Distributed Demand Response with Multi-Type Air Conditioner Integration: A Numerical Case

Tian Gao¹, Yu Liu¹,², Yiwen Shen³, Xin Zhao¹,², Shan Gao¹,², and Xueliang Huang¹,²

¹School of Electrical Engineering, Southeast University, 2 Sipailou, Xuanwu Dist., Nanjing 210018, China
²Jiangsu Provincial Key Laboratory of Smart Grid Technology and Equipment, Nanjing 210018, China
³State Grid Nanjing Power Supply Company, 1 Aoti Street, Jianye Dist., Nanjing 210019, China

* Corresponding author: yuliu@seu.edu.cn

Abstract. Green and clean energy are increasingly becoming the top priority of global energy development, in which demand response plays an important role to improve the consumption of green energy generation and the process of energy substitution. The cluster of air-conditioning loads has great potential to participate in demand response, while different control methods and operating characteristics corresponding to different air-conditioning types will have different effects on the results of demand response. Based on the research on the load features of fixed-frequency and variable-frequency air conditioners and the characteristics of participation in demand response, through a distributed response strategy of slacked consistency, the influence of different control methods and different proportions of two types of air conditioning loads is compared and analysed through simulation cases. The results show that when the number of response users is the same, the schedulable potential of air-conditioning cluster is positively correlated with the proportion of fixed-frequency air-conditioning in the cluster.

1. Introduction
Increasing green energy production and utilization is an imminent task of energy evolution among the whole world, and also the main goal of future energy system. A key to greatly improve the consumption of new energy power generation and accelerate the process of clean energy substitution is Demand Response (DR) technology, which is a hot area in the development and reform of the current power system. Demand response emphasizes the direct participation of users in market interaction, and has the advantages of rapidness and low cost. Among the objects that can participate in DR, the residential load has the great potential, in which air-conditioning load can be the primary one [1], especially large-scale air-conditioning load clusters. During the peak hours of air-conditioning use in summer, the air-conditioning load can reach more than 40% of the total loads [2]. Besides, the air-conditioning and its working environment have a certain heat storage capacity, and the short-term shutdown has little effect on the comfort of the human body [3]. Furthermore, the response time of the air conditioner can be shorter than one minute, which can absolutely meet the requirements of participating in the peak and frequency modulation of the power system. Therefore, air-conditioning load can become an important means for user demand side management, and it is of far-reaching significance to study the demand response of large-scale air-conditioning load on peak clipping and the interactive response of distributed energy.

When large-scale air-conditioning loads participate in the demand response process, due to the large number of individuals and scattered distribution, direct control is not feasible, so an effective load aggregation model needs to be established. The air-conditioning load is a temperature-sensitive load. The k-means algorithm can be used to cluster the air-conditioning load, and the aggregation model is established based on the
second-order Equivalent Thermal Parameter (ETP) model [4]. Considering the characteristics of the dynamic
distribution of air-conditioning parameters, the aggregation model can also be established by Monte Carlo
simulation or Markov chain methods [5] to improve the accuracy of the model. The control mode used when
the air-conditioning load participates in the demand response is generally divided into centralized control and
distributed control. The hierarchical and distributed control strategy can better suppress grid voltage
fluctuations [6], and comprehensively coordinate energy storage and photovoltaic inverters to provide active
and reactive power flexibility for the power grid [7]. The controlling structure generally adopts a Load
Aggregator (LA) demand response mechanism [8], and the large-scale air-conditioning load is always used as
the Thermostatically Controlled Loads (TCLs), which are controlled by modelling based on historical load
information [9]. Moreover, the air-conditioning load and can also be combined with other adjustable loads
and resources on the residential side in the smart grid environment in order to form a residential household
integrated energy management system [10].

All the above studies have focused on the air conditioning load modelling process and the selection or
application of control modes. However, some characteristics or features of the large-scale air conditioning
load will also change the demand response process and its results, such as the type of air conditioners and
their working status, etc. Most of the existing studies focused on fixed-frequency air conditioners and their
start-stop control methods in demand response, considering their duty ratio as the main control variable [11].
However, compared with traditional fixed frequency air conditioners, variable-frequency air conditioners or
inverter air conditioners are continuously occupying the market with their advantages of comfort and power
saving [12], and load clusters of inverter air conditioners also have unique advantages in participating in
system frequency modulation, and system frequency characteristics will be more significantly improved [13].
This paper studies the different types of air-conditioning load based on the hierarchical distributed demand
response controlling structure of LAs. Combined with Paxos algorithm and distributed strategy with slacked
consistency, some cases are provided to simulate the process of fixed-frequency and variable-frequency air-
conditioning loads participating in demand response, in order to analyse and explore the influence of air-
conditioning type on the potential of air-conditioning load to participate in demand response.

2. Basic model of air conditioning load demand response

The air-conditioning load is a kind of temperature-controlled load. The modelling of the air-conditioning
load needs to consider the physical characteristics of the air-conditioning itself and the indoor and outdoor
environment. Therefore, the air conditioning load modelling is composed of the building thermodynamic
model and the air conditioning unit electromechanical transformation model [14].

2.1 Building thermodynamic model

The thermodynamic model of a house usually adopts an equivalent thermal parameter model. In order to
simplify the calculation, the temperature difference between inside and outside and the it between air and
solid can be ignored, and only the change process of indoor temperature is considered. In this paper, the first-
order equivalent thermal parameter model [15] is used, as shown in Fig. 1.

![Figure 1. The first-order equivalent thermal parameter model](image)

The model equation is shown in equation (1):

\[
\frac{dT_i}{dt} = \frac{1}{RC} T_i(t) + \frac{1}{RC} \frac{Q_{ac}(t)}{C}
\]  

(1)

Where \( T_i(t) \) is the indoor temperature at time \( t \), which unit is °C; \( R \) is the equivalent thermal resistance,
which unit is °C/W; \( C \) is the heat capacity of the indoor air, which unit is J/°C; \( Q_{ac}(t) \) is the air conditioning
cooling capacity at time \( t \), which unit is W; \( T_{out}(t) \) is the outside temperature at time \( t \), which unit is °C.

Assuming that the outdoor temperature \( T_{out}(t) \) remains constant during the period of time \( [t_i, t_{i+1}] \), and use
\( T_i(t_i) \) as the initial value to solve the Equation (1) in order to obtain the indoor temperature at time \( t_{i+1} \).
\[ T_{in}(t) = T_{out}(t) - Q_{ac}(t)R \frac{-T_{out}(t) - Q_{ac}(t)R - T_{in}(t)}{e^{-\omega/RC}} \]  

(2)

This model is suitable for both fixed-frequency air conditioners and inverter air conditioners, which two have difference in cooling capacities \( Q_{ac}(t) \).

2.2 Electromechanical transformation model of air conditioners

The electromechanical transformation model of air-conditioners describes the relationship between the air-conditioning power and the cooling (heat) quantity, that is, the energy efficiency ratio. The energy efficiency ratio of fixed frequency air conditioners is a constant value, while the it of inverter air conditioners is related to the working frequency. This paper mainly focuses on the modelling research of fixed frequency and inverter air conditioners.

2.2.1 Fixed-frequency air conditioners

The fixed-frequency air conditioner adopts a fixed-speed compressor to control ON and OFF states. When the air conditioner is working, the controller periodically controls the compressor to start and stop according to the temperature \( T_{set} \), which is set by the user, so that the room temperature is ranging in a certain threshold near \( T_{set} \). The control process is cyclical, as shown in Fig.2, where upper and lower temperature limits, \( T_{max} \) and \( T_{min} \) are respectively \( T_{set} \pm \delta \). \( \delta \) is the parameter that characterize the control accuracy of the thermostat controller.

\[ S(t) = \begin{cases} 1 & T_{in}(t) \geq T_{max} \\ 0 & T_{in}(t) \leq T_{max} \\ S(t_{k-1}) & T_{min} < T_{in}(t) < T_{max} \end{cases} \]  

(3)

Figure. 2. Working characteristics of fixed frequency air-conditioning compressor

The relationship between the indicator \( S \) and indoor temperature can be expressed as:

\[ Q_{ac}(t) = Q_{ rated}(t)S(t) \]  

(4)

Where \( Q_{ rated}(t) \) is the rated cooling capacity of the air conditioner, which unit is W.

Therefore, the relationship between the indicator \( S \) and the electric power of the air conditioner \( P_{ac}(t) \) can be expressed as:

\[ P_{ac}(t) = P_{ rated}(t)S(t) \]  

(5)

Where \( P_{ rated}(t) \) is the electric power of the air conditioner, which unit is W.

The relationship between the cooling capacity of the fixed frequency air conditioner and the electric power is:

\[ Q_{ac}(t) = \eta P_{ac}(t) \]  

(6)
Where \( \eta \) represents the energy efficiency ratio of the fixed frequency air conditioner, which is a constant value.

2.2.2 Inverter air conditioners. The inverter air conditioner uses a frequency converter to drive the compressor, and continuously controls the cooling capacity by adjusting the working frequency and changing the compressor speed [16]. As shown in Fig.3, the frequency setting is related to the difference between the actual indoor temperature and the set temperature, which can be expressed by \( \Delta T \).

\[
f = \begin{cases} 
0 & \Delta T \leq -2^\circ C \\
\frac{f_{\text{min}} + (f_{\text{max}} - f_{\text{min}}) \cdot (\Delta T - (-1))}{4} & -2^\circ C < \Delta T \leq -1^\circ C \\
\frac{f_{\text{max}}}{4} & \Delta T > 3^\circ C
\end{cases}
\]  

(7)

Where \( f_{\text{max}} \) and \( f_{\text{min}} \) respectively represent the allowable maximum and minimum operating frequencies of the inverter air conditioner.

The electrical power and cooling capacity of general inverter air conditioners are positively correlated with the compressor operating frequency. Since the specific data is related to the air conditioner model and cannot be accurately obtained, the Equation (8) is generally used in engineering to express the functional relationship between compressor frequency \( f \) and electric power \( P_{ac} \) and cooling capacity \( Q_{ac} \) [17-18]:

\[
P_{ac} = mf + n \\
Q_{ac} = af^2 + bf + c
\]

(8)

Where \( m,n,a,b,c \) are coefficients.

3. Distributed Algorithm and Slacked Consistency Control Strategy

In a distributed computing environment, solving the problems of data synchronization between nodes, distributed resource competition and autonomous recovery of single node failures are the basic guarantees for the correctness and reliability of the distributed system [19]. Paxos algorithm is a consensus algorithm based on message passing and the highly fault-tolerant feature [20,21]. This paper holds that the inconsistent state of load data in the process of power demand response will not affect the overall availability and results of the demand response system. That is, the response results are only required to meet the task from grid, and the load data in the process are not required to be of strong consistency. Therefore, a demand response-oriented distributed strategy with slacked consistency is adopted in the case simulation to reduce the adjustable power loss caused by information transmission errors in the demand response process, so that the process of demand response of different types of air conditioners such as fixed frequency and variable frequency ones can be adjusted in simulation analysis. The proposed algorithm follows:

- Each user sends two sets of load information to the system pool when participating in demand response: the load response information of the current responding user and the upper-level user;
- It is necessary to verify whether the information received from the previous user is correct each time. If correct, update the current user information according to the received information and pass it on to other
users; if the upper-level user response information in the received information has errors, it should be corrected based on the historical information and continue the response process;
• After the current user information is updated, the remaining demand needs to be judged to determine whether the response process is over.

4. Case analysis
This chapter analyses specific cases of residential air-conditioning load participation in demand response. The switch control method is adopted for the cluster of air-conditioning loads. The decision variable of the switch control is generally the switch state [22]. According to the total number of users and the proportion of different types of household air-conditioning equipment, 4 different scenarios are set up to simulate the distributed demand response process of air-conditioning load and compare the response results.

4.1 User parameter setting
The samples used in the case analysis are set as follows:
• Number the users and determine the type of air conditioner for each user according to the set ratio of fixed-frequency and inverter air conditioners. The rated power of the fixed frequency air conditioner is 1500W, and the operating power of the inverter air conditioner is determined by its operating frequency, of which the range is 30-130Hz. According to the difference between the room temperature and the set temperature, the specific operating power is calculated by combining the power and frequency function relationship obtained by the fitting;
• Determine whether each user can participate in the demand response by setting a random number from 0 to 1, and, in this way, determine the power of the individual user's air-conditioning equipment participating in the demand response to obtain the maximum adjustable capacity of the air-conditioning. The theoretical proportion of users participating in demand response is 1/2, and the response amount is calculated according to the maximum adjustable capacity;
• The priority of each user to participate in demand response is determined by setting a random number to simplify the response process;
• There may be a certain error rate in the information transmission process. In this example, the information transmission error rate is set to 0%, 5%, and 10% respectively. At the same time, it is necessary to judge whether the demand response process is over according to the remaining power shortage after the current user response.

4.2 Results of simulation
• Case 1
Assuming that the outdoor temperature is 34°C at a certain time in summer in a certain area, the demand response research on the air-conditioning load of 5000 users in a certain cell is carried out. The total response tasks issued by load aggregators are 1000kW, 3000kW and 4000kW respectively. Set the ratio of fixed frequency and inverter air conditioners to 1:1.

Table 1. Simulation results of Case 1

| Tasks (kW) | Info. error rate | Actual response volume (kW) | Number of unresponsive users | Response power shortage (kW) |
|-----------|------------------|-----------------------------|-------------------------------|-----------------------------|
| 1000      | 0%               | 999.69                      | 0                             | 0.31                        |
|           | 5%               | 998.96                      | 26                            | 1.04                        |
|           | 10%              | 998.98                      | 74                            | 1.02                        |
| 3000      | 0%               | 2998.90                     | 0                             | 1.10                        |
|           | 5%               | 2867.80                     | 131                           | 132.20                      |
|           | 10%              | 2721.40                     | 252                           | 278.60                      |
| 4000      | 0%               | 3029.00                     | 0                             | 971.00                      |
|           | 5%               | 2869.00                     | 126                           | 1131.00                     |
|           | 10%              | 2700.60                     | 264                           | 1299.40                     |
• Case 2
Assuming that the outdoor temperature in a certain area is 34°C at a certain time in summer, a demand response study is conducted on the air conditioning load of 5000 users in a certain cell. The total response tasks issued by load aggregators are 1000kW, 3000kW and 4000kW respectively. Set the ratio of fixed frequency and inverter air conditioners to 3:2.

Table 2. Simulation results of Case 2

| Tasks (kW) | Info. error rate | Actual response volume (kW) | Number of unresponsive users | Response power shortage (kW) |
|------------|------------------|----------------------------|-----------------------------|----------------------------|
| 1000       | 0%               | 998.71                     | 0                           | 1.29                       |
|            | 5%               | 999.70                     | 39                          | 0.30                       |
|            | 10%              | 999.89                     | 76                          | 0.11                       |
| 3000       | 0%               | 2999.80                    | 0                           | 0.20                       |
|            | 5%               | 2999.50                    | 112                         | 0.50                       |
|            | 10%              | 2954.00                    | 251                         | 46.00                      |
| 4000       | 0%               | 3289.20                    | 0                           | 710.80                     |
|            | 5%               | 3112.00                    | 138                         | 888.00                     |
|            | 10%              | 2965.40                    | 244                         | 1034.60                    |

• Case 3
Assuming that the outdoor temperature in a certain area is 34°C at a certain time in summer, a demand response study is carried out on the air conditioning load of 10,000 users in a certain cell. The total response tasks issued by load aggregators are 1000kW, 4000kW, 6000 kW and 8000kW. Set the ratio of fixed frequency and inverter air conditioners to 3:2.

Table 3. Simulation results of Case 3

| Tasks (kW) | Info. error rate | Actual response volume (kW) | Number of unresponsive users | Response power shortage (kW) |
|------------|------------------|----------------------------|-----------------------------|----------------------------|
| 1000       | 0%               | 999.24                     | 0                           | 0.76                       |
|            | 5%               | 999.49                     | 45                          | 0.51                       |
|            | 10%              | 999.52                     | 77                          | 0.48                       |
| 4000       | 0%               | 3998.50                    | 0                           | 1.50                       |
|            | 5%               | 3999.90                    | 182                         | 0.10                       |
|            | 10%              | 3998.90                    | 320                         | 1.10                       |
| 6000       | 0%               | 5999.40                    | 0                           | 0.60                       |
|            | 5%               | 5999.60                    | 236                         | 0.40                       |
|            | 10%              | 5765.30                    | 491                         | 234.70                     |
| 8000       | 0%               | 6405.20                    | 0                           | 1594.80                    |
|            | 5%               | 6088.10                    | 246                         | 1911.90                    |
|            | 10%              | 5799.70                    | 482                         | 2200.30                    |

4.3 Comparative analysis of demand response results

4.3.1 The influence of different number of users and tasks on response results. Comparing the results of different numbers of users responding to different power adjustment tasks when the ratio of the number of fixed-frequency and inverter air conditioners is 3:2 and the information error rate is 0, it can be easily to find that if more users respond to tasks and the task value is smaller, the success rate of demand response will go higher. The maximum response load that the air-conditioning load cluster can release is positively correlated with the number of users. The actual response when the information error rate is 0 can be approximated considered as the maximum response that users can afford. The maximum load that can be provided in
response is shown in Table 4 when 5000 and 10,000 users participate in the demand response. The simulation results under 5% and 10% error rates also conform to the rule that more users, smaller the response tasks, and higher the success rate of demand response.

Table 4. Maximum response volume of different numbers of users under the condition of 0 error rate

| Tasks (kW) | Number of users | Number of users actually response | Actual response volume (kW) |
|------------|----------------|----------------------------------|-----------------------------|
| 1000       | 5000           | 2523                             | 998.71                      |
|            | 10000          | 4963                             | 999.24                      |
| 4000       | 5000           | 2523                             | 3289.20                     |
|            | 10000          | 4963                             | 3998.50                     |

4.3.2 The influence of different ratios of fixed-frequency and inverter air conditioners on response results. Take the two sets of data in which the number of users is 5000, the response task is 3000kW, and the ratios of fixed and inverter air conditioners are 1:1 and 3:2 respectively. As shown in Table 5, when the ratio of fixed-frequency air conditioners to inverter air conditioners is 3:2, the total amount of load that users can release is greater. Under the same information transmission and load control mechanism, the response target can be better reached with a larger proportion of fixed-frequency air conditioners. It is because the fixed-frequency air conditioner operates at a fixed power of 1500W, and the inverter air conditioner power is related to its operating frequency, which is generally lower than the working frequency of the fixed-frequency air conditioner. Therefore, the fixed-frequency air conditioner can provide greater load capacity when participating in demand response, and the number of users needed to participate is correspondingly reduced.

Table 5. Demand response results with different ratios of fixed-frequency and inverter air conditioners

| Info. error rate | Type Ratios | Meet the demand | Actual response volume (kW) | Number of unresponsive users |
|------------------|-------------|-----------------|-----------------------------|------------------------------|
| 0%               | 1:1         | Yes             | 2998.90                     | 0                            |
|                  | 3:2         | Yes             | 2999.80                     | 0                            |
| 5%               | 1:1         | No              | 2867.80                     | 131                          |
|                  | 3:2         | Yes             | 2999.50                     | 112                          |

5. Conclusion
The research in this paper shows that different control methods and operating characteristics corresponding to different air-conditioning types will have different effects on the results of demand response. This paper combines the distributed control strategy with slacked consistency to simulate the process of air-conditioning load participating in demand response under different control scenarios. By analysing the data, it can be known that the success of the demand response is related to the total load capacity of the air-conditioning cluster, and the schedulable potential of the cluster is positively related to the proportion of fixed-frequency air-conditioning in the cluster. Fixed frequency air conditioners have the advantages of low manufacturing cost and convenient maintenance. Large-scale load clusters with high proportion of fixed frequency air conditioners are more suitable for participating in the demand response process. The current research on the demand response characteristics of cluster air conditioners still lacks practical experience. In the further research, the characteristics of different air conditioners and their proportions should be more actually considered. It is of great practical significance that more detailed and targeted demand response control methods of air conditioning loads should be considered as well.

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6. References
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