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Power Retailer Air-Conditioning Load Aggregation Operation Control Method and Demand Response

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ABSTRACT Thermostatically controlled loads (TCLs) have become a major tool for the demand response (DR) program when air conditioners cause peak loads in a day during the winter or summer. To solve the problem of a direct load control with TCL usually affecting user comfort and hardly considering responsiveness, a power retailer air-conditioning load aggregation operation control and demand response method was proposed in this research. From the perspective of a power retailer, a compensation mechanism for TCL was constructed, which was composed of a basic incentive program and an additional incentive program. The basic incentive program aimed to encourage users with a low response degree to increase the response capacity in order to participate in DR. An auxiliary service market control strategy based on a new compensation mechanism of the electricity retailer was detailed, which fully considered the enthusiasm of the user in mobilizing the response and reducing the load reduction fluctuation when using the state-queuing (SQ) model. Case studies were provided to verify the effectiveness of the proposed method. Compared with other compensation schemes, the simulation results showed that the compensation mechanism provided in this research was more reasonable, and it could smooth the load and reduce fluctuations. The compensation distribution among the user groups could effectively control the uniform distribution in the user groups in the temperature range, and it could mobilize users at different temperatures to participate in DR.

INDEX TERMS Power system, air conditioning load, demand response, energy management, thermostatically controlled load, retailer, state-queueing model.

I. INTRODUCTION

With the rapid growth of China's economy, power consumption in the tertiary industries has increased rapidly, especially the air-conditioning load, which accounts for a large proportion of power terminal equipment [1]. Due to the frequent occurrence of extreme weather conditions in recent years, cooling loads in summer and heating loads in winter have become the main components of peak loads in these two seasons, resulting in a shortage of the power supply at certain times [2]. With the traditional operation mechanism of a power grid, if the load peak is encountered, peak units may be used, or power load management measures such as brownout can be adopted. However, the cost of peak units is often too high, and power brownout sacrifices the interests of users [3].

Demand response (DR) is considered to be an essential mechanism for supply−demand balance, and it is divided into price-based approaches and incentive-based approaches [2]. In the price-based approach, electricity users respond to the electricity price of an electricity company to change their electricity habits. In the incentive-based mechanism, users either actively change their habits by accepting economic compensation or they hand over electrical equipment to third-party agencies for control. Thermostatically controlled loads (TCLs) are useful for peak-shifting [4].

The summer air-conditioning load accounts for more than 40% of electricity consumption [5], and it has excellent potential in the application of TCLs. A large number of

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research have been conducted on TCL methods for air conditioners, and load regulators were used in [6] to respond urgently to the needs of retailers. The multi-objective problem of air-conditioning dispatch by solving multi-objective functions was proposed in [7]. It was also described in [8]–[11] that TCLs could offer flexibility to a power system, and the authors characterized the set of admissible aggregated power profiles that the aggregated TCLs consumed without violating any comfort or operational constraints in the state-queue model. Other extended state-space models considering different types of air conditioners were used in [12]–[14] to control air conditioners in real time. Air-conditioning loads were optimized by the temperature setpoint [15] and [16]. The static and dynamic clustering of air conditioners was considered in real-time control [17]. Intelligent temperature control equipment was applied to respond to air-conditioning control aggregator requests [18]. In [19], the multi-objective method was used to solve the problems of the excessive voltage, air-conditioning load, user comfort, and distribution network operating loss. The Taguchi method was used to solve the air-conditioning TCL problem [20]. In the above methods, the state-queuing (SQ) model was simple and effective, and the peak-shifting capacity could be predicted well, so it was widely used [21]. Most other methods can respond well to load shifting requirements. However, it is difficult to calculate the potential of air-conditioning peak shifting, and it is difficult to apply this potential in the programming of the TCL of power retailers.

Since TCL requires users to give up control of some of their powered devices [22], it affects the comfort of power consumption. Traditional strategies force consumers to take part in direct load control (DLC) regardless of the consumers' willingness to participate. The compensation for the influence of a user's comfort in participating in TCL is concerning for system operators. Two compensation mechanisms, including the comfort interval and the temperature setpoint deviation, have been considered [23]. The predictive mean comfort index was adopted to measure electrical comfort in [5] and [24]. Two compensation distribution mechanisms were established according to the peak-shifting compensation and the TCL management cost [25]. The multi-objective optimization method was used to consider the task of load shifting while considering the profit of the sales company, and the NSGA-2 method was used to solve the problem [26]. The data-driven method was used to consider the load peak-to-valley difference and the sales profit as a two-stage robust optimization problem in [27]. Game theory was used to deal with the game between the load peak-to-valley difference and the user electricity efficiency in [28]. The incentive method was adjusted according to the user's real-time response behavior in [2] and [29]. A linear model was used to compensate for the user's peak reduction contribution in [30] and [31]. A tariff discount for the user's peak shifting contribution was developed in [32]. In [33], the deep learning method was used to compensate the user for peak clipping compensation to achieve better results.

In the above compensation mechanisms for incentive DR and TCL, the contribution to the user's participation in peak clipping was linear with the peak-shifting profit of retailers in most articles. Other references focused on the distribution of the incentive for users with optimization algorithms, but most of the mechanisms were not suitable for compensating for the responsiveness of multiple users participating in DR. With the background of the retailer's participation in the auxiliary service market mechanism, if the enthusiasm of users participating in DR was not well mobilized, the profitability of the power retailer was indirectly affected. The research with SQ models has generally assumed that the air-conditioning queue was evenly distributed in the initial state. Due to the sparse or dense air-conditioning state group in the temperature interval, an air conditioner would be unevenly distributed in the temperature range. During the control period, the air-conditioning load of the entire SQ could cause the fluctuation of the load after the reduction on the one hand and an inaccurate peak reduction according to the request of the utility on the other hand. This would ultimately affect the interests of the power retailer. It is also worth noting that few articles have focused their efforts on this problem related to compensation for users participating in DR.

To overcome shortcomings of the above methods, a power retailer air-conditioning load aggregation operation control and demand response method was proposed in this research. An auxiliary service market control strategy based on a new compensation mechanism for an electricity retailer was detailed. The strategy fully considered the enthusiasm of the user for mobilizing the response and reducing the load reduction fluctuation when using the SQ model. This compensation mechanism was accompanied by a control strategy and it had the following advantages:

(1) With the aim of motivating users with low responsiveness, the basic compensation mechanism drew a convex quadratic curve by counting the response capacity of each group of users according to the user's response positive degree. In contrast to the original compensation mechanisms, the proposed method encouraged low-response users to increase their response capacity to participate in the DR corresponding control strategy, with the aim of maximizing the profit for retailers. Users with high responsiveness were scheduled first, which could further improve the enthusiasm of low-response users for participating in DR.

(2) With the aim of smoothing the load fluctuation, the additional compensation mechanism was a cross-group compensation mechanism that the user could choose to participate in. When the air conditioning was unevenly distributed within the temperature range in the SQ model, the user might choose to participate in the additional compensation mechanism for cross-group scheduling. The cross-group scheduling could reduce fluctuations in the load reduction due to the uneven distribution of the air-conditioning load temperature in the initial state of the temperature interval. For the case in which the user was not highly responsive to the additional compensation or the user had a densely distributed

temperature interval within the group, the air-conditioning load status queue needed to be re-divided to obtain a stable load reduction amount.

The specific structure of this study is as follows: Corresponding to the function of participating in the power market, Section 1 details the control system architecture and the bidding process of the power retailer. In Section 2, the residential decentralized air-conditioning models are provided. The control strategy for the air-conditioning loads and their compensation mechanism design are proposed in Section 3. Section 4 describes how the example analysis was carried out, and Section 5 elaborates on the conclusion.

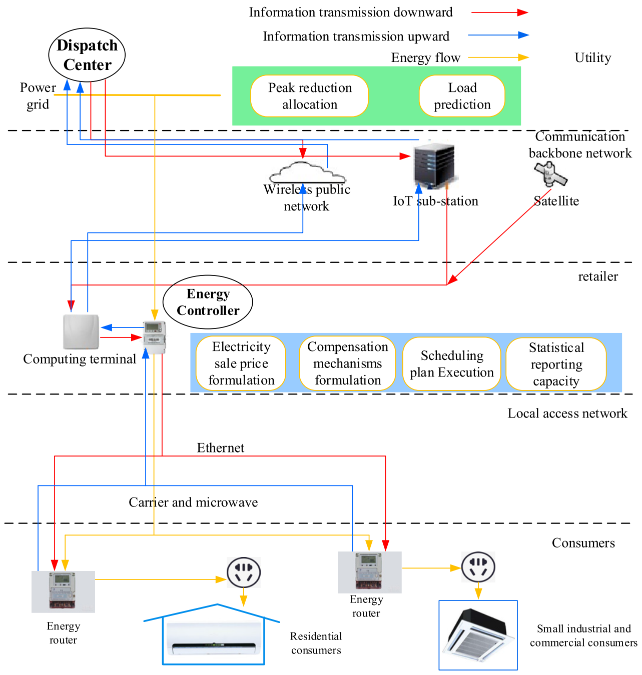

FIGURE 1. Power retailer operating system architecture.

II. POWER RETAILER CONTROL PROCESS AND BIDDING DECISION

A. POWER RETAILER CONTROL ARCHITECTURE

The operating system proposed for retailers was based on the concept of the Ubiquitous Power Internet of Things, as shown in Fig. 1. With an intelligent acquisition terminal as the core of the calculation and the user and value-added power service as the goal, the measurement system equipment, primary electrical equipment, and user intelligent equipment were widely interconnected and interoperable through the Internet of Things intelligent perception, recognition technology, and edge computing technology. This formed a network of all things interconnection, human−computer interaction, and the integration of heaven and earth.

In terms of systems, China is carrying out the market-oriented reform of electric power with separated distribution. Power retailers purchase electricity from the utility and then sell it to users. Therefore, the power retailers need to obtain operation information from users and to send information, such as electricity prices and orders to users. In terms of infrastructure, in recent years, the construction of China's smart grid and the ubiquitous power of the Internet of Things have made the two-way interaction between a utility, power retailers, and users applicable in the power system.

Residents and small industrial and commercial users have a large number of distributed air conditioners, which are widely distributed and demand to be dispatched by retailers. In this context, the electricity retailer can not only obtain profits through the sale of electricity but also gain profits by participating in the auxiliary service market in response to peak-shifting instructions. As a communication bridge between the utility and the power purchase users, the power retailer can replace the utility in managing air conditioners for small- and medium-sized industries, commercial enterprises, and residential users. The power retailer and the utility sign an agreement to complete the power company's corresponding dispatch plan to ease the power supply pressure according to day-ahead load prediction. In the agreement, the users must specify not only their temperature comforts but their exact number of air conditioners as well. Each air conditioner is controlled by the energy router so that the retailer knows the actual status of each air conditioner. However, the electricity retailer and the power purchase users sign an agreement for the formulated electricity prices. The retailer predicts outdoor temperature and load level by collecting the user's air-conditioning parameters and meteorological parameters. According to the information, the load reduction capacity can be predicted, and a reasonable compensation mechanism is constructed for users. The operating mode of the retailer is shown in Fig. 1.

Since the retailer performs TCL on multiple users, the TCL technology needs to meet the requirements for real-time interaction between the user and the retailer, as well as the real-time monitoring of the state of the user air conditioner. The interaction of the above information needs to meet the requirements of technical support of hardware technology and communication technology. In terms of hardware technology, since the utility needs to achieve day-ahead load forecasting, the retailer needs to realize the real-time detection and real-time control of the indoor temperature of air conditioners. Therefore, the energy router needs to be installed on the user side, while the energy controller is installed on the retailer side. An energy router implements the non-intrusive load identification technology, and load prediction can be achieved with user load decomposition technology. Energy routers and energy controllers are the core hardware of TCL. They need to have functions such as electrical parameter measurement, environmental parameter sensing, and control strategy output. They are generally implemented by embedding internal appliances and follow-up metering sockets. The above two technologies jointly achieve the perception of the user load and satisfy the depth perception and precise control of the home appliances. Communication technology requires the immediacy of communication. With the development of

Internet of Things technology [34] and 5G technology [35], information interaction and real-time control information have been satisfied.

B. CONTROL PROCESS AND RETAILER'S PEAK BIDDING DECISION

This study proposes the specific structure of an operation control strategy for a power company participating in the power system auxiliary service market. The operation control strategy was divided into two phases: day-ahead and intraday. In the day-ahead stage, the retailer predicted the schedulable capacity of each user by counting the comfort interval of each user and reporting it to the utility. The utility obtained the load value of the next day through load forecasting and evaluating the peak reduction. Additionally, the electricity retailer needed to set the electricity price for sales based on the user's electricity preference information. The power retailer determined the peak bid for the reduction according to the schedulable capacity and the peak-bidding curve obtained. The retailer determined whether to participate in the day's TCL through the profit function. In the intraday period, due to the uncertainty of the forecast information, there might have been cases where the peak shifting plan was unreasonable. To alleviate the error influence, a rolling optimization strategy was adopted in this research to refresh the initial state of the air conditioner in each period. The information on the forecast and the uncontrollable load was re-reported to the utility. If the scheduling plan was unreasonable, the response capacity needed to be re-allocated, and the TCL of the air conditioner was re-controlled so that the air-conditioning load reduction amount in the day re-aligned with the scheduling expectation and the grid remained secure and stable in real time.

The dispatching department of the utility determined the total peak shifting results and its period based on the load forecasting results. In this research, several retailers were bidding for competition. The power utility's dispatching department first informed the retailer of the total load reduction according to the load and demand balance, and the retailer reported back the load reduction and the bidding price. The bidding price was ordered from small to large. In order to find a cost-effective optimal solution for the peak reduction, power retailers with higher bidding prices were later selected to participate in the peak shifting plan when other retailers with lower bidding prices were chosen first.

In the case of stable market conditions, according to historical bidding information corresponding to a total reduction amount, the reduction capacity held by each retailer corresponded to an equilibrium price, so that each of the retailers achieved their own profit. AI technology was used to select the appropriate function as the bidding decision function [36]. The independent variable of the function was the total load reduction and the shifting capacity held by each retailer. The dependent variable was the peak bidding price.

III. TYPICAL DISTRIBUTED AIR-CONDITIONING LOAD MODEL

A. AIR-CONDITIONING LOAD MODEL

To analyze the strategies for the air condition load dispatching of residents and small business users, the necessary dynamic process of the thermodynamic model of the air-conditioning load had to be considered first. The first-order state model of the air-conditioning power and temperature changes is as follows [37]:

$$T_{\text{in}}(t+1) = \begin{cases} T_{\text{out}}(t+1) - (T_{\text{out}}(t+1) - T_{\text{in}}(t))e^{-\frac{\Delta t_{\text{air}}}{R_r C}} & \text{turn off} \\ T_{\text{out}}(t+1) - a\eta P R_r & \\ -(T_{\text{out}}(t+1) - a\eta P R_r - T_{\text{in}}(t))e^{\frac{\Delta t_{\text{air}}}{R_r C}} & \text{turn on,} \end{cases} \tag{1}$$

where C is the equivalent heat capacity, $T_{\text{in}}(t)$ and $T_{\text{in}}(t+1)$ are the indoor temperatures in the t^{th} and the $t+1^{\text{th}}$ periods, $T_{\text{out}}(t+1)$ is the $t+1^{\text{th}}$ period outdoor temperature, R_r is the room equivalent thermal resistance, P is the rated power for air conditioning, η is the efficiency between refrigeration and power consumption, Δt_{air} is one simulation step size and a represents 1000, which was used for the unit conversion calculation.

B. AIR-CONDITIONING LOAD ADJUSTABLE CAPACITY

The dispatchable capacity of the air-conditioning load was related to the comfort requirement of the users. A user's temperature comfort zone could be established as a temperature zone that was between the upper and lower temperature limits. In a control cycle, when the temperature reached the upper and lower limits, the air conditioner could be turned on or off, which made the room temperature fluctuate within a specific range. The lower the comfort requirement of users were, the longer the allowable shutdown time of air-conditioning refrigerators in a cycle was, and the higher the compensation price was that the aggregator could offer to users.

It was assumed that the user's requirement for indoor temperature was in an interval and that the outdoor temperature remained constant during the period when the air-conditioning load was controlled by direct load. Hence, according to the equivalent thermal model of the air-conditioning unit described in the previous section, the control period of the air-conditioning load could be obtained [37]:

$$\begin{aligned} T_{\max} &= T_{\text{out}}(1 - \varepsilon^{\tau_{\text{off}}}) + T_{\min}\varepsilon^{\tau_{\text{off}}} && (2) \\ \tau_{\text{off}} &= R_r C \ln(\frac{T_{\min} - T_{\text{out}}}{T_{\max} - T_{\text{out}}}) && (3) \\ T_{\min} &= (T_{\text{out}} - a\eta P R_r)(1 - \varepsilon^{\tau_{\text{on}}}) + T_{\max}\varepsilon^{\tau_{\text{on}}} && (4) \\ \tau_{\text{on}} &= R_r C \ln(\frac{a\eta P R_{\text{r}} + T_{\max} - T_{\text{out}}}{a\eta P R_{\text{r}} + T_{\min} - T_{\text{out}}}) && (5) \\ \tau_{\text{control}} &= \tau_{\text{on}} + \tau_{\text{off}}. && (6) \end{aligned}$$

For each decentralized air conditioner user, the predicted schedulable capacity is as follows:

$$P_{\text{shut},t}(i) = \frac{\tau_{\text{off},t}(i)}{\tau_{\text{control},t}(i)} P(i), \tag{7}$$

where $P(i)$ is total rated power for the i^{th} user, $\tau_{\text{off},t}(i)$ is the shutdown duration for the i^{th} user in the t^{th} period, and $\tau_{\text{control},t}(i)$ is the control cycle duration for the i^{th} user in the t^{th} period.

The total schedulable capacity of the air-conditioning load in the sales area is as follows:

$$P_{\text{shut},t} = \sum_{i=1}^{n} P_{\text{shut},t}(i), \tag{8}$$

where n is the total number of consumers in the sales area.

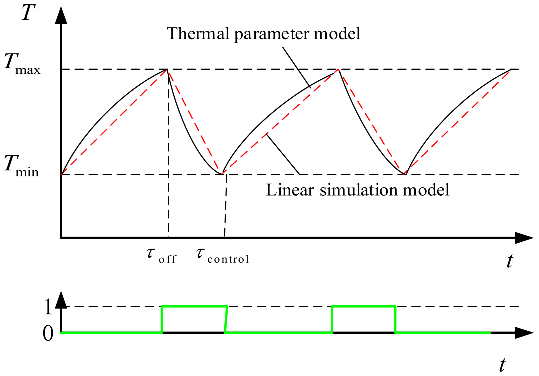

FIGURE 2. Linear simulation model for air-conditioning temperature regulation.

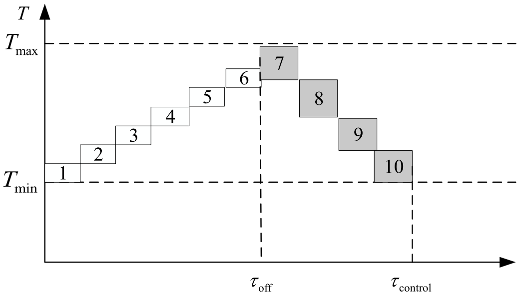

FIGURE 3. Schematic of the SQ model.

C. SQ MODEL

Air-conditioning control strategies based on the SQ control models have been widely adopted since their introduction according to [8]–[14]. A typical air conditioning SQ is shown in Fig. 4. As shown in the figure, there were 10 states in each operation cycle, including air-conditioning off SQ (1−6) and open SQ (7−10). During regular operation of the air conditioner, the conditions were sequentially switched through states one through ten to ensure that the room temperature was within the range.

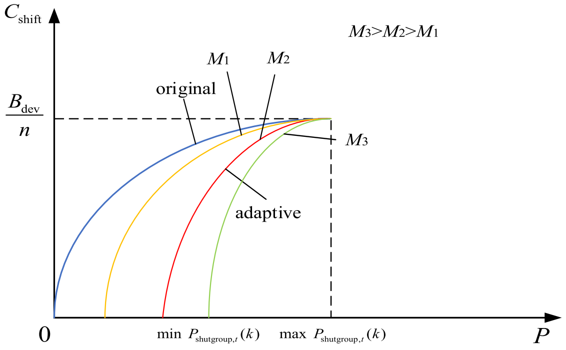

FIGURE 4. Inter-group compensation model of a quadratic curve.

IV. CONTROL STRATEGY FOR THE AIR-CONDITIONING LOADS

A. IMPLEMENTATION RULES FOR THE TCL CONTRACT

To reduce the difference in scheduling caused by the difference in the comfort of residents, residents and retailers needed to sign contracts for comfort intervals. Determining whether to participate in TCL was a free option for the user. Different types of TCL load contracts were set for the user's comfort difference. Users selected the allowable temperature range according to their comfort habits. The company allowed the regulation of the air conditioners, but it was necessary to ensure that the temperature was within the scope of the contract. The retailer conducted cluster control for users with the same type of contract, and the response capacity was determined by scheduling. Only users participating in TCL could obtain compensation. Each user who participated in DR was selectively informed about the compensation received within the same group and the users of other groups so that consumers were more reasonably guided to participate in the DR project.

B. TCL OBJECTIVE FUNCTION

For the residents' air-conditioning load scheduling, it was necessary to solve the massive optimization problem. The objective function was from the perspective of the load aggregator. The optimization goal was divided into three parts: maximizing the sales revenue, maximizing the peak profit, and minimizing the user peak shifting compensation. The above three parts meant that it was necessary to ensure that the utility's load reduction requirements were met while satisfying its profit maximization. While accurately fulfilling the DR task, the load adjustment amount was minimized, thereby reducing the load sales loss. When receiving the peak bidding profit from the utility, the response subsidy was as small as possible. Therefore, the air-conditioning load scheduling of the residents maximized the objective function of the retailer profit as follows:

$$\max C_{\text{profit}} = B_{\text{sell}} + B_{\text{shut}} - C_{\text{pay}} \tag{9}$$

$$s.t. \begin{cases} B_{\text{sell}} = \sum_{t=1}^{t_{\text{dayend}}} (\rho_{\text{sell},t} - \rho_{\text{buy},t}) \cdot \sum_{i=1}^{n} x_t(i) \\ B_{\text{shut}} = \sum_{t=t_{\text{start}}}^{t_{\text{end}}} \rho_{\text{shift},t} \cdot P_{\text{shut},t} \cdot \Delta t_{\text{shift}} \\ C_{\text{pay}} = \sum_{t=t_{\text{start}}}^{t_{\text{end}}} \sum_{i=1}^{n} (C_{\text{shift}}(S_t(i) \cdot P_{\text{shut},\,t}(i)) \\ \qquad + \rho_{\text{sell}}(t) \cdot S_t(i) \cdot P_{\text{shut},t}(i)) \cdot \Delta t_{\text{shift}}, \end{cases} \tag{10}$$

where B_{sell} is the sales profit of the electricity retailer before participating in the auxiliary service market, B_{shut} is the profit from the power utility, and C_{pay} represents the compensation for the peak payment to the user and the loss of the electricity sale. $\rho_{\text{sell},t}$ is expressed as the price of electricity sold, $\rho_{\text{buy},t}$ is the price of electricity purchased, t_{start} and t_{end} are the time beginning and ending of the DR project, $x_t(i)$ indicates the amount of electricity consumed by each user, $P_{\text{shut},t}$ corresponds to the quantity of reduction in each period, and $S_t(i)$ indicates the participation of the air-conditioning load in the TCL in each period, with the binary code being 0 or 1. When $S_t(i)$ was 0, the air conditioner was at the stage of shutting down. When $S_t(i)$ was 1, the air conditioner was at the stage of working. $C_{\text{shift}}(P)$ indicates the compensation for each household of the TCL of the air conditioner corresponding to the power reduction, and Δt_{shift} indicates the optimized step size of the TCL.

Determining whether to participate in the next day's TCL was an option for the power retailer. The judgment formula is as follows:

$$B_{\text{dev}} = \sum_{t=t_{\text{start}}}^{t_{\text{end}}} \rho_{\text{shift},t} \cdot P_{\text{shut},t} \cdot \Delta t_{\text{shift}} - \sum_{t=t_{\text{start}}}^{t_{\text{end}}} \sum_{i=1}^{n} \rho_{\text{sell},t} \cdot S_t(i) \cdot P_{\text{shut},t}(i) \cdot \Delta t_{\text{shift}} \geq 0, \tag{11}$$

where B_{dev} indicates the profit of the retailer before the compensation was allocated to the user. This formula indicated whether the peak-shifting profit could compensate for the loss caused by the reduction of electricity sales. When the above formula was more significant than zero, it meant that the peak-shifting profit was more significant and the retailer could participate in TCL. Otherwise, the retailer did not implement the ancillary service market the next day.

C. CONSTRAINTS FOR THE TCL STRATEGY

(1) Overall schedulable capacity constraints:

$$\sum_{i=1}^{n} S_t(i) \cdot P_{\text{shut},t}(i) \geq P_{\text{shut},t} \tag{12}$$

This formula indicated that the reduced load needed to meet the capacity reduction requirements.

(2) Individual schedulable capacity constraints:

In the process of dispatching, the continuous opening and closing times of each air conditioner are as follows:

$$\tau_{\text{on},t}(i) = \{\tau_{\text{on},t-1}(i) + [1 - S_t(i)] \cdot \Delta t_{\text{shift}}\}[1 - S_t(i)] \tag{13}$$

$$\tau_{\text{off},t}(i) = [\tau_{\text{off},t-1}(i) + S_t(i) \cdot \Delta t_{\text{shift}}] \cdot S_t(i). \tag{14}$$

It was necessary to ensure that each user's temperature range did not exceed $[T_{\max}, T_{\min}]$, so the continuous opening and closing time of the individual is constrained as follows [38]:

$$\tau_{\text{off},t}(i) \leq \tau_{\text{off}}(i) \tag{15}$$

$$\frac{\sum_{j=0}^{t} \tau_{\text{on},t}(i)}{\sum_{j=0}^{t} \tau_{\text{off},t}(i)} \geq \frac{\tau_{\text{on}}(i)}{\tau_{\text{off}}(i)}, \tag{16}$$

where the initial state was $\tau_{\text{off},0}(i) = 0$, $\tau_{\text{on},0}(i) = \tau_{\text{on}}(i)$.

Determining how to dispatch the air conditioner group was considered an issue here, so the statuses $S_t(i)$ of the air conditioners were the decision variables. The above solution process could be converted to 0-1 integer programming and solved by a specific solution strategy. However, the unreasonable design of the compensation mechanism led to the diversity and irrationality of solution results, and unreasonable scheduling might lead to the reduction of user responsiveness. When the responsiveness of customers was high, the reported reducible capacity increased, the number of allocated load reductions increased and the profit through the ancillary services market increased. Therefore, it was necessary to compensate for the responsiveness of various users involved in the TCL strategy.

D. COMPENSATION MECHANISM DESIGN

1) BASIC COMPENSATION MECHANISM

In the DR project, to reduce the load during the peak period of power consumption, the controllable air-conditioning load provided a specific reduction capacity, but during the control period, the change of user's electricity consumption habits also had a particular impact on the comfort degree of residential users. The compensation mechanism had to be set up to compensate for the loss of comfort degree. Compared with the compensation model proposed in other literature, in this research, a compensation model was proposed based on the quadratic curve. The compensation model was designed for the average inter-group response capacity, as shown in Fig. 4.

As users with the same temperature comfort constraints were treated equally, they were compensated individually as several groups. The maximum abscissa value shown in Fig. 4 was the maximum average controllable capacity group capacity of the air-conditioning load. The maximum longitudinal coordinate value was the average value of the uncompensated profit of the power retailer corresponding to the number of consumers. The min $P_{\text{shutgroup}}(k)$ and max $P_{\text{shutgroup}}(k)$ were calculated according to each user's temperature preference and the actual outdoor temperature. This mechanism allowed the power retailer to obtain profits from the program. The abscissa power could be expressed as an hour's controllable capacity, and the ordinate coordinate corresponded to an hour's subsidy. When the responsiveness

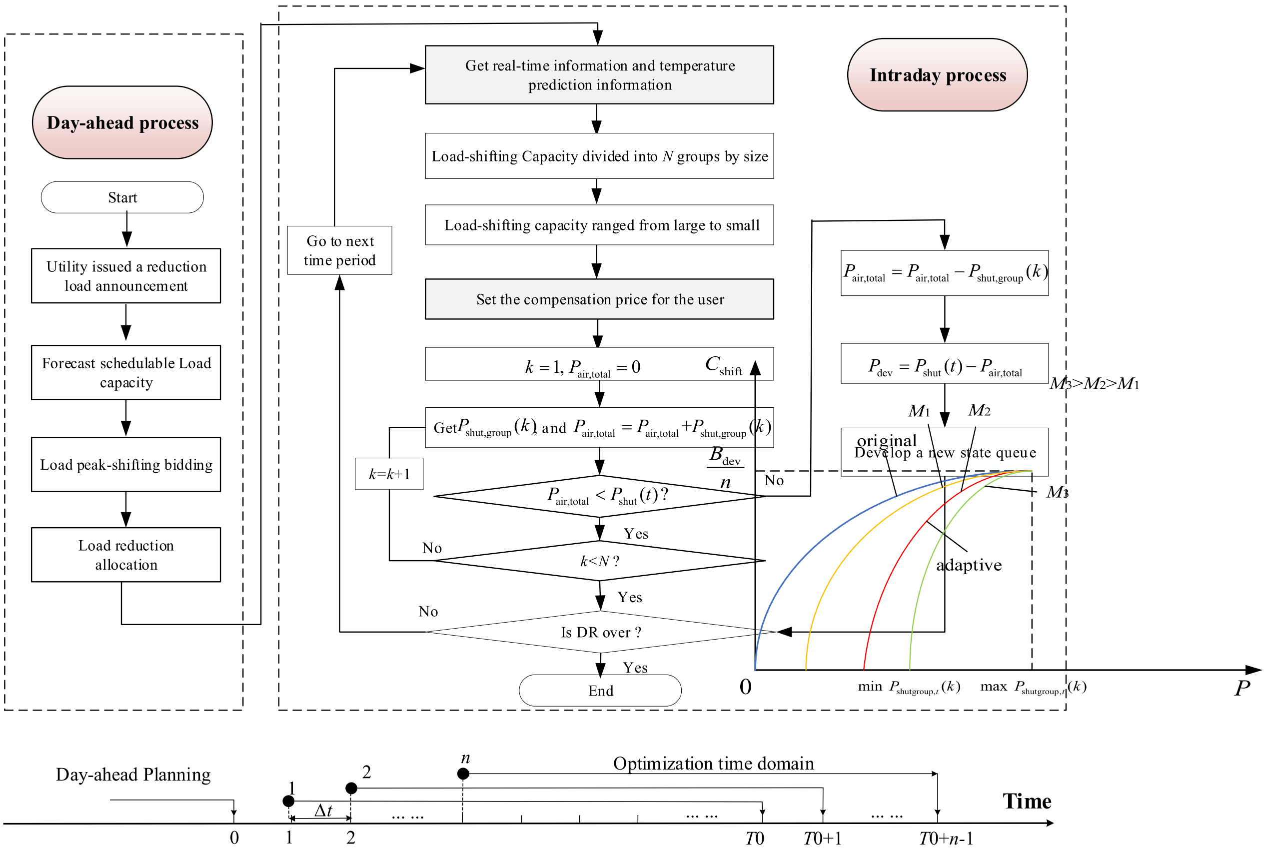

FIGURE 5. **Controllable air-conditioning scheduling strategy based on the basic compensation mechanism.**

of users was low, in order to encourage users to increase the reducible capacity further, each increase of the same reducible capacity could provide more compensation compared with the responsiveness of users with more considerable responsiveness. This was the reason for the application of this curve. It was required that the slope of the curve decreased with the increase of P, so the downward quadratic curve was used as the compensation curve. The equation for the blue line in Fig. 4 is shown as follows:

$$C_{\text{shift}}(P) = \frac{B_{\text{dev}}}{n \cdot \max P_{\text{shutgroup},t}(k)^2} \cdot (-P^2 + 2\max P_{\text{shutgroup},t}(k) \cdot P). \tag{17}$$

To increase the difference of compensation between groups in practical applications, it was necessary to adopt a quadratic curve with a more massive slope, as shown by the red line in Fig. 4, so the compensation curve is expressed as follows:

$$\begin{aligned} C_{\text{shift}}(P) &= M \cdot \frac{B_{\text{dev}}}{n \cdot \max P_{\text{shutgroup},t}(k)^2} \\ &\quad \cdot (-P^2 + 2\max P_{\text{shutgroup},t}(k) \cdot P) - (M-1) \cdot \frac{B_{\text{dev}}}{n}, \end{aligned} \tag{18}$$

where M is the adjustment parameter, which was greater than value 1. The value of the basic compensation for each user corresponded to the value in the curve projected to the ordinate scale. After adjustment, it was necessary to ensure that the difference between the groups was more visible. It is evident from Fig. 4 that the larger the value of M was, the less compensation users with low responsiveness were supposed to get. However, at the same time, the user with low responsiveness still needed a positive compensation value, that is, $C_{\text{shift}}(\min P_{\text{shutgroup},t}(k)) > 0$, so

$$1 < M < \frac{\max P_{\text{shutgroup},t}(k)^2}{(\max P_{\text{shutgroup},t}(k) - \min P_{\text{shutgroup},t}(k))^2}. \tag{19}$$

The compensation allocation for each user in the group also had to be compensated according to the corresponding average response capacity. To ensure the diversity of the initial states of each user in the group as much as possible, it was stipulated that compensation had to be equal in the group.

The setting of this compensation mechanism could further simplify the scheduling strategy from the perspective of the retailers. In response to the same capacity, the retailer hoped to achieve the minimum compensation. To encourage participation in the DR from the user's point of view, it was necessary to dispatch as much as possible from the controllable group with a large reduction capacity, which required (see the Appendix for proof):

$$M \leq \frac{\max P_{\text{shutgroup},t}(k)^2}{\max P_{\text{shutgroup},t}(k)^2 - \min P_{\text{shutgroup},t}(k)^2}. \tag{20}$$

Generally, it was difficult for the adjustable capacity to meet the peak reduction requirement, and some controllable air conditioners needed to be selected in the remaining group. There were also differences in the regulatory potential of users within the group. In the initial stage of direct load control, because the initial values of the indoor temperature of each air-conditioning user in the group were different, this may also have implied that the degree of willingness of users in the group was different. When the initial value of the indoor temperature was more significant, the user was more inclined to endure the temperature range. A high temperature indicated that the user's resistance to participation in DR was weaker. Conversely, when the initial temperature of the room was smaller, it meant that the user was more inclined to avoid the high temperature in the temperature range, suggesting that the user's resistance to the participation DR was stronger. To ensure the sustainability of the SQ model during scheduling, a new SQ was generated based on the redistributed capacity reduction. The scheduling strategy is shown in Fig. 5.

In the day-ahead process, the users signed the agreements with the power retailer and the retailer predicted the capacity of users in each group. The retailer made dispatching decisions according to the load reduction requirements of the utility. The scheduling policy shown in Fig. 5 indicated that for the users, the peak shifting capacity of the user could be divided into multiple groups according to the size, and the users in each group signed the same load control contract. First, it was necessary to judge the sum of the schedulable capacity of each group. When the schedulable capacity exceeded the normal situation, it was necessary to reselect the appropriate air-conditioning load according to the initial value of the indoor temperature in the group exceeding the expected load reduction. As a result, it was necessary to relocate the SQ capacity for the group.

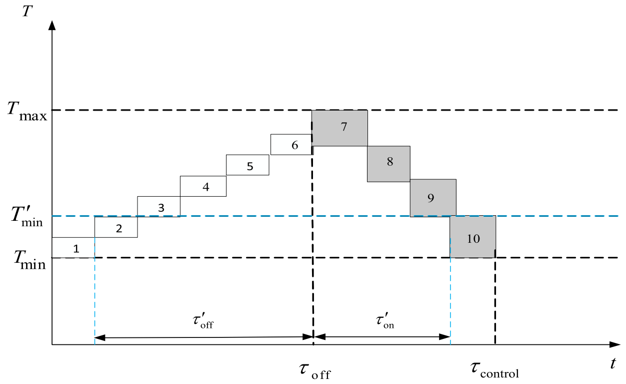

FIGURE 6. SQ after capacity redistribution.

Fig. 6 shows an SQ diagram after capacity redistribution. After the redistribution of the reduced capacity, the number of air-conditioning queues participating in the TCL system and the available capacity of the air conditioner in the corresponding queue might change. It was assumed that the lower limit of the queue temperature after capacity redistribution was $T'_{\min}$, and the relationship between the number of air conditioners N' participating in TCL and the number N of air conditioners in the group could be expressed as follows:

$$N' = \frac{T_{\max} - T'_{\min}}{T_{\max} - T_{\min}} \cdot N. \tag{21}$$

At the same time, in the ideal state (in which the initial state of the air-conditioning temperature was evenly distributed in the temperature range), the relationship between the actual shutdown duration τ'_{off}, the control cycle duration τ'_{control}, the original shutdown duration τ_{off}, and the original control cycle duration τ_{control} is as follows:

$$\tau'_{\text{off}} = \frac{T_{\max} - T'_{\min}}{T_{\max} - T_{\min}} \cdot \tau_{\text{off}} \tag{22}$$

$$\tau'_{\text{control}} = \frac{T_{\max} - T'_{\min}}{T_{\max} - T_{\min}} \cdot \tau_{\text{control}}. \tag{23}$$

The load reduction capacity of the overall air conditioning of the group involved in TCL $P_{\text{shutgroup},t}(k)'$ is as follows:

$$P_{\text{shutgroup},t}(k)' = \frac{N'}{N} \cdot P_{\text{shutgroup},t}(k). \tag{24}$$

After the capacity was re-allocated, the capacity of the entire regenerated SQ was generally reduced, but the average capacity stayed the same.

After N' was obtained from Equation (21), the upper and lower temperature limits, the control period, and the shutdown time of the new SQ in the ideal state could be found from Equations (22)–(24).

Figure 6 shows the situation when the capacity was reduced. Based on this situation, the capacity reduction that was increased in the day could also be analogized. In this case, the corresponding $T'_{\min}$ needed to be appropriately shifted down to expand the group's reduction capacity in response to the intraday response.

2) COMPENSATION AND REGULATION STRATEGY WITH UNEVEN INITIAL DISTRIBUTION

The above hypothesis was based on the assumption that the initial state diversity of the air-conditioning load at the initial stage of schedule was sufficient to satisfy the same number of air conditioners that could be in each state in the SQ, but in actual cases, the state diversity of the load could reach this level. On the one hand, this situation made the resulting load reduction fluctuate in the period, and the load could not correctly respond to the utility's required reduction requirements. On the other hand, the situation caused the queue's response capacity to deviate from expectation, which affected the scheduling plan. When the user's electricity behavior habits were fixed, to ensure the stability of the load reduction, it was necessary to rationally guide users to be involved in TCL. As a result, the additional compensation mechanism was proposed in order to eliminate the gap.

It was specified that the air-conditioning load per 0.5°C in the temperature range was a state group. The $n_{\mathrm{sta}}(j)$ was the number of air conditioners in the j^{th} state group, and the average number of air conditioners of other groups corresponding to the group was $\bar{n}_{\mathrm{sta}}(j)$. The value $\alpha \in (0,\ 1)$ was the standard value of the load distribution established by the retailer. When $n_{\mathrm{sta}}(j)/\bar{n}_{\mathrm{sta}}(j) < \alpha$ it could be considered that the initial state distribution of the air conditioner in the j^{th} state group was sparse. When $n_{\mathrm{sta}}(j)/\bar{n}_{\mathrm{sta}}(j) > 1/\alpha$ the initial state of the air conditioner in the state group could be considered to be densely distributed.

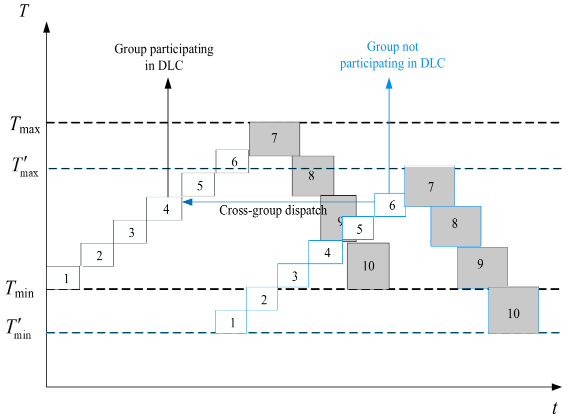

FIGURE 7. Schematic for cross-group scheduling.

Some individuals in the group corresponding to the capacity of $P_{\mathrm{shutgroup},t}(k)'$ were detected to be missing in the actual scheduling, and the cross-group scheduling for air-conditioners of the same initial state in other groups that did not participate in TCL had to be done. As shown in Fig. 7, we assumed that the number of consumers in the fourth state group that takes part in TCL were not enough in the SQ. Therefore, the other groups that did not participate in TCL were supposed to be cross-group dispatched to fill the gap. As shown in Figure 7, in the SQ that did not participate in TCL, the sixth state group had the same initial temperature with the fourth state in the group that took part in TCL. Consumers in state six could choose to take part in TCL according to their own will. In Fig. 8, the average reduction capacity that the group could provide is $P_{\mathrm{shutgroup},t}(k)$. When the A tangent to the curve was made at the abscissa value point $P_{\mathrm{shutgroup},t}(k)$ on the corresponding basic compensation curve, the corresponding additional compensation $w_{\mathrm{shift}}(P_{\mathrm{shutgroup},t}(k))'$ of the group could be expressed as follows:

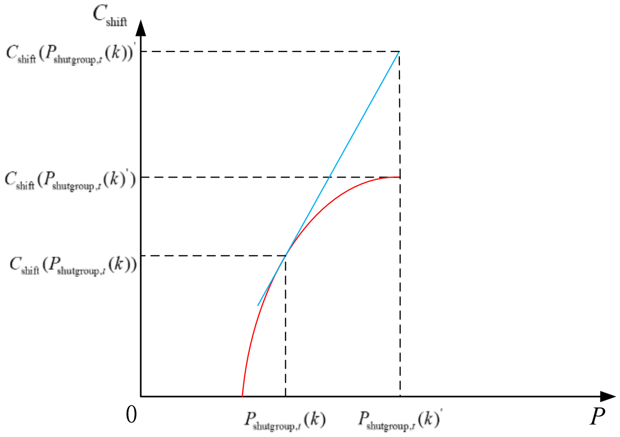

FIGURE 8. Design of the additional compensation mechanism.

$$\begin{aligned} & C_{\mathrm{shift}}(P_{\mathrm{shutgroup},t}(k))' \\ & = \frac{M \cdot B_{\mathrm{dev}}}{n \cdot \max P_{\mathrm{shutgroup},t}(k)^2} \cdot (-2P_{\mathrm{shutgroup},t}(k)' \\ & \cdot P_{\mathrm{shutgroup},t}(k) + P_{\mathrm{shutgroup},t}(k)^2 + 2 \max P_{\mathrm{shutgroup},t}(k) \\ & \cdot P_{\mathrm{shutgroup},t}(k)') - (M-1) \cdot \frac{B_{\mathrm{dev}}}{n}. \end{aligned} \tag{25}$$

The additional compensation mechanism was an alternative, and the user could choose whether to accept additional compensation to participate in cross-group scheduling.

It was also necessary to determine the cross-group users who participated in the scheduling. For the above additional compensation mechanism, it was still necessary to select the air-conditioning load from the non-controllable group with a significant average capacity reduction was because the more extensive the average reduction capacity, the lower the slope of the additional compensation line was, and the less compensation the electricity retailer needed to pay. The initial compensation value that was obtained by the user with a sparsely distributed state group was set to be the additional compensation value described above. For the users in the temperature range where the distribution within the group was dense, it was necessary to reduce the compensation value of the state group appropriately, but it also had to be slightly larger than the compensation of the contract group with lower capacity. This approach encouraged the user to shift from the initial state distribution dense state group to the sparse state group. The information about the additional compensation value was selectively given to the users within the group. When it was detected that there was a state group with both sparse and dense initial state distributions in the group, notice for the additional compensation value was preferentially given to the densely distributed state groups. When there are only state groups with sparse states, all other state groups were notified of the additional compensation value. When there were only state groups with dense states, notice for the compensation value of the other state groups was given to the group with dense states.

Since each user in the group had different considerations for comfort and economic compensation, the formulation of the compensation value in actual engineering applications needed to be partially adjusted to achieve the final stability of the SQ.

3) SQ REPARTITION

In the process of correcting the compensation value, if the user's responsiveness to cross-group scheduling was not high, the load fluctuation caused by the peak shifting would still exist. When such circumstances happened, it was necessary to reform the SQ. The main idea of this technique was to eliminate the load fluctuation caused by a specific sate. Therefore, it was necessary to make sure that the sparsely or densely distributed group was not in the controlling SQ.

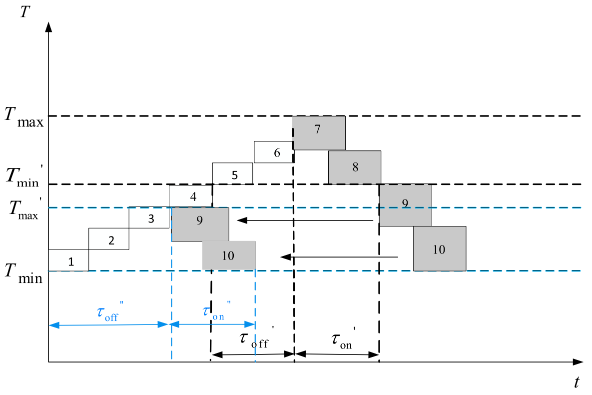

FIGURE 9. **SQ repartition.**

As shown in Fig. 9, when some initial states in the status queue were considered to be sparse, it was impossible to find air conditioners from the other TCL groups that were in the same initial state to participate in cross-group dispatching (that is, some users did not accept additional compensation mechanisms). For example, when the state of the fourth state group in the figure was sparse, the SQ needed to be re-divided. The first SQ in Fig. 9 was divided into two queues, with the fourth state group as the dividing line. The fourth state group air conditioner did not participate in the TCL system, but it did obtain the corresponding additional compensation set in Section 3.4.3. The other state groups were compensated according to the amount of reduction when the queue was not re-divided in order to encourage other users to adjust the initial state of the air conditioner to the fourth state group at the beginning of the scheduling. If the response capacity was allocated to the regenerated queue, then the re-allocation of the response capacity was prioritized for the queue that had more reduction capacity in the regenerated status queue.

There as a situation in which a group that did not participate in TCL was converted into a group that participated in TCL when the capacity was redistributed in intraday dispatching. Some users in the group achieved cross-group scheduling through an additional compensation mechanism. As a result, some states in the status queue of the group were sparse. At that time, it was first necessary to determine whether it was possible to determine that the air conditioners could be scheduled across groups from other groups that did not participate in TCL. Otherwise, the group was re-divided.

V. CASE ANALYSIS

For the electricity retailer, the decision-making stage was divided into the day-ahead stage and the intraday stage. In the day-ahead stage, the retailer needed to determine the price of electricity sold per period, count the user's capacity to be reduced, report the capacity to the utility and bid for the peak, respond to the allocation of load-reduction, and determine whether to participate in the next day's TCL strategy. During the intraday process, the power retailer needed to re-count the capacity of the controllable air conditioner in each optimized period, accept the redistribution of the response from the utility, and formulate the compensation mechanisms and control strategies.

The mathematical problem we formulated could be regarded as a linear or quadratic programming problem. Therefore, it was possible to adopt a CPLEX solver to solve the problem.

A. DAY-AHEAD PROCESS

1) SCHEDULABLE CAPACITY STATISTICS

In this section, a case is discussed in which the controllable air conditioners for all of the users under the same power sales area were the same model, the rated power was 3.5 kW, the temperature control parameter was $C = 0.18$kWh/°C, $R = 5.56$°C/kW and the energy efficiency ratio was $\eta = 3$. The average outdoor temperature prediction during the TCL was 37°C. Through investigation, the user's lower limits for the comfort interval were concentrated in the interval of [22°C, 25.5°C], and the upper limits of the user's comfort interval were concentrated in the interval of [25°C, 28.5°C]. According to the above statistical information, the electricity retailer and the user signed eight kinds of contracts, each T_{max} and T_{min} in the contract had a difference of 0.5°C, and the number of users signing each type of contract was equal.

In the day-ahead process, the utility planned to reduce the peak from 12:00 to 13:00 the next day. The upper and lower limits of the temperature were substituted into equations (4) and (6). τ_{on} was in the interval of [7.614, 8.319] min, and τ_{off} was in the interval [24.347, 33.6] min. The schedulable capacity was in the interval of [2.609, 2.853] kW. The statistical table of schedulable capacity is shown in Table 1. For each type of contract, it was assumed that the initial state of the indoor temperature of the air-conditioning load was evenly distributed within the scope specified by the contract.

After calculation and summation, it could be concluded that the total available capacity reduction of the retailer was 2.889 MW in the day-ahead process.

2) PEAK BIDDING DECISION

Figure 10 shows the bidding surface plot based on the bidding function $\rho_{shift,t} = 0.12P_{total,t} \cdot (10 - \sqrt{P_{shuttotal,t}})$. The variable $P_{total,t}$ is the total load reduction, $P_{shuttotal,t}$ is the

TABLE 1. Schedulable capacity statistics.

Contract	1	2	3	4	5	6	7	8
τ_{on} /min	3.803	3.84	3.885	3.928	3.971	4.015	4.061	4.107
τ_{off} /min	16.479	15.754	15.091	14.481	13.919	13.399	12.917	12.468
Average capacity/ kW	2.934	2.904	2.874	2.843	2.813	2.783	2.753	2.723

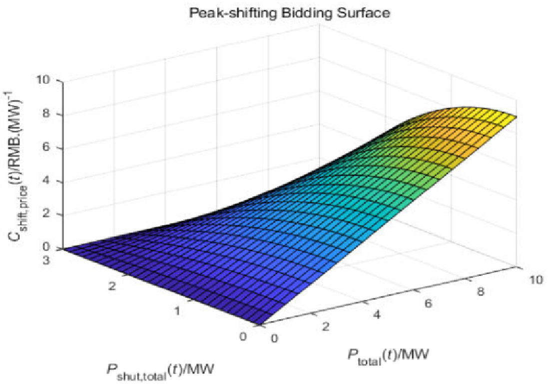

FIGURE 10. Peak bidding decision surface.

TABLE 2. Air-conditioning load compensation.

Contract	Compensation cost/RMB				
	1	2	3	4	5 (91consumers)
Peak reduction	3.399	3.397	3.389	3.376	3.359

load reduction potential of each retailer, and $\rho_{shift,t}$ is the peak shifting value.

For the total demand reduction of 10 MW and the schedulable capacity of 2.889 MW, the retailer determined the competitive value of 3 RMB/(kWh) during this period according to the bidding function and reported it to the utility. The utility decided to allocate 1.7 MW to the retailer after calculation.

3) COMPARISON OF THE COMPENSATION MECHANISMS

In the eight types of air-conditioning contracts signed, according to the scheduling strategy shown in Fig. 5, the air-conditioning loads of the first to fourth types of contracts were all involved in DR, and the load of the fifth type of contract was a redistribution of 225.5 kW. Ninety-one air conditioners in the fifth group participated in DR. The total response capacity of the group was 227.21 kW and the average capacity was 2.840 kW. The upper and lower limits of the original temperature of the fifth group of loads were $T_{max} = 26.5°C$, $T_{min} = 23.5°C$, and $T_{min}' = 24.6°C$ after redistribution. The known parameters were brought into Formula (11) to obtain $B_{dev} = 3399.15$RMB.

The retailer could participate in the auxiliary service market the next day. The value range of M was $1 < M < 7.212$, so we considered M to be 7. The air-conditioning load compensation per user for the five groups participating in TCL is shown in Table 2. In the day-ahead process, by participating in the ancillary services market, the profit of the electricity retailer was 1398.36 RMB.

To further compare the distribution problems of various compensation mechanisms, the compensation proposed in this research was compared with the compensation method proposed by [23] according to the temperature setting deviation (the temperature setting value was 25.25°C) and the contribution of the peak shifting proposed in [25]. To ensure the fairness of the comparison, the total compensation that could be allocated was the same. The values of compensation for each group are shown in Fig. 11.

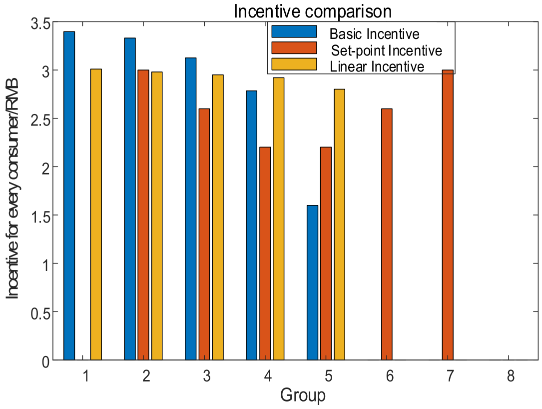

FIGURE 11. Comparison of the three compensation mechanisms.

As shown in Fig. 11, when the deviation of the temperature setting value was small, the scheduling of the control group needed to be prioritized to maximize the profit. This compensation mechanism had three defects: 1) All of the users' temperature comfort was considered together. 2) The users were encouraged to participate in the control group that deviated from the temperature set value to a certain extent, but the mechanism could not guarantee the promotion of users' enthusiasm in the participation of control groups with more reduction capacity, and 3) Control groups with considerable capacity reduction could not all be compensated.

While the compensation mechanism provided in [25] could be compensated according to the user's contribution to peak shifting, due to the linear compensation model, the compensation difference between groups was not visible enough. It was difficult to encourage users to actively participate in control groups with a large reduction capacity.

In contrast, the primary compensation method mentioned in this paper could not only compensate users according to the contribution of peak shifting, but also increase the difference of compensation between groups and encourage users to actively participate in DR. Because the overall reduction capacity of the users under the former two compensation mechanisms was likely to be lower than the capacity under the compensation mechanism of this research, the profit obtained by the retailer was affected by the decrease of the user's responsiveness.

4) REGULATING STRATEGY FOR THE UNEVEN DISTRIBUTION OF INITIAL STATES

The initial states of operation of the air conditioner were considered to be ideal distributions in the above scheduling strategy, but the initial temperature states of the air-conditioning load in each group were challenging to evenly distribute within the range of the signed temperature contract. Therefore, it was necessary to properly schedule the air conditioner for this situation, and to consider the case for which a particular state distribution was sparse in the temperature interval.

It was assumed that the value of the peak was 1.7 MW at this time and $\alpha = 2/3$. The load amount of the third group was judged to be sparse in the temperature range of 25.5−26°C, and $n_{\text{sta}}(j)/\overline{n_{\text{sta}}(j)} = 1/3$. We considered a comparison of the three compensation cases:

(1) Compensation when cross-group scheduling and state-queue repartition methods were not used;

(2) Compensation when the cross-group scheduling method was used; and

(3) Compensation when the SQ repartitioning method was used.

5) COMPENSATION FOR THE FIRST SITUATION

To ensure peak shifting requirements, it was necessary to consider the case of minimum peak reduction. The reduction capability of each air conditioner of the third group air conditioner was unchanged, and the third group of users was considered in the scheduling plan. $C_{\text{dev}} = 3399.26$ RMB. The compensation allocation for the case of no additional compensation and no state-queue repartition is shown in Table 3. Since the fifth group had 15 air conditioners missing in the 25.5−26°C state group, 107 users participated in TLC in the fifth group. The profit was reduced to 1395.67 RMB.

TABLE 3. **Compensation for the first situation.**

Contract	Compensation cost /RMB				
	1	2	3 (110 consumers.)	4	5 (107 consumers.)
Peak reduction	3.398	3.397	3.389	3.376	3.359

6) COMPENSATION FOR THE SECOND SITUATION

The temperature range of the third group air conditioner was set to [24.5°C, 27.5°C], in which the load state was sparse in the temperature range of 25.5−26°C, the sixth group (the temperature interval was set to [23°C, 26°C]) did not participate in the TCL and the group could be compensated for the cross-group scheduling in the range of 25.5°C–26°C. There were seven air-conditioning loads in the state group of the TCL, and 15 air conditions were missing in the state. We considered a circumstance in which users actively responded to the cross-group dispatching. Therefore, it was necessary to cross-group the scheduling from the load of the corresponding temperature section of the sixth group. The average load reduction capacity of the third group corresponded to $P_{\text{shut,air}}(t, 3)' = 2.874$kW. The average load reduction capacity of the sixth group corresponded to $P_{\text{shut,air}}(t, 6) = 2.783$kW, and $B_{\text{dev}} = 3399.15$ RMB.

Therefore, after compensation by the additional compensation mechanism, compared with Table 2, the compensation obtained by each group was as shown in Table 4.

TABLE 4. **Compensation for the second situation.**

Contract	Compensation cost/RMB						
	1	2	3 (103 consumers.)	3 (7 consumers.)	4	5 (91 consumers.)	6 (15 consumers.)
Peak reduction	3.399	3.397	3.389	3.412	3.376	3.359	3.412

It could be seen that the users in the third group were divided into additional compensation users (temperature range 25.5°C–26°C) and basic compensation users when users in the sixth group were compensated with additional compensation mechanism. After calculation, the retailer obtained 1397.85 RMB and the revenue decreased compared with evenly distributed initial temperature states. Considering the fact that the cross-group scheduling was performed under ideal conditions if the cross-group scheduling responsivity of the sixth group users was not high enough to cover missing states, the retailer's profits were further reduced.

7) COMPENSATION FOR THE THIRD SITUATION

When the responsiveness for the load in Groups 6−8 was not high enough to compensate for the missing state of the third group, an additional compensation mechanism could not be applied. The loads in the third group needed to be re-divided into two SQs. The air conditioners with a temperature range of 25.5°C–26°C did not participate in the TLC but they did accept the compensation of the additional compensation mechanism.

When the peak was 1.7 MW after the users of Groups 1−5 participated in TCL, they were allocated a 328.99 kW reduction, a total of 114 users participated in DR, and the actual response was 331.17 kW. The average reduction of the capacity was 2.807 kW, and $B_{\text{dev}} = 3399.26$ RMB. Table 5 shows the compensation for each group after the SQ was reassigned on an hourly time scale.

TABLE 5. **Compensation for each group after the SQ was regenerated.**

Contract	Compensation cost /RMB					
	1	2	3 (60 consumers)	3 (43 consumers)	4	5 (114 consumers)
Peak reduction	3.399	3.397	3.389	3.389	3.376	3.359

As shown in Table 5, there were two kinds of compensation values due to queue repartitioning for the users with a temperature range between 25.5°C and 26°C. Although they did not participate in the TCL system, additional compensation values were obtained to encourage other users in the group to adjust the initial temperature state to this temperature range. Compared with Table 4, the number of users participating in the DR of Group 5 increased, because after the SQ was regenerated, the reduction capacity of the third group was reduced. The profit of the electricity retailer was calculated to be 1359.77 RMB. To achieve the smoothness of the load reduction, the re-division of the status queue weakened the schedulable capacity of participating in the TCL group so that more users participated in the peak shifting, and the retailer needed to pay more compensation so that the profit was reduced compared with the second situation.

The compensation distributions for each group of users in the above three cases are shown in Fig. 12.

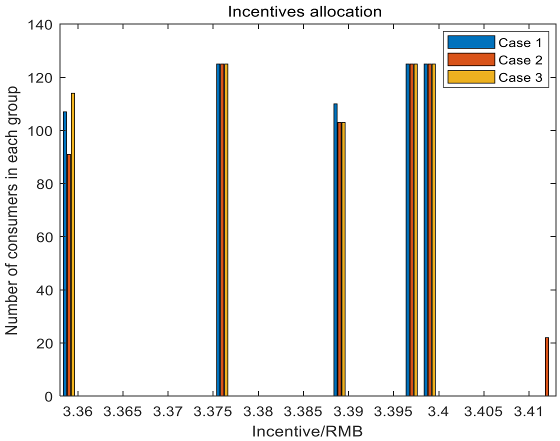

FIGURE 12. **Comparison of the compensation allocations in the three cases.**

As can be seen from Fig. 12, since cross-group scheduling only occurred in the second case, the additional compensation value was only attributed in the second case. The compensation values of the three cases were different in the third group and the fifth group. The number of users participating in the TCL in the fifth group was different due to the different response capacities of the third group. In the second case, due to the situation of the cross-group scheduling, the response capacity of the third group was the largest. In the third case, sparsely distributed air conditioners were divided from the SQ, so the response capacity of the third group was the lowest at this time.

B. INTRADAY PROCESS

Considering the prediction error of the day-ahead stage, the redistribution of the peak-shifting index due to the unpredictable load prediction error occurred in the daytime.

1) LOAD REDUCTION RE-RESPONSE

In the intraday progress, since the prediction of the uncontrollable load was not accurate enough, if there was a situation in which the load peak was higher or lower than the previous predicted value in the daytime, the compensation needed to be recalculated when the retailer re-responded to the utility.

We considered a case during the scheduling period at 12:30−12:40. The utility needed to shift more load peak during the period through load forecasting. The value that was allocated to the retailer was 2 MW, and the value for other periods was still 1.7 MW.

When the peak reduction was redistributed during the day, it was necessary to reformulate the control strategy based on the assigned value. After the response index was increased to 2 MW, the price of the peak-bidding changed from 3 RMB/(kWh) to 3.5 RMB/(kWh). According to Table 2, the air-conditioning load of the one to sixth contract was signed, and the sixth load was redistributed to obtain a total of 204 kW of reduced capacity. In total, 74 air conditioners in this group participated in TCL, and the actual response total capacity was 205.94 kW. $B_{\text{dev}} = 4998.06\text{RMB}$ was for the profit of 2 MW peak shifting in the time scale of an hour.

When the peak shifting values were 1.7 MW and 2 MW, respectively, the compensation value corresponded to the amount of a one-hour reduction load. Therefore, the compensation for each group of loads needed to be linearly adjusted according to the time scale. When the peak was cut by 2 MW, the compensation was performed in 10 min, while the compensation for 1.7 MW peak-shifting was performed in 50 min. The compensation for each group is shown in Table 6.

TABLE 6. **Compensation after the load reduction re-response.**

Contract	Compensation cost/RMB					
	1	2	3	4	5	6
2 MW Peak reduction	0.833	0.832	0.831	0.827	0.823	0.818 (74 consumers)
1.7 MW Peak reduction	2.833	2.831	2.824	2.813	2.799 (91 consumers)	/

As shown in Table 6, after the peak reduction was redistributed in the intraday process, the compensations of each group participating in TCL were less than the compensation of 2 MW peak reduction, and slightly larger than the compensation of 1.7 MW peak reduction. The retailer made a profit of 1419.53 RMB.

2) SQ REPARTITION AFTER CROSS-GROUP DISPATCHING

There was a circumstance when cross-group dispatching and SQ repartition happened at the same time. The case of cross-group scheduling that occurred as described in Section 4.1.7 based on the load re-response in Section 4.2.1 was considered. According to the calculation method above, the 2 MW peak-reduction compensation of the one-hour scale could be calculated, as shown in Table 7. Therefore, the compensation for users between 12:00 and

TABLE 7. Compensation for each group with SQ repartition and cross-group dispatching.

Contract	Compensation cost/RMB							
	1	2	3 (103 consumers)	3 (7 consumers)	4	5	6 (15 consumers)	6 (74 consumers)
Peak reduction	4.998	4.995	4.983	5.017	4.964	4.939	5.017	4.909

Table 8 Compensation for each group with SQ repartition and cross-group dispatching

Contract	Compensation cost /RMB							
	1	2	3 (103 consumers)	3 (7 consumers)	4	5	6 (15 consumers)	6 (74 consumers)
2 MW Peak reduction	0.833	0.832	0.831	0.836	0.827	0.823	0.836	0.818
1.7 MW Peak reduction	2.833	2.831	2.824	2.843	2.813	2.799 (91 consumers)	2.843	

TABLE 8. Compensation for each group with SQ repartition and cross-group dispatching.

Contract	Compensation cost /RMB							
	1	2	3 (103 consumers)	3 (7 consumers)	4	5	6 (15 consumers)	6 (74 consumers)
2 MW Peak reduction	0.833	0.832	0.831	0.836	0.827	0.823	0.836	0.818
1.7 MW Peak reduction	2.833	2.831	2.824	2.843	2.813	2.799 (91 consumers)	2.843	

13:00 followed, as shown in Table 8. The profit of the retailer was calculated to be 1418.99 RMB, and after additional compensation and re-division of the SQ, the profit was less than the profit described in Section 4.2.1.

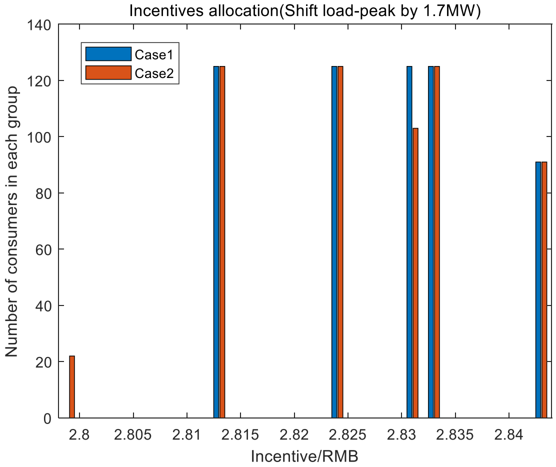

FIGURE 13. Comparison of the compensation distribution in two cases with 1.7 MW peak reduction.

The compensation distribution comparisons for the above two cases are shown in Figs. 13 and 14. The difference in the compensation distribution peak shifting of 1.7 MW and 2 MW was due to the difference in additional compensation and due to the additional compensation results in a reduction in the sales profit to avoid peak shifting fluctuations.

VI. CONCLUSION

Based on other references, in this study, a basic compensation scheme for the response degree of multi-user participation in TCL based on the strategic control of air-conditioning load peak-shaving is proposed with the background of the participation of power retailers in ancillary service markets, and for the process of load reduction, an additional compensation scheme is proposed. The two compensation schemes corresponded to the TCL strategy. For the basic compensation method, the scheme increased the difference in the compensation between groups and gave priority compensation to users with high responsiveness. It was also a novelty for the additional compensation schemes and cross-group dispatching, which considered load fluctuation based on the basic compensation schemes. The additional incentives also considered a case in which users did not react to the cross-group dispatching. Under such circumstances, the concept of SQ repartition was presented. In the case study, we came up with comparisons of the compensation distribution for the day-ahead and intraday processes. In conclusion, compared with other compensation schemes in the literature, this compensation mechanism was more reasonable, and it could smooth load reduction fluctuations.

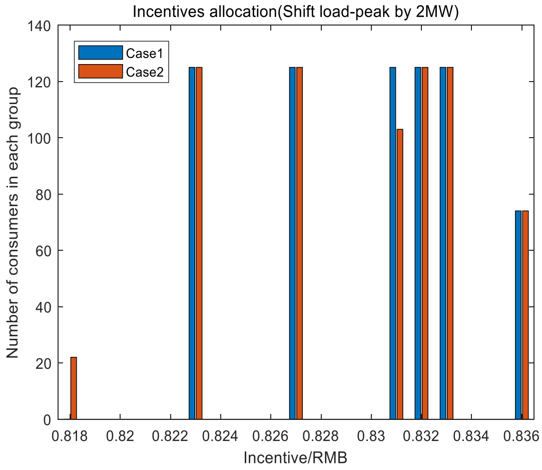

FIGURE 14. Comparison of the compensation distribution in two cases with 2 MW peak reduction.

This research focused on the compensation allocation among groups of users under different temperature contracts. Since it was necessary to control the uniform distribution of users within groups within the temperature range as far as possible, the compensation allocation among groups of users should be further discussed based on an additional compensation mechanism to fully mobilize users at different temperatures to participate in DR.

APPENDIX

Assuming that the number of users corresponding to the K^{th} control group participating in DLC is $N(k)$, the problem is converted to a solution according to the principle of minimum compensation under the premise of meeting the peak shaving requirements:

$$\min \sum_{k=1}^{K} N(k) \cdot C_{\text{shift}}(P_{\text{shut,group}}(t,k)) \tag{A1}$$

$$s.t. \left\{ \begin{array}{c} \sum\limits_{k=1}^{K} N(k) \cdot P_{\text{shut,group}}(t,k) = P_{\text{shut}}\ (t) \\ N(k) < n(k) \end{array} \right\} \tag{A2}$$

While

$$\begin{aligned} & N(k) \cdot C_{\text{shift}}(P_{\text{shut,group}}(t,k)) \\ & = M \cdot \frac{B_{\text{dev}}}{n \cdot \max P_{\text{shut,group}}(t,k)^2} \cdot (-N(k) \cdot P_{\text{shut,group}}(t,k)^2 \\ & \quad +2 \max P_{\text{shut,group}}(t,k) \cdot P_{\text{shut,group}}(t,k)) - (M-1) \\ & \quad \cdot \frac{B_{\text{dev}}}{n} \cdot N(k) \end{aligned} \tag{A3}$$

Transforming the original problem into solving

$$\begin{aligned} \max \sum_{k=1}^{K} & N(k) \cdot P_{\text{shut,group}}(t,k) \cdot (M \cdot \frac{B_{\text{dev}}}{n \cdot \max P_{\text{shut,group}}(t,k)^2} \\ & \cdot P_{\text{shut,group}}(t,k) + (M-1) \cdot \frac{B_{\text{dev}}}{n} / P_{\text{shut,group}}(t,k)) \end{aligned} \tag{A4}$$

To schedule as many highly responsive users as possible, it is guaranteed that

$$\begin{aligned} M \cdot & \frac{B_{\text{dev}}}{n \cdot \max P_{\text{shut,group}}(t,k)^2} \cdot P_{\text{shut,group}}(t,k) \\ & + (M-1) \cdot \frac{B_{\text{dev}}}{n} / P_{\text{shut,group}}(t,k) \end{aligned} \tag{A5}$$

is the incremental function of [min $P_{\text{shut,group}}(t,k)$, max $P_{\text{shut,group}}(t,k)$] for the variable $P_{\text{shut,group}}(t,k)$.

After derivation, there is the constraint as follows.

$$\min P_{\text{shut,group}}(t,k)^2 \geq \frac{M-1}{M} \cdot \max P_{\text{shut,group}}(t,k)^2 \tag{A6}$$

Therefore, it is concluded that

$$M \leq \frac{\max P_{\text{shut,group}}(k)^2}{\max P_{\text{shut,group}}(k)^2 - \min P_{\text{shut,group}}(k)^2} \tag{A7}$$

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