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Demand-Response-Oriented Load Aggregation Scheduling Optimization Strategy for Inverter Air Conditioner

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Abstract: In recent years, the peak–valley differences in urban power loads have been increasing. It is difficult to maintain the real-time balance of a power system by relying solely on the generation-side resources. As a typical flexible load, an air conditioning load can balance the supply and demand of a power grid by adjusting power using the thermal inertia of buildings. From the perspective of a load aggregator, this study models and aggregates the dispatch of a single inverter air conditioner distributed in a region to determine the adjustment potential of an air conditioning cluster. Then, according to the demand response capacity requirements, an optimal strategy for the aggregate dispatch of an inverter air conditioner considering incentive compensation measures is proposed with the objective of maximizing the load quotient economic benefit. The sensitivity analysis of the compensation factor for temperature rise is also performed. The results show that 3000 inverter air conditioners in the load quotient dispatch area participate in the demand response for 4 h, with a load reduction of 1.267 MW and a net income of RMB 14,435.97. Secondly, an increase in the temperature rise compensation factor will reduce the cost of temperature rise compensation by the loader to the user, but it will also reduce the load reduction and the net income of the loader. This study has practical significance for load aggregators to formulate compensation strategies and improve the economic benefits of participating in demand response.

Keywords: demand response; inverter air conditioner; regulatory potential; load control aggregation model; air conditioning load; control strategy; demand response; energy consumption; potential evaluation

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1. Introduction

In recent years, with the rapid development of China's economy, the load of the power grid has increased year by year, resulting in insufficient energy supply during the summer peak, especially in developed regions. In addition, the air conditioning load accounts for the largest proportion in the summer peak period. For example, in Beijing and Shanghai, the air conditioning load accounts for 50% of the electricity in the summer peak period and will continue to increase [1]. In addition, the grid-connected capacity of new energy sources such as distributed generation [2] and photovoltaic and wind power is increasing continuously. The revolutionary development of renewable energy and the wide integration of wind power generation have brought challenges to the management and operation of the electricity system due to limited regulation, high randomness, and uncertainty [3].

Power regulation has become possible. Flexible loads such as air conditioning load [4], water heater load [5], and electric vehicle load [6] can provide auxiliary services such as frequency modulation [7], voltage modulation [8], and standby mode [9] to help power systems maintain power balance [10] by adjusting power consumption or transferring time periods. As a typical flexible load, air conditioning load, on the one hand, can use building thermal inertia to adjust power while guaranteeing user comfort. On the other hand, flexible loads have a large volume. The demand response potential is huge, and through reasonable regulation, peak regulation can be effectively achieved [11]. In recent years, this has become a research hotspot in the field of demand response.

Unlike large industrial and commercial air conditioning loads, when civil air conditioning loads participate in demand-side response, a large number of distributed “micro” air conditioning loads need to be aggregated to represent a cluster of controllable load resources. In the demand response market environment, a load aggregator can participate in market declaration as an agent of a variable frequency air conditioning load.

The scheduling and control of an air conditioning load depend on the hardware support of smart grid technology. Load aggregators can directly perceive the status of a user air conditioning load (such as room temperature and start-up status) and control user air conditioning through smart technology. Advanced metering infrastructure (AMI) [12] in a smart grid has a complete set of hardware systems, which can use smart meters and two-way communication networks to acquire time-scaled or real-time (quasi-real-time) measurements of end power users with time scales and transmit them to the measurement data management system. These systems can also switch on and off terminal power devices remotely or locally [13].

Demand response (DR) is an effective strategy to stabilize load fluctuation and reduce peaks and valleys [14]. The responsiveness of a single user cannot meet the market threshold for participating in DR projects. However, the overall response potential is huge. From the perspective of system scheduling, the load aggregator (LA) can integrate users’ DR resources through professional technical means and provide them to independent system operators (ISO), thus providing users with DR participation opportunities [15].

As shown in Figure 1, the flow of an inverter air conditioner (IA) load participating in demand response is as follows: (1) the power network dispatch sends market information within demand response days to load aggregators, including demand response time periods and required reductions; (2) the load aggregator evaluates the adjustment potential of the inverter air conditioner cluster according to the duration of demand response, and reports and quotes the market within the demand response day; (3) the power network dispatching carries out market clearing according to the quotation of the load aggregator and sends the clearing result to the load aggregator; (4) the load aggregator optimizes the control of the inverter air conditioner load through frequency control according to market volume.

In the existing research, the air conditioning load that participates in demand response is mainly fixed-frequency air conditioning, mostly for the start–stop control of fixed-frequency air conditioning, and the duty–cycle ratio is the control variable. Compared with traditional fixed-frequency air conditioning, the inverter air conditioner has become the mainstream product type, with its advantages of comfort and power saving. Therefore, it is necessary to study the demand response of the inverter air conditioner load. An inverter air conditioner adjusts the speed of the compressor through a frequency converter. The compressor power accounts for more than 80% of the air conditioning operation power [16]. The adjustment of the air conditioning load is actually the adjustment of the compressor load [17], so its control strategy is different from fixed-frequency air conditioning. For modeling, the virtual energy storage model of an inverter air conditioner is built in [18,19], and the quantitative evaluation model of user comfort is built in [19]. Secondly, based on parameter identification [20], Monte Carlo simulation [21], or Markov chain [22], a large number of characteristic distributed air conditioning loads are aggregated to achieve the overall adjustment of the air conditioning group. Specific demand response means of air conditioning loads mainly include load transfer, direct load reduction, and load suspension. Document [23] studies the feedback control of a distributed air conditioning load to provide fast demand response assistance services. Document [24] designed a simple target quantity parameterized aggregation controller and achieved good results in Australia. Document [25] predicted the controllable capacity of an ideal air conditioning load under direct load control and put forward a dispatch plan of double-layer optimal control. In the application scenario, the studies [26–28] help power system peak, frequency, pressure, and wind power fluctuation by adjusting the inverter air conditioner. Document [29] used active response and passive response control methods to apply frequency regulation and the absorption of power fluctuation of tie lines, respectively.

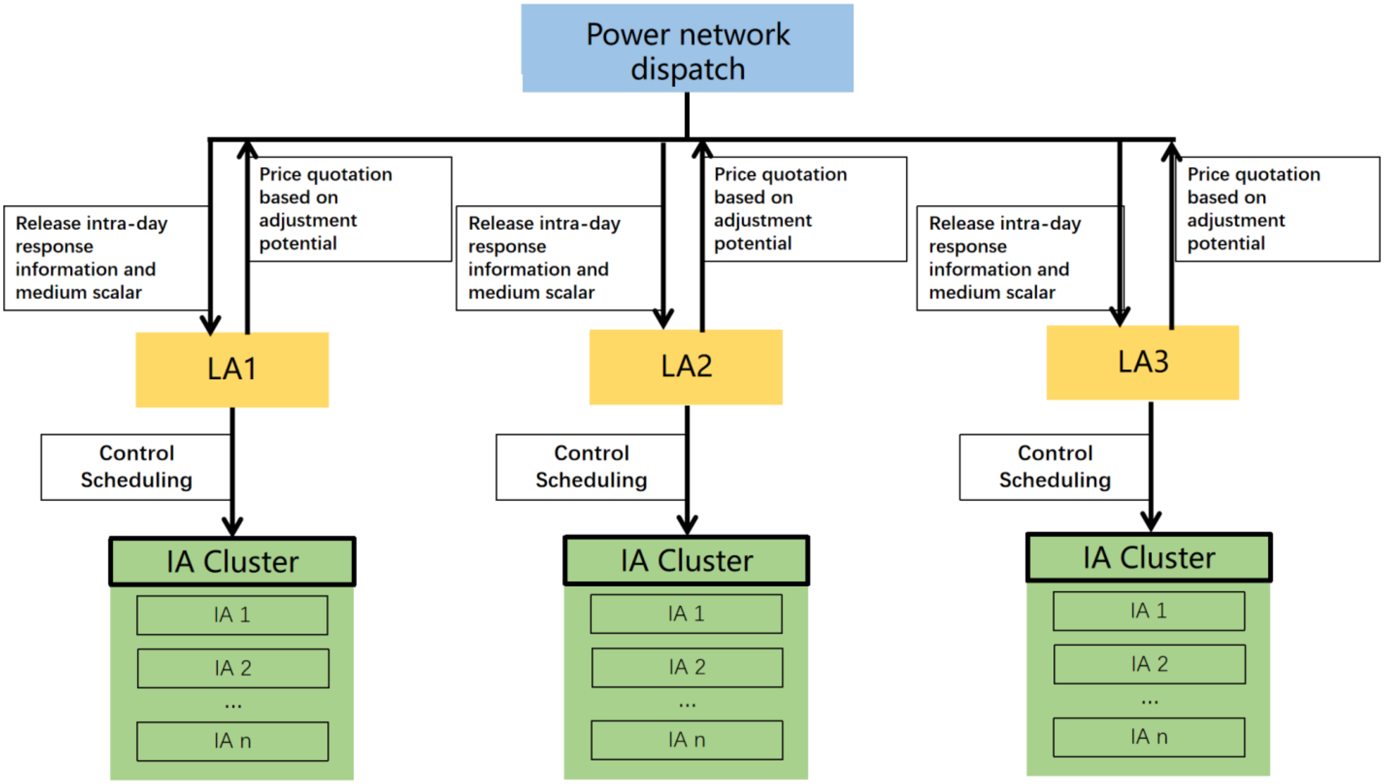

Figure 1. Information interaction in demand response process.

The innovation points of this paper are as follows:

(1) In order to improve the enthusiasm of air conditioning users to participate in demand response, the load quotient is considered to stimulate the load reduction of users and compensate the rise in room temperature on the basis of the conventional aggregation scheduling of variable frequency air conditioning groups. Thus, an optimization strategy for the aggregation scheduling of variable frequency air conditioning systems that comprehensively considers the incentives and compensation is proposed. The research shows that this strategy can ensure that the load supplier can maximize its own economic benefits on the premise that the air conditioning users receive certain subsidies.

(2) Through the sensitivity analysis of the temperature rise compensation coefficient in the optimization strategy, the study found that this factor has a direct impact on the load curtailment and the net income of the load provider. The increase in the temperature rise compensation coefficient will reduce the load curtailment. Although the temperature rise compensation expenditure is reduced, the net income of the load provider is also reduced, and the low temperature rise compensation coefficient will inevitably lead to the reduction in the user's thermal comfort. Therefore, the formulation of an appropriate temperature rise compensation coefficient will directly affect the economic benefits of the load provider, which provides a theoretical basis for the future load provider to formulate appropriate variable frequency air conditioning group scheduling strategies.

2. Model of Single Inverter Air Conditioner

The single inverter air conditioner load model includes the relationship between compressor power and electric power and the refrigeration capacity of the inverter air conditioner and the thermodynamic model of the air conditioned room made up of heat exchange between the inverter air conditioner and the room. This section establishes the load model of a single inverter air conditioner and puts forward the frequency control method of the inverter air conditioner according to the established model, which establishes the theoretical basis for further tapping the maximum adjustment potential of the inverter air conditioner group and formulates the scheduling optimization strategy.

2.1. Thermodynamic Model of Air Conditioned Room

The key to simulating the electric energy consumption of air conditioners is to accurately simulate the heat exchange process of air conditioners. The thermodynamic principle of air conditioning units for household and small industrial and commercial users is described by the equivalent thermal parameter model (ETP model) [30]. The model composition is shown in Figure 2.

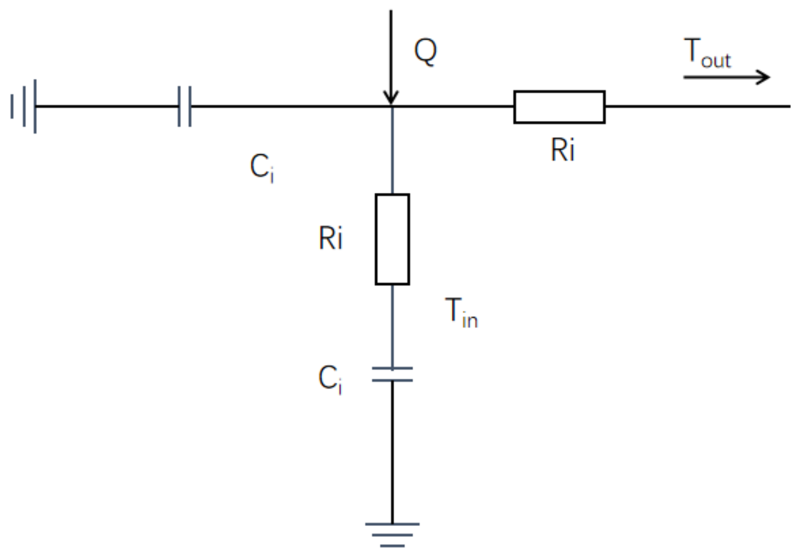

Figure 2. Equivalent thermal parameter model of a single air conditioning unit.

In Figure 2, Q (kW) is the cooling/heating capacity of the air conditioning unit; C_i (kJ/°C) and R_i (°C/kW) represent the equivalent heat capacity and equivalent thermal resistance, respectively; and Tout (°C) is the outdoor temperature.

The above model can be simplified into a first-order equation, and the functional relationship between indoor temperature Tint and cooling capacity Q_t can be obtained as follows:

$$T_{in}^{t+1} = T_{out}^{t+1} - Q^t R - (T_{out}^t - Q^t R - T_{in}^t)e^{-\frac{\Delta t}{RC}} \quad (1)$$

where ${T_{in}}^t$ is the indoor temperature at time t; ${T_{ou}}^{tt}$ is the outdoor temperature at time t; Q^t is the cooling capacity of air conditioner at time t; ΔT is the time interval between t and t + 1; and C and R are the equivalent heat capacity and thermal resistance of the air conditioned room, respectively, which are calculated by multiplying the room volume by the specific heat capacity of air, physical parameters, and thermal conductivity.

2.2. Relation between Frequency, Electric Power, and Refrigerating Capacity of Inverter Air Conditioner Compressor

The inverter air conditioner regulates the compressor speed through the frequency converter, and automatically adjusts the cooling (or heat) amount according to the room heat (or cold) load. The compressor power accounts for more than 80% of the operating power of the air conditioner. The adjustment of the air conditioning load is actually the adjustment of the compressor load.

The energy efficiency ratio (the ratio of electric power to refrigerating capacity) of an inverter air conditioner compressor is not a constant, but related to frequency. According to the experimental results in references [31,32] and after further simplification, it can be concluded that the relationship between the electric power and cooling capacity of the inverter air conditioner and the frequency is as follows:

$$P_{AC} = k_1 f + l_1 \tag{2}$$

$$Q_{AC} = k_2 f + l_2 \tag{3}$$

where P_{AC} is the electric power (kW) of inverter air conditioner; Q_{AC} is the refrigerating capacity of inverter air conditioner (kW); f is the frequency of inverter air conditioner compressor (Hz); k_1 and k_2 are primary coefficients; and l_1 and l_2 are constant coefficients.

2.3. Relation between Compressor Frequency and Indoor Temperature

The functional relationship between compressor frequency and indoor temperature is generally determined by the temperature difference between indoor temperature $\mathrm{T_{in}}$ and set temperature T_{set}. When the temperature difference is greater than *n*+, the compressor operates at the highest frequency, and when the temperature difference is less than *n*-, the compressor operates at the lowest frequency, as shown in Formulas (5) and (6) [33].

$$\Delta T^t = T_{in}^t - T_{set}^t \tag{4}$$

$$f^t = \begin{cases} f_{\max} & \Delta T > n \\ f^{t-1} + K\Delta T & n_- < \Delta T < n_+ \\ f_{\min} & \Delta T < n_+ \end{cases} \tag{5}$$

where ΔT^t is the temperature difference between the indoor temperature and the set temperature in t period; ${T_{set}}^t$ is the set temperature of time period t; f_{max} and f_{min} are the upper limit and lower limit of compressor frequency, respectively; and K is a constant, $K > 0$.

Equations (1)–(5) construct the relationship between the electrical power of the inverter air conditioner load and indoor temperature, which is the basic model of inverter air conditioner load. Therefore, the electric power of inverter air conditioner can be continuously adjusted by adjusting the compressor frequency *f*.

2.4. Frequency Control Method of Inverter Air Conditioner

The inverter air conditioner regulates the compressor speed through the frequency converter, and automatically adjusts the cooling (or heat) amount according to the room heat (or cold) load. Compared with directly regulating the set temperature of the air conditioner, frequency regulation has the characteristics of stable temperature change, small frequency change range and more stable working condition of the compressor. Therefore, the frequency control method is used to regulate the single inverter air conditioner.

Assuming that the outdoor temperature is constant T_{out} and the set temperature is T_{set}, the compressor frequency f_{set} under stable operation can be calculated according to the single inverter air conditioner load model. ${T_{in}}^{t+1} = {T_{in}}^t = T_{set}$ is substituted into Formula (4), and the following is obtained:

$$Q_{AC} = \frac{\mathrm{T_{out}} - \mathrm{T_{set}}}{R} \tag{6}$$

Substituting Equation (6) into Equation (1), the following is obtained:

$$\mathrm{f_{set}} = \frac{\frac{\mathrm{T_{out}} - \mathrm{T_{set}}}{R} - \mathrm{l_2}}{\mathrm{k_2}} \tag{7}$$

where f_{set} is the frequency during stable operation. Substituting it into Formula (1), the power during stable operation can be obtained as follows:

$$P_{AC} = k_1 \cdot \frac{\frac{T_{out} - T_{set}}{R} - l_2}{k_2} + l_1 \tag{8}$$

According to the derivation of Equations (6) to (8), the power saving potential of a single air conditioner can be obtained

$$\Delta P = PAC - PAC_0 \tag{9}$$

3. Load Aggregation Scheduling Method for Inverter Air Conditioner

3.1. Introduction to Dispatching Methods

Using the control method of a single inverter air conditioner described in Section 2, in the process of participating in the demand response, the user's air conditioner operating status and indoor temperature and other data are obtained through the intelligent terminal installed on the user's side. According to the actual situation, on the premise of ensuring the thermal comfort of the air conditioner users, each inverter air conditioner participating in the demand response is controlled through the frequency adjustment method to achieve the goal of reducing peak load.

3.2. Aggregation Method Based on Parameter Identification

The main power consumption of temperature-controlled loads such as air conditioners, refrigerators and water heaters comes from induction motors [34,35], which have load characteristics similar to motor loads [36]. Therefore, the aggregation model of such loads can be characterized by the aggregation method based on parameter identification and the aggregation model of motors [37,38]. According to the mathematical model of a third-order induction motor and the difference in air conditioning loads, reference [39] proposed the aggregation modeling of an air conditioning load based on a self-organizing neural network to better simulate the dynamic characteristics of an air conditioning group.

The load aggregation method based on parameter identification is a passive aggregation method, which is mainly aimed at the aggregation method of temperature-controlled loads such as air conditioners, refrigerators, and water heaters when participating in system voltage regulation. In essence, it is the calculation of a large number of air conditioning (water heaters, refrigerators, etc.) load equivalent circuits in the power grid.

In Figure 3, U represents bus voltage, s represents motor rotor, R_s represents motor stator winding resistance, X_s represents motor stator leakage reactance, X_M represents motor magnetizing reactance, X_R represents motor rotor leakage reactance, and R_R represents motor rotor resistance.

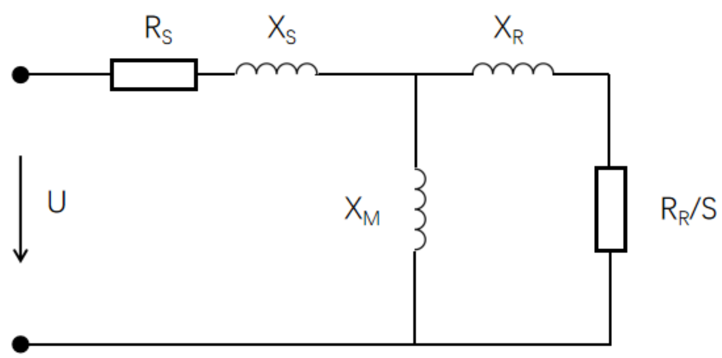

Figure 3. Motor equivalent circuit diagram.

3.3. Intelligent Terminal Settings

In Figure 4, the load aggregator configures home intelligent terminal equipment (ITS) for each user, which is connected to the central controller of the load aggregator. On the one hand, the intelligent terminal collects the operation status, compressor frequency, indoor and outdoor temperature, and other data of the user's inverter air conditioner and reports them to the load aggregator. On the other hand, it receives the dispatching signal from the polymerization company and controls the air conditioner accordingly.

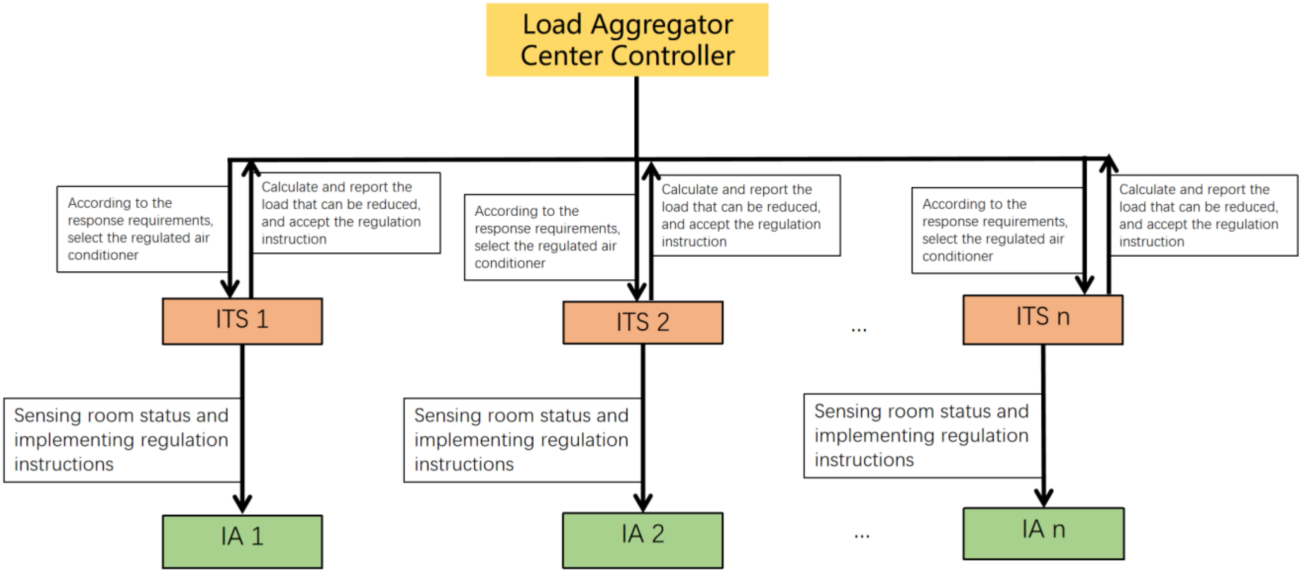

Figure 4. Settings of AC intelligent terminal.

3.4. Incentive and Compensation Measures for Load Supplier to Respond to User Participation Demand

In practical scenarios, to ensure users' willingness to participate in demand response, on the one hand, load aggregators need to provide users with incentives based on load reduction according to the actual situation of users participating in demand response. On the other hand, long-term operation of air conditioning at higher temperatures will reduce the thermal comfort of users, which will affect the enthusiasm of users to participate in demand response, and incentives for users to accept room temperature rise also need to be taken. Therefore, after evaluating the maximum adjustment potential of an inverter air conditioner load cluster, the load quotient must consider the incentive and compensation measures based on these two aspects. The load supplier should formulate an optimal dispatching strategy for the inverter air conditioner group on the premise of realizing the load reduction goal and ensure its own economic benefit after considering the expense of incentive and compensation measures. For the contribution degree of user participation in demand response, load aggregators use $p_1(t)$, which participates in demand response to incentive $p_2(t)$ by dividing the income of $p_1(t)$ into users in a fixed proportion and the incentive price for the power network to reduce the load of the load aggregator; $p_2(t)$ is the load reduction incentive price for loaders to users. For the reduction in thermal comfort caused by room temperature rise in air conditioned rooms, the load quotient compensates the user for the temperature rise according to the difference between room temperature and human comfort temperature (26 °C). The relationship between compensation and temperature rise is as follows:

$$p_{\Delta t}(i,j) = a * \Delta T(i,j) \tag{10}$$

where $p_{\Delta t}(i,j)$ is the compensation price (RMB/min) for the temperature rise in the first variable frequency air conditioner in the j-time period; a is the compensation factor for temperature rise (RMB/(°C*min)); and $\Delta T(i,j)$ is the temperature difference between indoor temperature and human comfort temperature of the first variable frequency air conditioner in j period (°C).

3.5. Model Optimization

On the basis of guaranteeing user comfort, the demand response control of the inverter air conditioner cluster with n air conditioners was carried out, and the maximum adjustment potential of the demand response of the variable frequency air conditioning cluster was evaluated. The objective was to optimize the economy of the load aggregator on the premise of meeting the specified load reduction.

1. Target function

With the objective of optimizing the economy of the load aggregator, the difference between the benefits of requiring the load aggregator to participate in the demand response market and the incentive compensation fees of the load aggregator to participate in the demand response users is the greatest. The objective function is as follows:

$$\mathrm{f1} = \max\left(\sum_{\mathrm{i}=1}^{\mathrm{n}}\sum_{\mathrm{t}=1}^{T}\Delta P(i,\mathrm{t})\mathrm{p}_1(t) - \sum_{\mathrm{i}=1}^{\mathrm{n}}\sum_{\mathrm{t}=1}^{T}\Delta P(i,\mathrm{t})\mathrm{p}_2(t) - \sum_{\mathrm{i}=1}^{\mathrm{n}}\sum_{\mathrm{t}=1}^{T}\Delta T(i,\mathrm{t})\mathrm{C}(t)\right) \quad (11)$$

where $\Delta P(i, \mathrm{t})$ is the reduction potential of the first air conditioner in the t period; $\mathrm{p}_1(t)$ is the profit price at which the load aggregator participates in the demand response market; $\mathrm{p}_2(t)$ is the load reduction incentive price of the loader to the user; $\Delta T(i, \mathrm{t})$ is the acceptance temperature rise during the t period of the first air conditioner; and $\mathrm{C}(t)$ is the temperature rise incentive price of the load aggregator to the user.

2. Constraints

- Load reduction constraints

  Load reduction of the inverter air conditioner group under the control of the load aggregator should be no less than the load reduction specified by power network dispatch during the demand response period; that is, in the formula, ΔP_{set} is the specified amount of the load reduction for power network dispatch.

- Operation constraints of air conditioning

  The frequency conversion air conditioning operation frequency must be within the frequency range specified by the factory, that is,

$$\mathrm{f_{min}(i) \leq f(i,t) \leq f_{max}(i)} \quad (12)$$

- User temperature comfort constraints

  The indoor temperature of an air conditioned room during dispatch must be within the upper and lower limits of the room temperature acceptable to the user, that is,

$$\mathrm{T_{min}(i,t) - \Delta T \leq T(i,t) \leq T_{max}(i,t) + \Delta T.} \quad (13)$$

- Compressor operation constraints

In the simulation process, in order to achieve the optimization goal, the intelligent terminal system may tend to frequently change the set temperature of the inverter air conditioner, causing the compressor to frequently change the frequency, which may lead to a temperature dead zone within the operating temperature range and reduce the working life of the inverter air conditioner. For this problem, the minimum time interval for allowing the set temperature of the air conditioner to change is set to 3 min in the study. This value refers to the recommended value of the air conditioning industry for switching air conditioners and temperature regulation.

$$\Delta \mathrm{T_{Tset}} \geq 3 \quad (14)$$

4. Example Analysis

4.1. Example Background Conditions

Using the load aggregation dispatching method of the inverter air conditioner proposed in Section 3, a residential area in Shanghai was taken as an example to simulate and analyze the load reduction potential of the variable frequency air conditioning participating in demand response. The actual load reduction and the income of the load aggregator were calculated considering load reduction and indoor temperature rise incentives. The number of inverter air conditioners participating in demand response in this residential area is 3000, and the demand response time is 12:00–16:00 during the peak period of the day. According to the market transaction situation of the loader in the demand response day, the load reduction of the inverter air conditioner group is required to be not less than 1 MW and last no less than 1 h.

The main parameters that affect the aggregation results of frequency conversion air conditioning in residential areas are outdoor temperature, air conditioning set temperature, building parameters of the air conditioned room, and air conditioning rated power. Because the selected inverter air conditioners belong to the same residential area, according to the aggregation method based on parameter identification, it can be assumed that the building parameters and outdoor temperature of each room in the residential area are similar, and the typical daily temperature in summer is shown in Figure 5.

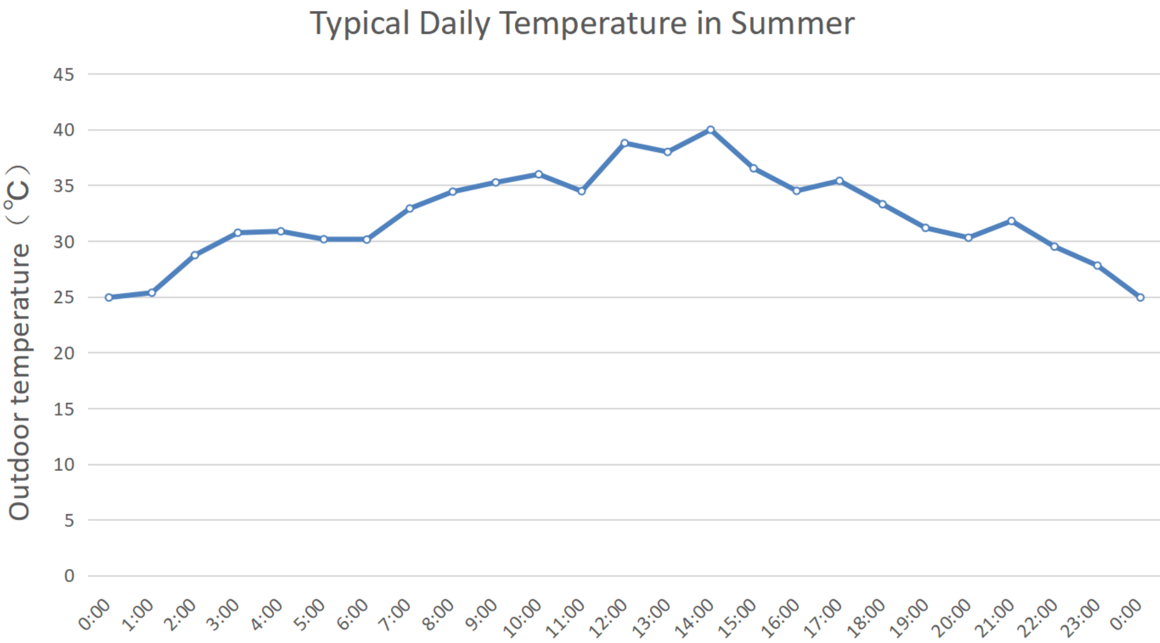

Figure 5. Typical Daily Temperature in Summer.

In order to meet the thermal comfort requirements of air conditioning users, it is stipulated that during the period of participating in demand response, the indoor temperature of an air conditioned room is between 23–28 °C, and the temperature control deviation of 0.5 °C is allowed. The relationships between Q, R, C, and the refrigeration area of the room were determined by the method of reference [40]. The settings of the equipment parameters of variable frequency air conditioning are shown in Table 1.

Table 1. Setting of multi-inverter air conditioners and air conditioned room.

Parameter Name	Numerical Value
Minimum frequency of compressor/Hz	5
Maximum frequency of compressor/Hz	110
Primary coefficient of electric power rate and compressor frequency k1	Normal random distribution with mean 0.04 and variance 0.008
Constant coefficient of electric power and compressor frequency l1	Normal random distribution with mean 0.35 and variance 0.05
Primary coefficient of refrigerating capacity and compressor frequency k2	Normal random distribution with mean 0.12 and variance 0.006
Constant coefficient of refrigerating capacity and compressor frequency l2	Normal random distribution with mean 2.8 and variance 0.25
Indoor initial temperature/°C	Evenly distributed at 23–28 °C
Upper limit of indoor temperature setting/°C	28
Lower limit of indoor temperature setting/°C	23
Temperature control deviation/°C	0.5
Room equivalent thermal resistance/(°C/kW)	Normal random distribution with expectation of 10 and variance of 1
Room equivalent heat capacity/(kJ/°C)	Normal random distribution with expectation of 200 and variance of 0.5

4.2. Evaluation of the Regulation Potential of Inverter Air Conditioner Cluster

The maximum adjustment potential of an inverter air conditioner group is that the air conditioning compressor runs at a lower frequency, so that the room temperature in the air conditioned room is always at the upper temperature setting limit, at which time the load reduction of the inverter air conditioner group is the largest. According to the frequency control method, the refrigeration capacity of the inverter air conditioner corresponding to the set upper room temperature limit is calculated, and the compressor frequency and the power of the variable frequency air conditioner matching the refrigeration capacity are further calculated. Through simulation calculation, the load reduction capacities of the inverter air conditioner group under different dispatch times are shown in Table 2.

Table 2. Power reduction of inverter air conditioner cluster under different control times.

Load Reduction/MW	Percentage Reduction/%	Accept Schedule Duration/h
2.551	42.81	1
2.499	41.93	2
2.499	41.93	3
2.499	41.93	4

From the data in Table 2, when the inverter air conditioner group participates in the 1 h demand response scheduling, the load reduction is 2.551 MW, which is slightly higher than the load reduction for a longer period of time. When the load reduction is reduced to 2.499 MW, the inverter air conditioner group can keep running at a partial load, at which time the set temperature of all air conditioners is kept at the set room temperature upper limit of 28.5 C, and the load reduction is stable.

4.3. Analysis of Optimal Control Strategy for Inverter Air Conditioner Cluster Considering Incentive Compensation Measures

Based on the above incentives for load reduction and compensation measures for room temperature rise, the load reduction incentive price $p_1(t) = 4$(RMB/kWh) for the power grid to load aggregator and the load reduction incentive price $p_2(t) = 0.25 \times p_1(t)$ (RMB/kWh) for the loader to user are taken as examples. The temperature rise compensation factor a = 0.020 (RMB/((°C∗min)). The simulation of the demand response for 3000 inverter air conditioners with a dispatch time of 4 h shows the following results.

It can be seen from Table 3 that the load aggregator dispatching a cluster consisting of 3000 inverter air conditioners to participate in a 4 h demand response can reduce 1.267 MW of electricity load on average and bring RMB 14,435.97 of net income to the load aggregator.

Table 3. Load reduction and aggregator income of air conditioning cluster under set conditions.

Accept Schedule Duration/h	Average Load Reduction/MW	Net Income/RMB
4	1.267	14,435.97

As shown in Figure 6, considering the cost of temperature rise compensation measures, smart terminals tend to keep the indoor temperature of an air conditioned room at 26 °C for as long as possible to reduce the cost of user temperature rise compensation. As shown in Figure 7, at the beginning and end of the demand response, the air conditioning compressor runs at the lowest frequency, and the load on the cluster is also the lowest. In the middle period, in order to keep the air conditioning running at the set temperature, the compressor will increase the power, so that the frequency conversion air conditioning will run at a partial load.

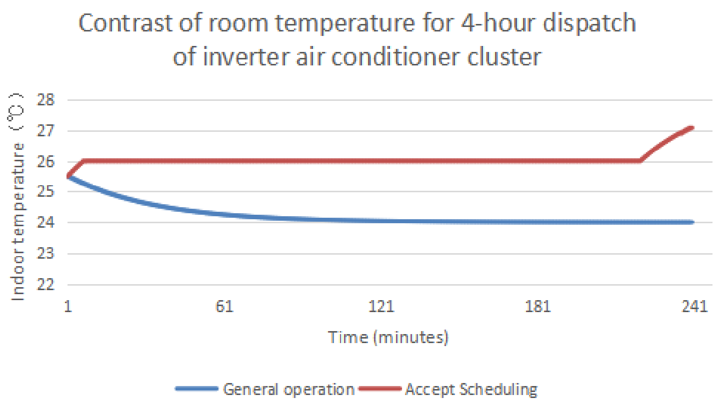

Figure 6. .Contrast of room temperature for 4-h dispatch of inverter air conditioner cluster.

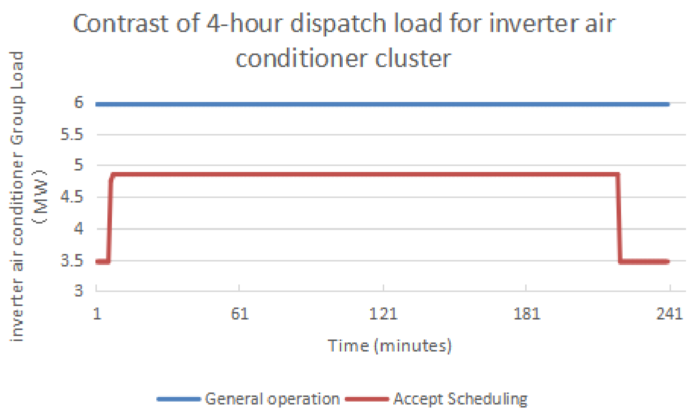

Figure 7. Comparison of 4 h dispatching load received by inverter air conditioning cluster.

4.4. Sensitivity Analysis of Temperature Rise Compensation Factor to Reduction and Load Quotient Net Income

Based on the simulation results in Section 4.3, under the premise that the external factor of the incentive price of load reduction does not change, the net income is directly affected by the temperature rise compensation factor set by the loader. In order to ensure the economic optimum of the loader aggregator, the temperature rise compensation factor will highly affect the set temperature of the variable frequency air conditioner in the dispatch strategy. This will then affect the amount of load reduction in the demand response period of the inverter air conditioner cluster. Therefore, based on the results of the previous section, the sensitivity analysis of the temperature rise compensation factor was further conducted.

Table 4 shows that with the increase in the temperature rise compensation factor, the cost of temperature rise compensation for users decreases, but at the same time, the amount of load reduction decreases. The decrease in load reduction directly affects the total income of the load aggregator participating in demand response. The final result shows that the increase in the temperature rise compensation factor will lead to a decrease in the total income and net income of the load aggregator participating in demand response. It can be seen from the table that when the temperature rise compensation factor is as low as 0.010 RMB/(°C*min), the load reduction reaches 2.499 MW, which is the upper limit of the adjustment potential of the inverter air conditioner cluster. At this time, all inverter air conditioners controlled by the aggregator can minimize the load, participate in the demand response completely, and the total income of participating in the demand response reaches the maximum value of RMB 39,999.40. It can be seen that the temperature rise compensation factor has a significant impact on the effect of demand response and the economic benefit of the load quotient, which is one of the important factors that the load quotient should pay attention to when making strategies.

Table 4. Influence of different temperature rise compensation coefficients on demand response results.

Temperature Rise Compensation Factor (/(°C*min))	Variation Rate of Temperature Rise Compensation Factor (%)	Load Cuts (MW)	Total Revenue from Participating Demand Response (RMB)	Temperature Rise Compensation Expense (RMB)	Load Aggregator Net Income (RMB)
0.010	−50%	2.499	39,998.40	1499.70	28,499.10
0.015	−25%	1.337	21,392.00	1320.39	14,726.61
0.020	0%	1.267	20,284.92	777.72	14,435.97
0.025	+25%	1.238	19,821.96	581.49	14,284.98
0.030	+50%	1.221	19,544.16	466.41	14,191.71

Figures 8 and 9 show the relationship between the load reduction and the expenditure income of the load aggregator and the temperature rise compensation coefficient, respectively, in the form of line graphs. From the trend, it can be found that both the load reduction and the net income of the load aggregator decrease with the increase in the temperature rise compensation coefficient.

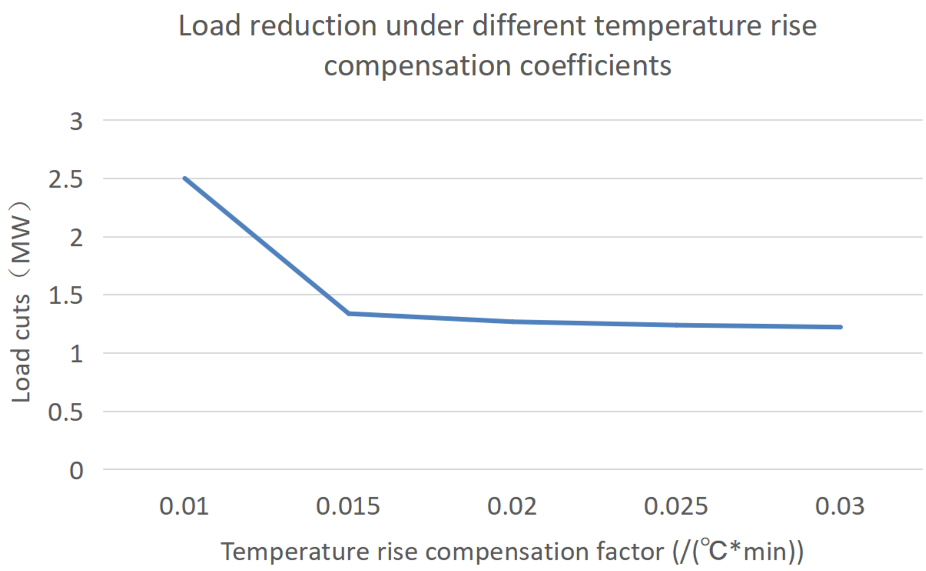

Figure 8. Load reduction under different temperature rise compensation coefficients.

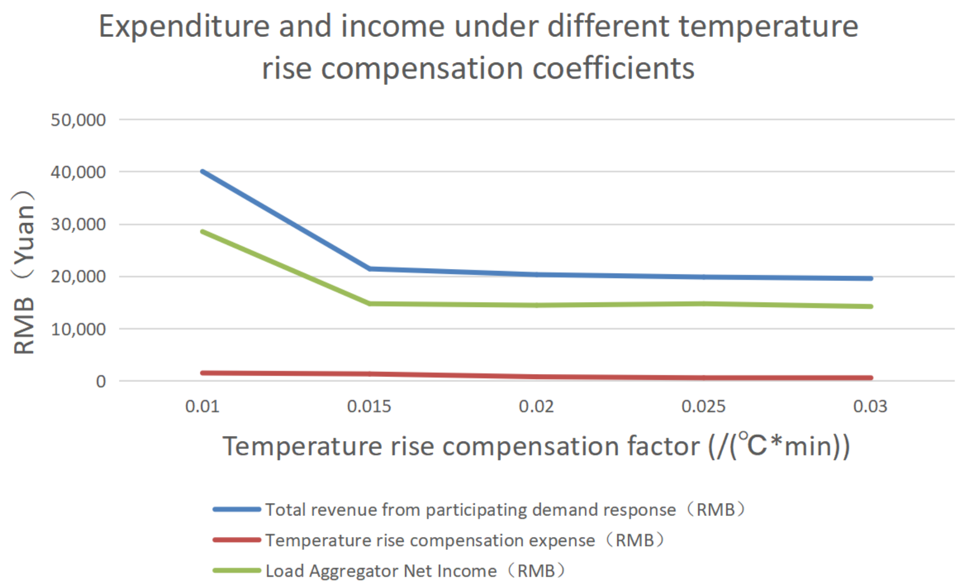

Figure 9. Expenditure and income under different temperature rise compensation coefficients.

5. Discussion and Conclusions

In this paper, the demand response of inverter air conditioner participation is studied. The specific contents are summarized as follows:

- Based on the first-order equivalent thermal parameter model, the relationship between air conditioning compressor frequency and air conditioning power and refrigeration capacity was determined by regression analysis, and the inverter air conditioner load model was established. Using the aggregation method based on parameter identification, the inverter air conditioners with similar parameters in the same area were aggregated and controlled by the load aggregator through the smart terminal installed on the user side.
- Detecting the running status of air conditioned rooms through smart terminals, uploading status information to the load aggregator, and accepting dispatch instructions for the load control of the inverter air conditioner group were performed, under the premise of satisfying human comfort, to determine the adjustment potential of inverter air conditioner participation in demand response.
- Based on the overall adjustment potential of the inverter air conditioner group, considering the measures of load reduction incentive and temperature rise compensation by the load merchant to users, an optimal control strategy for an inverter air conditioner group was formulated in the actual situation, and the corresponding load reduction amount and net income of the load quotient were calculated. Based on the simulation results, the temperature rise compensation factor was further studied and sensitivity analysis was carried out. It was found that the temperature difference compensation factor has a significant impact on the economic benefit of the load quotient of the demand response effect, which provides a basis for the load quotient to formulate related strategies in the future.

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