Hierarchical Optimal Scheduling for Air Conditioner’s Load Aggregator

Xiaoyu XIE$^1$ and Yongjun ZHANG$^1$

1 School of Electric Power, South China University of Technology, Guangzhou, Guangdong, China
E-mail: zhangjun@scut.edu.cn

Abstract. In this paper, a scheduling framework based on air-conditioning load aggregator is first proposed. Then the split constant frequency air-conditioning load is optimized by minute level. The step function characteristic between the average air-conditioning load per hour and the temperature difference set at the beginning and the end of the time is obtained and linearized. A temperature difference-power model suitable for air-conditioning hourly scheduling is established. Secondly, aiming at the multiple load aggregators existing in the distribution area, this paper proposes a non-cooperative game model of air-conditioning load aggregators. Considering the problem of discretization of control variables in the game revenue function, this paper introduces continuous intermediate variables, establishes a hierarchical optimization model of the game, and gives the proof that the hierarchical optimization of the game has a unique pure strategy Nash equilibrium solution and the solution method. Finally, the feasibility of the proposed method is verified by numerical simulation.

1. Introduction

Demand Response (DR) is an act of changing the electricity habit of power users in response to power companies' electricity price or incentive signal [1], which can peak the grid load and improve grid equipment’s utilization [2-3]. Air conditioning is an important demand side response resource, which is not only an important part of the resident load, but also has strong adjustable performance [4]. However, due to the large number of air-conditioning users in the distribution network, wide distribution and insufficient information interaction with the grid companies, it is difficult for the grid companies and users to dig deep into the resources that respond to air-conditioning demand. In some countries, Load Aggregator (LA) can act as an intermediary between power companies and users [5], using specialized means to integrate user demand response resources, so as to fully utilize demand response resources.

In the existing literature, the physical models of fixed-frequency air conditioners mostly refer to the Equivalent Thermal Parameter (ETP) modelling method [6], and the control methods are mainly temperature control [7], start and stop control [8] and periodic pause control [9]. At present, in most studies, the time scale of air conditioning control is minute level [10]. When long-term scheduling is required, it is easy to cause dimension disaster, due to the high time dimension. Even the methods of periodic pause control and temperature control provide a feasible method for long-term scheduling, they lack the flexibility of scheduling. It is difficult to dig deep of the translational load characteristics of the air conditioner.

With the liberalization of the electricity market, a single region does not only contain a single LA, but multiple LAs competing with each other, forming a non-cooperative game between multiple entities [11]. At present, there are many literatures on the application of the game in the demand response of
the power market. Literature [12] proposes a non-cooperative game model for the PV user group as the main body of the game based on the user's automatic demand response. Literature [13] establishes a hierarchical non-cooperative game model for the multi-class load of residential users. However, the translational load is not refined in this literature.

In view of the problems mentioned in the above literature, this paper firstly performs minute-level optimal scheduling according to the air-conditioner equivalent heat path model with one hour as the scheduling period. The ladder function relation between the minimum average load of air conditioner in one hour and the temperature difference at the beginning and end of the hour is obtained and linearized. The air conditioning temperature difference-power characteristic model, which is suitable for hourly scheduling, is established. Then, based on the temperature difference-power model parameters, a model of multiple air conditioning LA non-cooperative games is established. Finally, the simulation demonstrates the feasibility and effectiveness of the proposed method.

2. Load aggregator scheduling architecture
LA plays a role in the power supply companies and users. The benefits of LA are mainly reflected in the difference between the purchase cost of the grid for its demand response resources and the cost of compensation to users. In general, LA is only responsible for regulating the partial load of users' participation in the demand response, and the normal power usage behaviour is still directly handed over by the grid to the user [14].

The electricity demand price of the demand response resources issued by grid companies is related to the total load reduction in the market. When there are multiple LAs in a certain area, there will be a certain competition relationship between the LAs. In the analysis of this paper, this kind of game can be regarded as a complete information static game. The relationship between LA and grid companies and users is shown in Figure 1:

![Figure 1. Load aggregator scheduling architecture.](image)

3. Air conditioning temperature difference-power model
The air conditioning load temperature change model is shown as below:

$$\theta_{\tau+1} = \xi \theta_{\tau} - S_{\tau} (1-\xi) \theta_{\tau} + (1-\xi) \theta_{\tau+1}$$

where \(\tau\) represents the time sequence number in the scheduling period, minutes; \(\theta_{\tau}\) and \(\theta_{\tau+1}\) represent the indoor temperature at \(\tau\) min and \(\tau+1\) min, respectively; \(\theta_{\tau+1}\) represents the outdoor temperature at \(\tau+1\) min, °C; \(\xi\) represents the heat dissipation coefficient; \(\theta_{\tau}\) represents the contribution of the cooling power of the air conditioner to the indoor temperature drop under the condition that the air conditioner is on, °C; \(S_{\tau}\) indicates the on-off state of the air conditioner in \(\tau\)-minute, when its value is 1, it indicates that the air conditioner is in the on state, otherwise it is in the off state.

The following optimization problem is solved based on formula (1), and the average power minimum of the air conditioning load in a certain scheduling period under the upper and lower limits of temperature can be obtained:
where $P_{av}$ is the average power in the scheduling period; $P_0$ is the instantaneous power of air conditioner in the on state; $H$ is the total number of times in the scheduling period; $\theta_{\text{min}}$ is the indoor temperature lower limit; $\theta_{\text{max}}$ is the indoor temperature upper limit; $\theta_{\text{set}}$ and $\theta_{\text{end}}$ are the set temperature of scheduling initial time and ending time respectively.

Assume that the instantaneous power of the air conditioner $P_0$ is 4kW, the heat dissipation coefficient $\zeta$ is 0.96, and the upper and lower limits of the temperature are 27°C and 23°C respectively. The contribution of the air conditioning refrigeration power to the indoor temperature drop $\theta_c$ is 39°C, and the scheduling period is 60 minutes. The outdoor temperature is 34°C. By continuously changing the set temperature of the initial and end time of the scheduling period, the minimum power in the scheduling period is as shown in figure 2:

![Figure 2](image_url)

It can be seen from the figure that when the temperature difference between the initial and the end time in the scheduling period is the same, the average power is basically the same. Let the points in the coordinate chart with the same temperature at the initial time and the end time be connected to form a temperature isochromatic line. Judging from the direction perpendicular to the temperature isochromatic line, the average power of the air conditioner shows the nature of a step function. In fact, by simulating the air conditioning load under different parameters, the stepped power characteristics similar to those in Figure 3 can be obtained, except that the power level and temperature difference range of each step may change with the air conditioning characteristic parameters change. The characteristic represented by the mathematical model is linearized and shown as follow:

\[
\begin{align*}
\min P_{av} &= \frac{P_0 \sum_{\tau=1}^{N} S_{\tau}}{H} \\
\theta_{r+1}^{\text{in}} &= \xi \theta_r^{\text{in}} - S_r (1-\xi) \theta_r + (1-\xi) \theta_r^{\text{out}} \\
\theta_{\text{min}}^2 \leq \theta_{\text{r}}^{\text{in}} &\leq \theta_{\text{max}}^2 \\
\theta_{\text{in}}^{\text{out}} &= \theta_{\text{set}} + \theta_{\text{end}}^2
\end{align*}
\] (2)

\[
\begin{align*}
P_i(t) &= \sum_{n=1}^{N} P_{i,n} x_{i,n} \\
\sum_{n=1}^{N} x_{i,n} \Delta \theta_{i,n}^{\text{in}} &\leq \theta_i(t+1) - \theta_i(t) \leq \sum_{n=1}^{N} x_{i,n} \Delta \theta_{i,n}^{\text{out}} \\
\sum_{n=1}^{N} x_{i,n} &= 1
\end{align*}
\] (3)
where $t$ is the time serial number in hours; $P_i(t)$ represents the average load of the air conditioner $i$ at $t$-hour; $P_{i,t,N}$ represents the $N$th power level value of the air conditioner $i$ at $t$-hour; $\Delta \theta_{i,lo}$ and $\Delta \theta_{i,up}$ are the $N$th temperature difference indicating the air conditioner $i$’s upper and lower limit thresholds at $t$-hour; $\theta_i(t)$ is the initial indoor temperature set value at the $t$-hour of the air conditioner $i$, and the indoor temperature set value at $t$-1-hour at the end time; $\theta_i(t+1)-\theta_i(t)$ reflects the difference between the temperature set values at the beginning and the end time at $t$-hour.

The binary logic variable $x_{i,t,N}$ is introduced in the formula. $x_{i,t,N} = 1$ indicates that the temperature difference set value of the air conditioner $i$ at the beginning and the end of $t$-hour, $\theta_i(t+1)-\theta_i(t)$, is between $\Delta \theta_{i,lo}$ and $\Delta \theta_{i,up}$; Otherwise, $x_{i,t,N} = 0$, the temperature difference set value of the air conditioner $i$ at the beginning and the end time of $t$-hour, $\theta_i(t+1)-\theta_i(t)$, is less than $\Delta \theta_{i,lo}$ or greater than $\Delta \theta_{i,up}$. The third constraint defines the temperature difference between the beginning and the end of the air conditioning scheduling period can and can only be within a temperature threshold interval.

Since the number of air conditioners may reach several hundred or even several thousand within the jurisdiction of a LA. This paper clusters according to the air conditioning temperature difference-power characteristic parameters.

4. Hierarchical optimization model of game
The power grid companies usually use the real-time electricity price of the demand response market for the power-cutting price of LA. The electricity price has a certain linear relationship with the total load, as shown below [13, 15]:

$$p^{DR} = aL + b$$  \hspace{1cm} (4)

In the formula, $p^{DR}$ is the real-time electricity price of the demand response market in a certain period; $L$ is the total network load of the period; $a$ and $b$ are positive electricity price coefficients, which means that the demand response price grows higher as the total load increases.

According to formula (4), the income function of aggregator $j$ is:

$$R_j = \sum_{i=1}^{K_j} \left[ a \left( \sum_{i=1}^{K_j} L_i(t) + L_{base}(t) \right) + b \left( \theta_{j,l}(t+1) - \theta_j(t) \right) \right]$$

$$- \frac{1}{2} \sum_{i=1}^{K_j} k^{\text{com}} \left( L_{base}(t) - L_j(t) \right)^2$$  \hspace{1cm} (5)

Among which,

$$L_j(t) = \sum_{i=1}^{U_j} P_i(t)$$  \hspace{1cm} (6)

where, $L_j(t)$ and $L_k(t)$ are the load size of the aggregators $j$ and $k$ at $t$-hour; $L_{other}(t)$ is the sum of all other uncontrollable loads in the network within $t$ hours; $L_{base}(t)$ is the pre-scheduling load of the aggregator $j$ at $t$-hour; $k^{\text{com}}$ indicates the compensation cost coefficient of the aggregator $j$ to users; $t_1$ and $t_2$ indicate the start and end time of the grid-to-aggregate peak compensation respectively; $T_1$ and $T_2$ indicate the start and end time of the entire scheduling period respectively; $K$ represents the total number of load aggregators; $U_j$ represents the number of air conditioning units included in the aggregator $j$; $P_i(t)$ is the power for the $i$-th group air conditioning load at $t$-hour. The first term of equation (5) represents the peaking benefit obtained by grid companies, and the second term represents the LA’s compensation fee for users.

This paper adopts the stratified optimization method to introduce continuous intermediate variables $Q_j(t)$. In the upper optimization model, the N-equal solution is optimized for $Q_j(t)$, In the underlying optimization model, the discrete variable $L_j(t)$ is optimized to be as close as possible to the continuous variables $Q_j(t)$.

For each LA body, its upper objective function is:
The constraints in the upper game optimization are:

\[
Q_j^{\text{min}}(t) \leq Q_j(t) \leq Q_j^{\text{max}}(t)
\]

\[
G_{\text{min}}(t) \leq L_j^{\text{max}}(t) - Q_j(t) \leq G_{\text{max}}(t)
\]

\[
W_j^{\text{min}} \leq \sum_{i \in I} Q_j(t) \leq W_j^{\text{max}}
\]

where, \(Q_j^{\text{min}}(t)\) and \(Q_j^{\text{max}}(t)\) represent the lower and upper limits of the air conditioner power of the aggregator \(j\) at \(t\)-hour respectively; \(G_{\text{min}}(t)\) and \(G_{\text{max}}(t)\) are the lower and upper limits of the power of the load reduction amount of the to-be-scheduled area at \(t\) hours respectively; \(W_j^{\text{min}}\) and \(W_j^{\text{max}}\) are the total power consumption of the air conditioner, indicating the aggregator \(j\)’s lower and upper limits in the dispatch period.

The lower objective function is:

\[
\min G_j = (L_j(t) - Q_j(t))^2
\]

The constraints in the lower layer optimization are equation (3) and equation (6).

The upper layer optimization takes \(Q_j(t)\) as the optimization variable, the lower layer optimization takes \(L_j(t)\) as the optimization variable, and the upper layer optimization results as the known parameters in the lower layer optimization.

Similar to the game equilibrium solution method given in [16], this paper uses the loop iteration method to solve the equilibrium solution of the game. This article will not be repeated here.

5. Study simulation

5.1. Air conditioning grouping method

This paper selects the air conditioner in a certain power supply area in summer to analyse the example, assuming that most users in holiday are temporarily at home, that is, most air conditioners are in use. Suppose there are 4,325 split air conditioners for all users in the area. The intraday demand response participation rate is 83\%. There are three LAs in the region, and the number of air conditioners that can be scheduled by each LA is 1453, 1019 and 1118 respectively. The parameters \(\zeta\) and \(\theta_c\) of all user air conditioners satisfy \(N(0.96,0.0016), N(39,0.7)\) distribution respectively. Assume that all air conditioners absorb 4 kW of electric power at the time of opening.

It is prescribed that the peaking time is between 19:00 and 23:00 at night, that is, grid companies will give LA economic compensation according to the peak clipping amount during this period of time. The price parameters of the power grid clipping \(a\) and \(b\) are \(8.25 \times 10^{-5}\) and 0.2, respectively, and the compensation price parameter assumed by LA to the user \(k_{\text{com}}\) is 0.00045 yuan/(kW)². The scheduling period is initially set from 16:00 in the afternoon to 2:00 in the morning.

5.2. Effect analysis of scheduling model

According to the classification method given in Section 3.1, the air conditioner users controlled by each LA are clustered into 10 groups. This section will simulate the non-cooperative game model of air conditioner aggregators under various scheduling periods to analyse the impact of scheduling time length on this scheduling method. Taking the peak clipping time as the center of the scheduling period, the net income of each air conditioner LA under different scheduling time lengths is shown in the following table:
Table 1. Comparison of net income of load aggregators under different scheduling periods.

| Scheduling cycle | Spacing | Total net income / yuan |
|------------------|---------|------------------------|
| Starting time    | End Time| Aggregator 1 | Aggregator 2 | Aggregator 3 |
| 16:00            | 2:00    | 993.31    | 730.17    | 783.73    | 2507.21    |
| 17:00            | 1:00    | 1009.18   | 738.38    | 798.20    | 2545.76    |
| 18:00            | 0:00    | 1006.99   | 736.21    | 794.27    | 2537.47    |
| 19:00            | 23:00   | 716.52    | 518.96    | 531.93    | 1767.41    |

It can be seen from the table that as the length of the scheduling period decreases, the net income of all LA’s increases first and then decreases. This is because if the scheduling period is too long, the LA will compensate for the air conditioning load usage behaviour in the time when there is no obvious scheduling gain, which increases the compensation of the LA to the users; if the scheduling period is too short, the LA cannot cut the peaking time. The air conditioning load is transferred to the non-peaking period by the temperature difference-power characteristic, which reduces the peak clipping benefit of LA.

For the economic indicators of LA after optimization, this paper will compare and analyse in three scenarios. Scene 1 is the optimal control according to the temperature difference-power model proposed in this paper; scene 2 is LA for all air conditioners in accordance with the optimization formula (3) for minimum optimization control every hour, but the set values of start and end temperature each hour do not change, that is, the air conditioning temperature difference-power characteristic is not considered to be the translational characteristic of the hourly time scale; in scene 3, all air conditioners do not participate in the optimal scheduling. Obviously, the peak clipping income, compensation cost to users and net income of all air conditioners LA in this scene are all 0. The LA cost benefits under scene 1 and scene 2 are shown in Table 2.

Table 2. Comparison of load aggregator cost and return in two scenarios.

|                  | Aggregator 1 | Aggregator 2 | Aggregator 3 |
|------------------|--------------|--------------|--------------|
| Peak cut income  | scene 1      | 1134.49      | 802.44       | 874.54      |
| / yuan            | scene 2      | 885.02       | 601.63       | 642.79      |
| User compensation| scene 1      | 125.31       | 64.06        | 76.34       |
| / yuan            | scene 2      | 104.66       | 53.32        | 64.33       |
| Net income / yuan| scene 1      | 1009.18      | 738.38       | 798.20      |
|                  | scene 2      | 780.37       | 548.30       | 578.46      |

It can be seen from the table that whether scene 1 or scene 2 is more profitable than scene 3 without optimization, and the net benefit under scene 1 is more, indicating that the model proposed in this paper can effectively improve the economic benefits of LA. In the three scenes, the peak value of the total load in the distribution network area is 11.346MW, 11.676MW and 12.098MW respectively. For the grid companies, it is obvious that the scheduling strategy in scene 1 can reduce the adverse impact of load peak on the grid.

5.3. Influence of electricity price parameters on optimal scheduling

In this section, sensitivity analysis is made for the electricity price parameters \( a, b \) and \( k^\text{w} \) in the non-cooperative game model of LA for air conditioning. When analyzing a certain electricity price parameter, it is assumed that all other parameters remain unchanged, as the parameter values given in Section 5.1. After the simulation calculation, the total net income of LA under different electricity price parameters and the total load peak value in the distribution network area of the example are...
shown in Table 3. The electricity price parameter ratio index represents the ratio of the corresponding electricity price parameter to the electricity price parameter value given in Section 5.1.

Table 3. Influence of different electricity price parameters on optimization results.

| Electricity price parameter ratio | Total load peak / MW | Aggregator total net income / yuan |
|----------------------------------|----------------------|-----------------------------------|
|                                  | a        | b        | k_{com} | a        | b        | k_{com} |
| 0.25                             | 11.408   | 11.354   | 11.322  | 825.43   | 2148.59  | 2737.05 |
| 0.5                              | 11.379   | 11.347   | 11.324  | 1395.41  | 2277.86  | 2670.17 |
| 0.75                             | 11.360   | 11.363   | 11.331  | 1965.86  | 2406.88  | 2603.25 |
| 1                                | 11.346   | 11.346   | 11.346  | 2536.76  | 2536.76  | 2536.76 |
| 1.25                             | 11.342   | 11.354   | 11.364  | 3017.93  | 2666.20  | 2470.64 |
| 1.5                              | 11.341   | 11.351   | 11.370  | 3679.00  | 2795.64  | 2404.69 |
| 0.25                             | 11.408   | 11.354   | 11.322  | 825.43   | 2148.59  | 2737.05 |
| 0.5                              | 11.379   | 11.347   | 11.324  | 1395.41  | 2277.86  | 2670.17 |
| 0.75                             | 11.360   | 11.363   | 11.331  | 1965.86  | 2406.88  | 2603.25 |
| 1                                | 11.346   | 11.346   | 11.346  | 2536.76  | 2536.76  | 2536.76 |

It can be seen from the table, the change of the parameter $a$ and $k_{com}$ have a certain impact on the load peak. In addition, as can be seen from the above table, it is difficult to further reduce the load peak after being reduced to 11.322 MW, which indicates that the load curve of the model has reached the minimum value under the constraint condition, and the load peak value changed by the electricity price parameter has a certain limit.

For the total net income of LA, there is an approximate linear relationship between it and the electricity price parameters. The total net income of LA increases linearly with the increase of the parameter $a$ or $b$, and decreases linearly with the increase of $k_{com}$. It is not difficult to analyze the nature of the three types' electricity price parameters. The values of parameters $a$ and $b$ are positively correlated with the income of LA. As it gradually increases, LA will get more benefits, and the parameter $k_{com}$ is positively correlated with the cost of LA. As its parameter value increases, LA will pay more cost and correspondingly reduce its revenue. It can be seen from the peak value of the load in the table that although the change of the electricity price parameter changes the load curve, the changing effect is relatively less obvious. It is not difficult to see from formula (11) that the load curve is approximately unchanged. There is indeed a linear relationship between the total net income of LA and the price parameter.

6. Conclusion

1) The temperature difference-power model proposed in this paper, which is suitable for air conditioning hourly scheduling, provides a flexible and effective method for air conditioning long-term scheduling, avoids the possible dimensionality disaster, and can deeply excavate the translatable load characteristic of the air conditioner.

2) Based on the temperature upper and lower thresholds and power level characteristic parameters in the air conditioning temperature difference-power model, clustering the air conditioning load can achieve good clustering effect, and the characteristic parameters of the same group of air conditioners have little difference.

3) In the LA non-cooperative game model based on the temperature difference-power characteristic of air conditioning load established in this paper, too long or too short a scheduling period is not conducive to the economy of the load aggregator. The main impact indicators of electricity price parameters are the cost and income of LA, which have certain impact on the peak load, but have little impact.
The air-conditioning temperature difference-power model proposed in this paper has certain expansion significance for other residential loads with energy storage properties, such as electric vehicles, water heaters, etc. In the future, further research can be conducted on the joint optimal scheduling of various types of residential energy storage loads and demand response scheduling considering uncertainty.

7. References

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