effect of frequency modulation control strategy.

4. Air conditioning loads participate in the system's secondary frequency modulation.

When the air conditioning load participates in the power system frequency modulation process, it may be required to participate in the system frequency modulation multiple times. The method of changing the temperature setting value by distinguishing the working state of the air conditioning load can not only solve the problem of "secondary peak load", but also solve the problem of "absence of richness" of the load, that is, to meet the requirement that the air conditioning load can participate in the system frequency modulation multiple times\(^7\).

Suppose the upper and lower limits of the indoor temperature change are $[T_{\text{min}}, T_{\text{max}}]$, and the upper and lower limits of the indoor temperature change after the temperature setting value is changed are $[T'_{\text{min}}, T'_{\text{max}}]$. The turn-on time and turn-off time of the air-conditioning load in a complete cycle can be obtained by using a single air-conditioning load model, and then a linearized state sequence model of the air-conditioning load can be obtained\(^8\).

According to the difference of the air conditioning load on/standby state, the temperature setting value is changed and processed. This method can solve the problem of "secondary peak load" generated when the temperature setting value is changed. The specific process is shown in Figure 5.

![Figure 4. Average power comparison chart of cluster group using substitution method.](image)

**Figure 4. Average power comparison chart of cluster group using substitution method.**

In order to verify whether the proposed method of distinguishing the working state and changing the temperature setting value can effectively solve the above problems, this section simulates the 500 air conditioners. The average rated power of the air conditioners is 2.5kW; and the average heating energy efficiency ratio is 2.0; the equivalent heat capacity is 0.18kWh/°C. The equivalent thermal...
resistance is 2°C/kW; the initial temperature of each air conditioner is randomly generated between [20°C, 22°C]; and the period of collecting the air conditioner status duration is set to 20s. When \( t=3s \), the air conditioning load group participates in the system frequency modulation for the first time, and the temperature setting value changes by 0.2°C. When the first frequency modulation is over, when \( t=10s \), the air conditioning load participates in the frequency modulation again, and the temperature setting value changes by 0.2°C again. The simulation results are shown in Figure 6 and Figure 7.

Figure 6. Load aggregation power change when the temperature setting is lowered by 0.2°C.

Figure 7. Load aggregate power change when the temperature setting is lowered again by 0.2°C.

It can be seen from Figures 7 and 8 that the load change amount of the air conditioning load during the first frequency modulation is almost the same as that of the second time. The time for the two air conditioning loads to participate in the frequency modulation can also be considered to be approximately the same. The simulation results show that the method of the temperature setting is changed by distinguishing the working state can solve the "secondary peak load" problem and ensure that the air conditioning load can participate in the system frequency modulation multiple times.

5. Time-sharing packet frequency modulation control strategy.

5.1. Frequency modulation control strategy.

Before the air-conditioning load group participates in the second frequency modulation, the load aggregator needs to obtain the power deficit and the commitment time from the superior distribution network dispatching center. The load aggregator can optimize the control of the air-conditioning load group under its jurisdiction to complete the task of superior distribution to the greatest extent.

According to the received frequency modulation task, a certain load aggregator needs to bear about \( P_{load} \) power deficit within time \( t \). There are a total of \( N_{AC} \) air-conditioning aggregation groups in its jurisdiction. Each group has preset its temperature setting value \( T_{set} \), the indoor temperature range \([T_{min}, T_{max}]\), the maximum temperature change \( \Delta T_{max} \) and the minimum temperature change \( \Delta T_{min} \). \( \Delta T_{min} \) is set according to the accuracy of the temperature controller inside the temperature-controlled load, and the minimum value of \( \Delta T_{min} \) is 0.1°C from reference [9]. According to the above variables,
it is possible to set different frequency modulation schemes for each group of air conditioning loads, that is, to change the temperature setting value of the air conditioning loads.

Suppose a certain air-conditioning aggregation group is in the heating state; the temperature setting value is 21°C; the indoor temperature upper and lower limits are [20 °C, 22 °C]; the outdoor temperature is 0 °C; and the maximum change of the temperature setting value is 1 °C. As shown in Figure 9. It can be seen that the load power change curve is close to the trapezoidal wave. In this paper, the ideal model of the load change of the air conditioning load, that is, the "trapezoid-like curve" is first established. The specific expression is:

\[
P_i(t) = \begin{cases} 
\frac{P_i}{T_{\text{load,begin}} - T_{\text{begin}}} t \cdot \frac{P_T}{T_{\text{load,begin}} - T_{\text{begin}}} \left( T_{\text{begin}} \leq t < T_{\text{load,begin}} \right) \\
\frac{P_i}{T_{\text{load,begin}} - T_{\text{begin}}} \left( T_{\text{load,begin}} \leq t < T_{\text{load,over}} \right) \\
\frac{P_i}{T_{\text{load,over}} - T_{\text{over}}} \left( T_{\text{load,over}} \leq t < T_{\text{over}} \right)
\end{cases}
\]

In the Formula (7), \( P_i(t) \) is the peak load change of the i-th load; \( T_{\text{begin}} \) is the time when the load starts to adjust the frequency; \( T_{\text{load,begin}} \) is the time when the load initially reaches the peak of the load; \( T_{\text{load,over}} \) is the time when the load reaches the upper and lower limits of the new temperature; \( T_{\text{over}} \) is the time when the load ends participating in frequency modulation. According to the trapezoid-like curves of different frequency modulation schemes of the air-conditioning load group, the value of the maximum load change \( \Delta P_{\text{load,max}} \) of each scheme of the air-conditioning load group can be estimated, and the relationship between \( \Delta P_{\text{load,max}} \) and the change \( \Delta T \) of the temperature setting value is fitted.

![Figure 8. Comparison between load trapezoid curve and actual power change curve.](image)

Based on the relationship between \( \Delta P_{\text{load,max}} \) and \( \Delta T \), the load aggregator determines the frequency modulation scheme for each group of air conditioning load according to the frequency modulation target \( P_{\text{Target}} \) and \( T_{\text{Target}} \). In the same time period, a single air conditioning load group may participate in the frequency modulation, or multiple air conditioning load groups may participate in the frequency modulation. The specific decision process of the load scheme is shown in Figure 9.
According to Figure 10, the air conditioning load at time \( t \) is:

\[
P_{\text{total}} = \sum_{i=1}^{k} P_{i,k},
\]

and \( k \) is the scheme number of group \( i \) air conditioning load. The optimal objective expression of the decision model is:

\[
\min \sum_{i=1}^{k} \left( P_{\text{target}} - P_{\text{total}} \right)^2.
\]

The simulation time for air conditioning load to participate in frequency modulation is \( t \). The priority queue is designed, and air conditioning load group \( h \) is selected to participate in frequency modulation. The maximum frequency modulation capacity \( P_{\text{total}} \) provided by each group is compared with the required frequency modulation capacity \( P_{\text{target}} \). If \( P_{\text{total}} < P_{\text{target}} \), it indicates that the frequency modulation capacity provided by the air conditioning load does not meet the demand. If \( P_{\text{total}} > P_{\text{target}} \), the air conditioning load scheme of each group needs to be adjusted. The number of schemes for each group of air conditioner to participate in frequency modulation can be multiple. When the maximum temperature setting value of air conditioner load is not exceeded, the air conditioner load group can participate in frequency modulation again after the air conditioning load group participates in frequency modulation and reaches a stable state. According to the temperature margin of each group of air conditioning load, the air conditioning load group with large temperature margin is preferred to participate in frequency modulation again.

\[
\Delta T_{i,j} = \Delta T_{i,1} + \Delta T_{i,2} + \cdots + \Delta T_{i,n}
\]

In the Formula (8), \( \Delta T_{i,j} \) represents the temperature margin of the \( i \)-th group of air-conditioning loads; \( \Delta T_{i,n} \) is the amount of change in the temperature setting value of the \( n \)-th group of air-conditioning loads participating in frequency modulation for the \( n \)-th time.

5.2. Example simulation.
Using the clustering results of 5000 air conditioners in Section 3.2, 5000 air conditioners are divided into 3 groups. The maximum temperature setting value change is 1°C; the minimum temperature setting value change is 0.2°C; and each group of air conditioners has 10 kinds of temperatures.
variation scheme. According to the temperature setting value change strategy in Section 4.2, the effect of the aggregate power change of each scheme can be simulated as shown in Figure 10, 11 and 12.

Figure 10. Group 1 load change temperature setting value aggregate power change effect diagram.

Figure 11. Group 2 load change temperature setting value aggregate power change effect diagram.

Figure 12. Group 3 load change temperature setting value aggregate power change effect diagram.

According to the change curves of the aggregated power of the air conditioners in Figures 10, 11, and 12, the "trapezoid-like curve" method can be used to obtain the maximum load cut/increment and duration provided by the three groups of air conditioner loads when executing each plan. In this paper, the most important parameters such as the maximum load change \( \Delta P_{\text{load,max}} \), the start frequency adjustment time \( T_{\text{begin}} \), the load change initial settling time \( T_{\text{load,begin}} \), the load change end stable time \( T_{\text{load,over}} \), and the end frequency modulation time \( T_{\text{over}} \) are counted. Using these parameters, the relationship between the maximum load change \( \Delta P_{\text{load,max}} \) of each scheme and the load temperature set value change \( \Delta T_{ij} \) can be fitted as shown in formula (9), (10), (11). The fitting error calculation results of each fitting curve are shown in Table 2.

\[
\Delta P_{\text{load,max}} = \begin{cases} 
2148 \times \Delta T_{1,j} + 23 \left( \Delta T_{1,j} < 0 \right) \\
1050 \times \Delta T_{1,j} + 17 \left( \Delta T_{2,j} > 0 \right) 
\end{cases}
\]  
(9)
\[
\Delta P_{\text{load,max}}^2 = \begin{cases} 
2755 \times \Delta T_{2,j} + 1.3 (\Delta T_{2,j} < 0) \\
1845 \times \Delta T_{2,j} + 3.2 (\Delta T_{2,j} > 0)
\end{cases}
\]

(10)

\[
\Delta P_{\text{load,max}}^3 = \begin{cases} 
1359 \times \Delta T_{3,j} - 3.5 (\Delta T_{3,j} < 0) \\
1034 \times \Delta T_{3,j} + 2.2 (\Delta T_{3,j} > 0)
\end{cases}
\]

(11)

### Table 2. Fitting error

| Group 1 load \((\Delta T_{1j}>0)\) | 0.0097 |
| Group 1 load \((\Delta T_{1j}<0)\) | 0.0143 |
| Group 2 load \((\Delta T_{2j}>0)\) | 0.0897 |
| Group 2 load \((\Delta T_{2j}<0)\) | 0.0256 |
| Group 3 load \((\Delta T_{3j}>0)\) | 0.0126 |
| Group 3 load \((\Delta T_{3j}<0)\) | 0.0332 |

The above simulation results show that the time-sharing group secondary frequency control strategy proposed in this paper can be achieved by ingeniously changing the temperature setting value of air conditioning load, so that multiple groups of air conditioning load can cooperate to complete the frequency modulation task. This strategy only needs to modify the temperature controller, which has strong controllability and good practical application value.

### 6. Conclusions.

This paper establishes the equivalent thermal parameter model of the first-order air conditioner, and verifies the validity of the model through simulation. The K-Means clustering algorithm is used to cluster air-conditioning loads reasonably, and the influence of air-conditioning load characteristic parameters on the clustering algorithm is analyzed. Simulation shows that the clustering effect is the best when the clustering center \(k=3\). Based on this, a method of equivalently replacing the characteristic parameters of other loads in the aggregation group with the characteristic parameters of the cluster center load is proposed, and the feasibility of the proposed equivalent replacement method is verified by means of simulation.

Aiming at the problem of multiple groups of air conditioning loads cooperating in the secondary frequency modulation of the power system, firstly, a method for distinguishing the working state and adjusting the change of the load temperature setting value is designed. This method cleverly solves the problems of "secondary peak load" and "absence of richness" caused by changing the load temperature setting value. On this basis, a time-sharing group FM control strategy was designed, and a decision model of FM schemes with different air-conditioning load groups participating in FM was established. Three clusters of air-conditioning loads obtained by clustering were used to simulate, and it was verified that the strategy can determine the frequency change time and temperature setpoint change amount of each group load each time, so as to meet the air-conditioning load required by the system when the frequency event occurs.

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