A bilayer interaction strategy for air-conditioning load aggregators considering market-based demand response

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Abstract: With considerable portion of air-conditioning load in total power consumption, air-conditioning load aggregators are authorised to participate in power market by aggregating large amounts of air-conditioning load with or without ice storage system. This paper studies on a bilayer interaction strategy for air-conditioning load aggregators considering market-based demand response, on the basis of a hierarchical deregulated day-ahead market architecture. In the upper layer, load aggregators submit their bids to independent system operator (ISO), after evaluating their load regulation potential. With the aim of minimising load dispatch cost, ISO optimises the dispatch schedule and informs each LA of its bid-winning capacity under a pay-as-bid pricing scheme. In the lower layer, air-conditioning load aggregator adopts a flexible control strategy to optimise the control actions in an effort to maximise its own benefits, as well as keeping indoor temperature within the temperature range in the contract and achieving the desired aggregated demand response capacity allocated by ISO in the upper layer. Thermal dynamic characteristics and corresponding power consumption characteristics of air-conditioning load control strategies are analysed. The resulting model is a mixed-integer non-linear optimisation problem. Finally, simulation verifies the feasibility and effectiveness of the proposed strategy.

1 Introduction

Demand response (DR) is regarded as one possible solution to load reduction in peak hours. Take Jiangsu Province in China for an example, its peak load reached up to 92,440 MW on 26 July 2016. By carrying out the DR program, 3520 MW load was curtailed [1]. With fast increase of both economy and electricity demands, electricity shortage usually takes place in peak load periods in summer or winter, where thermostatically controlled loads (TCLs) take up an increasing proportion in total power consumption [2]. TCLs, such as air conditioners, water heaters, and refrigerators, if aggregated through DR programs, could balance the variability caused by local renewable energy and provide multiple auxiliary services, due to their characteristics of quick response and high controllability [3, 4].

On this background, load aggregators (LA) take an increasingly significant role in acting as intermediaries between ISO and small- or medium-sized home users with flexible loads [5, 6]. By aggregating large amounts of small loads collectively for DR programmes, LAs are able to utilise and accumulate the great potential of TCLs like air-conditioning loads, which we address here.

In recent years, some researches are carried out on deregulated market architecture. In [7], the authors investigate the role of aggregators based on a hierarchical market model design. The established three-layer optimisation model includes three objectives targeting at three kinds of self-interested entities, that is, utility operator, some aggregators, and plenty users.

Multiple control strategies are employed by LAs to realise multiple optimisation objectives, for example, profit maximisation, load shedding maximisation, output deviation minimisation, and user satisfaction maximisation [8]. In [9], a price-based self-scheduling model is proposed to determine LA’s optimal participation schedule based on various contracts of four kinds of loads, assuming that ISO will pay for as much capacity as LA offers. In [10], a scheduling and operation strategy based on model predictive control is proposed for the load aggregator with electric energy storage, with the aim of minimising electricity cost in day-ahead market.

However, in most of the research, the specific type of load that LA aggregates, for example, air-conditioning load, and flexible control strategy taking consideration of its thermal dynamic characteristics to realise specific aggregation goal rather than to maximise its DR potential in a deregulated market environment, are not considered in detail. Also, the evaluation of DR potential of air-conditioning load aggregators and the estimation of thermal parameters is usually not mentioned.

In light of the above, this paper researches on the interactions of LA with both ISO and users based on a two-level market architecture. In the upper layer, day-ahead dispatch of ISO is implemented under a pay-as-bid pricing scheme, where every LA gets its allocated load reduction capacity from ISO schedule. In the lower layer, LA exercises direct load control over each individual air-conditionational user to maximise its profits, as well as achieving the desired aggregated demand response capacity.

2 Market-based interaction structure for LAs

Here, a day-ahead electricity market, consisting of one independent operator (ISO), several LAs and various kinds of users, especially commercial users with air-conditioners, is considered, as it is depicted in Fig. 1.

First, users choose appropriate LAs and sign mid- or long-term contracts with one of them. They authorise LAs to establish control over their electric appliances during certain time slots when needed, and in return they could get certain amount of financial compensation at the sacrifice of comfort or convenience.

Then, LAs participate in demand-side bidding in the market, offering their bidding price and bidding capacity after the ISO announces the amount of scheduling demand. ISO decides the dispatch schedule and informs each LA of its bid-winning capacity at each time interval.

Finally, LA optimises its own load control strategy to coordinate a large group of users to realise the allocated DR amount from ISO.

In addition, each small- or medium-sized user with certain amount of controllable load could participate in the day-ahead
3 Upper level: interaction between LAs and ISO

To realise peak shaving/shifting, DR programme is implemented, where area utility operators like ISO decide load reduction schedule at each time interval in a distribution market. LA usually submits its controllable capacity and corresponding bidding price to ISO in advance. Here, a pay-as-bid pricing scheme is employed to avoid intended low bidding price under uniform market clearing price.

With the aim of minimising load dispatch cost, the objective function for ISO is:

$$\min \sum_{t \in T} \sum_{k \in K} D_{k,tt}p_{k,tt} + \sum_{t \in T} F(\Delta D_t)\Delta T_t$$

(1)

where TS denotes the set of time slots for bidding, $K$ stands for the set of LA groups, $D_{k,tt}$, $p_{k,tt}$ are the bidding capacity and bidding price of load reduction allocated to $k$th LA at time interval $tt$, respectively. $\Delta T_t$ is the length of time slot. $\Delta D_t$ is the imbalance between the total load reduction capacity $p_{k,tt}$ that system needs at time interval $tt$ and total amount of allocated load to all LAs. $F(\Delta D_t)$ is the cost of imbalance and is expressed as follows, where $K_1$ and $K_2$ are coefficients of costs.

$$\Delta D_t = \sum_{k \in K} D_{k,tt} - p_{k,tt}^{\text{dem}}$$

(2)

$$F(\Delta D_t) = \begin{cases} K_1\Delta D_t^2 & \Delta D > 0 \\ K_2\Delta D_t^2 & \Delta D < 0 \\ 0 & \Delta D = 0 \end{cases}$$

(3)

Imbalance cost function $F(\Delta D_t)$ is like the costs of imbalance between supply and demand for virtual power plant. After it is added to optimisation model, intended malicious high bidding price could be avoided. If the bidding price of some LAs in management of large DR resources that ISO needs is too high, ISO would rather take the imbalance costs than take its bid.

The following constraints should also be met:

$$D_{k,tt}^{\text{min}} \leq D_{k,tt} \leq D_{k,tt}^{\text{max}}$$

(4)

$$|D_{k,tt+1} - D_{k,tt}| \leq \Delta D_{\text{max},k}$$

(5)

where $D_{k,tt}^{\text{min}}$, $D_{k,tt}^{\text{max}}$ are the minimum and maximum load reduction that $k$th LA can offer at time interval $tt$. (5) is a ramping constraint, where $\Delta D_{\text{max},k}$ is the maximum load reduction variation.

Especially, the value of $D_{k,tt}^{\text{min}}$ should not be too small, because too little participation or pay, causes a much higher possibility of failing to motivate LAs to realise the allocated load reduction or to participate next time. The value of $D_{k,tt}^{\text{max}}$ should be close to load regulation potential that is briefly pre-evaluated by LAs, the calculation of which will be mentioned in Section 6.1.

From the model above, the set of variables $\{D_{k,tt}^{\text{em}}\}$ is optimised, that is, a set of load reduction schedules allocated to LAs is determined.

4 Lower level: interaction between LA and users

4.1 Cost-profit analysis of LAs

Take Jiangsu Province in China for an example [11]. Critical peak pricing mechanism is established, in which the electricity price during critical peak load period for large industrial users increases 0.1 RMB/kWh on the basis of peak price. Only when the highest temperature in a day is higher than 35°C (not included) according to certain weather forecast, the DR program is allowed to be implemented. DR gain of a LA could be expressed as multiplying its allocated load reduction amount by bidding price under a pay-as-bid pricing scheme, which is provided by ISO who actually gets this compensation for LAs from the profits attained by critical peak pricing mechanism.

With the profit supported by ISO, LAs are able to offer multiple contracts to different kinds of consumers in an effort to encourage them to participate in DR programmes with economic incentives. Generally, users usually get compensation based on their real-time load reduction amount.

With the aim to maximise the payoff, the objective function for LA is:

$$\max \sum_{k \in K} \left(D_{k,tt}^{\text{em}}p_{k,tt} - p_{k,tt}^{\text{comp}}\Delta T_t - \Delta P_{k,p}^{\text{pen}}(\Delta T_t)\right)$$

(6)

$$\text{st.} \Delta P_{k,p}^{\text{pen}} = \begin{cases} \Delta P_k & |\Delta P_k| \geq \Delta P_{\text{max}} \\ 0 & |\Delta P_k| < \Delta P_{\text{max}} \end{cases}$$

(7)

The first item is the profits of LAs from ISO, the second item is the compensation LA provides for users, and the last item is the penalty LA might be charged by ISO.

$D_{k,tt}^{\text{em}}$ is the smaller value of real load shedding amount $p_{k,tt}$ and desired load reduction $D_{k,tt}$, $p_{k,tt}^{\text{comp}}$ denote the compensation price per unit of energy power at time interval $t$, $\Delta P_{k,p}$ and $\Delta P_{k,p}^{\text{pen}}$ denote the load shedding deviation for penalty and penalty price per unit of energy power. $\Delta T_t$ is the length of time interval. (7) explains that only when the load shedding deviation $\Delta P_k$ exceeds the maximum deviation $\Delta P_{\text{max}}$ will LA be penalised.

4.2 Air-conditioning load model and its flexible load control strategy

First-order equivalent thermal parameter (ETP) model [12] is adopted to characterise the thermodynamics of the heat exchange process of air-conditioner. In summer, its mathematical dynamic model can be expressed as follows: (see (8)) where $T_{in}$ and $T_{out}$ are indoor and outdoor temperatures, $R$ and $C$ are thermal resistance and capacitance of building parameters, $P$ and $C$ are the rated power and coefficient of performance of air-conditioners. $x(t)$ is the state variable of air-conditioner, 0 for ‘off’ and 1 for ‘on’.

$$x(t) \text{ satisfies } (9):$$
\[ x(t) = \begin{cases} 0 & T_{\text{off}}(t) \leq T_{\text{on}} \\ 1 & T_{\text{off}}(t) \geq T_{\text{on}} \end{cases} \]  

(9)

where \( T_{\text{max}} \) and \( T_{\text{max}} \) are minimum and maximum indoor temperatures.

During the winter air-conditioning months, the situation is just reverse.

The deployment of smart grid will enable two-way communication and control between smart buildings and utility control centres. Air-conditioning loads are usually regarded as cyclic loads due to their abilities of inherent thermal storage. Hence, their power consumption modes could be controlled by switching ON/OFF via LAs over a long distance, while bringing negligible disturbance to the thermal comfort degree of common end users [13].

Here, a more flexible control strategy is applied to air-conditioner groups in an effort to achieve expected aggregation goal while minimising total costs, where on/off schedules are determined based on the reasonable assumption that the cost of start-up and turn-down could be ignored.

In comparison, the advantage of traditional control strategy lies in that it could maximise load reduction amount of single load. However, the deregulated market environment brings about new challenges. LAs are required to be responsible for the coordination of several groups of end users to accomplish desired aggregated load response, which is usually lower rather than just near the maximum DR potential of LA. Under this circumstance, the flexible control strategy incorporates various modes of control actions, including those of traditional control strategy, since that LA could turn on/off the appliances more freely, thus better aggregating the flexibility of aggregated loads. By operating in a more flexible way, LA could achieve a DR amount of any desired capacity between 0 and maximum DR potential while bringing less disturbance to user comfort.

\( \tau_{\text{on}} \) and \( \tau_{\text{off}} \) are on and off duration of air-conditioner, the expressions of which could be derived from (8):

\[ \tau_{\text{on}} = RCl(t) \left( \frac{R\rho_{\text{p}} + T_{\text{max}} - T_{\text{on}}}{R\rho_{\text{p}} + T_{\text{max}} - T_{\text{off}}} \right) \]  

(10)

\[ \tau_{\text{off}} = RCl(t) \left( \frac{T_{\text{out}} - T_{\text{off}}}{T_{\text{out}} - T_{\text{max}}} \right) \]  

(11)

Since the values of \( RC \) are rather small, asymptotic equilibrium temperatures are generally far beyond \( T_{\text{max}} \) the exponential rising curve and falling curve could be approximately recognised as linear between \( T_{\text{min}} \) and \( T_{\text{max}} \) to simplify analysis [15]. With the same temperature limits, the slopes of the curves in Fig. 2b are almost the same as those in Fig. 2a.

**4.3. Optimisation model for LA**

The objective function of the \( k \)-th LA in (6) and (7) can be rewritten as:

\[ \max \sum_{i \in I} \left( D_{k,\text{real}}^{i} P_{i} \Delta T_{i} - \sum_{i \in I} x_{i} P_{i} \rho_{i}^{\text{comp}} \Delta T_{i} - \Delta P_{k}^{i} \rho_{k}^{\text{comp}} \Delta T_{i} \right) \]  

(12)

\[ D_{k,\text{real}}^{i} = \min \left( \sum_{i \in I} x_{i} P_{i} D_{k,\text{ref}} \right) \]  

(13)

\[ \Delta P_{k}^{i} = \max \left( D_{k,\text{ref}} - \sum_{i \in I} x_{i} P_{i} - \Delta P_{\text{max}}, 0 \right) \]  

(14)

where \( I \) denotes the set of users, binary decision variable \( x_{i} \) denotes the state of air-conditioner, 1 for ‘off’ and 0 for ‘on’. Only when the air-conditioner is in ‘off’ state will the total load be reduced by its rated power \( P_{i} \), as depicted in Fig. 2a.

Also, suppose that the indoor temperature has already reached \( T_{\text{min}} \) at the beginning. The model subjects to a series of temperature upper limits:

\[ T_{\text{max},t} + \sum_{i \in I} \left( 1 - x_{i} \right) K_{\text{off},i} + x_{i} K_{\text{on},i} \Delta T_{i} \leq T_{\text{max},t} \]  

(15)

where \( K_{\text{off},i} \) and \( K_{\text{on},i} \) are the slopes of linear rising and falling temperature curves, which could be expressed as follows:

\[ \tau_{\text{on},i} = R_{\text{C},i} \left[ \left( R_{P,i} \rho_{i} + T_{\text{max},t} - T_{\text{off},t} \right) \right] \]  

(16)

\[ \tau_{\text{off},i} = R_{\text{C},i} \left[ \left( T_{\text{out},t} - T_{\text{off},t} \right) \right] \]  

(17)

\[ K_{\text{off},i} = \frac{T_{\text{max},t} - T_{\text{min},t}}{\Delta T_{i}} \]  

(18)

\[ K_{\text{on},i} = \frac{T_{\text{max},t} - T_{\text{min},t}}{\Delta T_{i}} \]  

(19)

The optimisation model established above is a mixed-integer non-linear optimisation problem. The control strategy for the DR time next day is determined after the set of variables \( \{ x_{i} \} \) is optimised by the model, which refers to the switching on/off control actions at each time interval.
5 Special issues in application for LAs
5.1 DR potential evaluation

Equation (4) limits the maximum load reduction \( D_{\text{max}}^{\text{in}} \) that LA can offer, which should be near but lower than its maximum load reduction, or evaluated DR potential \( P_{\text{h,max}} \). If \( P_{\text{h,max}} \) is much lower than its real DR potential, LA will get less benefits; if \( P_{\text{h,max}} \) is much higher than its real DR potential, LA is likely to fail to achieve the desired aggregated load reduction amount, thus being faced with high penalty from LA. Therefore, LA should carefully evaluate its own DR potential before submitting its bidding capacity.

As is illustrated in Fig. 2, the DR potential \( P_{\text{h,max}} \) of air-conditioning load groups could be evaluated through:

\[
P_{\text{h,max}} = \sum_{i=1}^{K} \frac{\tau_{\text{off},i} \cdot P_i}{\tau_{\text{on},i} + \tau_{\text{off},i}}
\]  

(20)

5.2 Estimation of equivalent thermal parameters

\( R \) and \( C \) are different equivalent thermal parameters for users with different architectural parameters, which is needed in the description of indoor temperature curves. In most of the research, \( R \) and \( C \) are recognised as known parameters. However, they are just computationally equivalent parameters, which could not be calculated or measured directly. Here, we introduce a simple method for rough estimation of \( R \) and \( C \).

When the outdoor temperature is \( T_{\text{out}} \) and indoor temperature is \( T_{\text{max}} \), turn off the air-conditioner until the temperature is \( T_{\text{max}} \) and record ‘off’ time duration \( \tau_{\text{off}} \) turn on the air-conditioner until the indoor temperature is \( T_{\text{min}} \) again recording ‘off’ time duration \( \tau_{\text{on}} \). All the temperatures could be accurately measured through remote sensors, the signals of which will be transmitted to LAs. Then, (21) and (22) are formed according to the process, where only \( R \) and \( C \) are unknown elements.

\[
\tau_{\text{on}} = R C \ln \left( \frac{\text{RPCop} + T_{\text{max}} - T_{\text{out}}}{\text{RPCop} + T_{\text{max}} - T_{\text{out}}} \right)
\]  

(21)

\[
\tau_{\text{off}} = R C \ln \left( \frac{T_{\text{out}} - T_{\text{min}}}{T_{\text{out}} - T_{\text{min}}} \right)
\]  

(22)

Then, \( R \) and \( C \) is the joint solution of (21) and (22), which can be expressed as follows:

\[
m = \tau_{\text{on}} / \tau_{\text{off}} \ln \left( \frac{T_{\text{out}} - T_{\text{out}}}{T_{\text{out}} - T_{\text{min}}} \right)
\]  

(23)

\[
R = \frac{(e^m - 1)T_{\text{out}} - e^m T_{\text{out}} + T_{\text{max}}}{(e^m - 1)\text{RPCop}}
\]  

(24)

\[
C = \frac{\tau_{\text{off}}}{m \ln \left( \frac{T_{\text{out}} - T_{\text{min}}}{T_{\text{out}} - T_{\text{min}}} \right)}
\]  

(25)

5.3 Air-conditioning load with ice storage system

The air-conditioning load considered in the model above is common air-conditioner without ice storage system. However, there also exist a large number of air-conditioners with ice storage system, which have great potential for peak load shaving or shifting. For commercial air-conditioning load with ice storage system, the energy supporting its work could be set from electricity or from the ice it stores or from the combination of electricity and ice. Suppose it usually works in the mode of combined electricity and ice before and after DR, and the ratio of electricity in total energy is fixed, denoted as constant \( R\% \).

As is depicted in Fig. 2, for an air-conditioner with or without ice-storage system but of the same rated power, the load reduction is the same when the air-conditioner is in off state. It is the same with the slopes of the falling temperature curves, because there is no power element in (17) and (18).

However, the slopes of the rising temperature curves will change, since that the cooling effect of an air-conditioner with ice-storage system whose rated power is \( P_i \) could be regarded as the same as that of a common air-conditioner whose rated power is \( P_i / R\% \). For an air-conditioner with ice-storage system, (16) should be changed into (26):

\[
\tau_{\text{on},i} = R C \ln \left( \frac{\text{RPCop} / R\% + T_{\text{max}} - T_{\text{out},i}}{\text{RPCop} / R\% + T_{\text{max}} - T_{\text{out},i}} \right) + T_{\text{out},i}
\]  

(26)

The objective function and other constraints remain the same. Thus, a simple model of air-conditioning load with ice storage is incorporated into the optimisation model, making it possible for LA to coordinate a wider range of air-conditioners.

6 Case studies

Suppose it is predicted that average outdoor temperature during 13:00–14:00 of some certain day will reach up to 37°C, and electricity shortage will probably happen. Hence, DR programme is implemented, including market bidding and control strategy optimisation in day-ahead market.

6.1 Day-ahead market bidding

Before submitting bids to ISO, LAs should assess their own DR potential to determine the bidding capacity. Take one air-conditioning load aggregator (ID:1) for example, who manages 5,000 commercial air-conditioners.

Suppose the maximum and minimum temperatures of all users require in the contracts are 21°C and 24°C. The average rated power of air-conditioners is 3.5 kW and average coefficient of performance is 3. The average pre-measured thermal parameters for all users satisfy \( C = 0.18\text{kWh/°C} \), \( R = 5.56\text{C/kW} \).

With all the elements known, we could calculate the values of \( \tau_{\text{on}} \) and \( \tau_{\text{off}} \) from (10) and (11), and evaluate its DR potential \( P_{\text{h,max}} \) from (20). We get \( \tau_{\text{on}} = 4.19 \text{ min} \), \( \tau_{\text{off}} = 11.74 \text{ min} \), and \( P_{\text{h,max}} = 12.89 \text{ MW} \).

Table 1 shows the bidding information of all LAs submitted to ISO (assuming that the time slot \( \Delta T_i = 10 \text{ min} \) in upper layer and penalty price \( \rho^i \) is 120 $/MWh). Here, LAs could be different kinds of aggregators with different controllable loads, for example, electric vehicles or electric water heaters, thus controlling and reducing load at different levels of costs related with load characteristics and user demands.

Table 2 shows the dispatch results of ISO based on the optimisation model (\( K_i = 120 \text{$/kW} \), \( K_j = 140 \text{$/kW} \)). The total operational cost that ISO is expected to pay to LAs is $4478.5.

It can be concluded from Table 2 that the aggregator who bids at lower price will be more likely to win the bid. For example, from 13:50–14:00, the bidding prices of LA 6 and LA 8 are lower than others, hence getting bids of 20 and 8 MW. However, LA 6 gets less profits than LA 6 under the pay-as-bid pricing scheme. Besides, if the bidding price is too high, LA will lose the bid; if the bidding price is too low, LA will gain limited profits or even...
suffer a deficit. Therefore, it is a trade-off between bidding price and possible bid-winning capacity based on the prediction of market demand and other competitors' behaviour, which requires further investigation.

6.2 Flexible load control strategy

Here, we also take air-conditioning load aggregator 1 for example. The aggregation goal of LA 1 is illustrated in Table 2, which is set to be performed from 13:20 to 13:50.

LA 1 manages 5,000 commercial air-conditioners, divided into ten air-conditioning groups with 500 air-conditioners for each, where air-conditioners with similar electric and thermal parameters should be put into the same group. The total capacity for each group numbered from 1–10 is 1.8485, 1.6940, 1.4310, 2.0705, 1.5635, 1.4625, 1.9575, 2.0100, 1.5725, and 1.8900 kW. The contract between LA and users provides that the compensation prices at time intervals of 13:10–13:20, 13:20–13:30, 13:30–13:40, and 13:40–13:50 are 45, 50, 60, 60 $/MWh, respectively.

Suppose the time interval $\Delta T = 2$ min for control in lower layer and $\Delta P_{\text{max}} = 0.1$ MW. After simulation, the total payoff of LA 1 is $201.625$ and the optimal solution of flexible load control model is shown in Table 3. The total amount of optimised load shedding, and total deviation between instructed and optimised load shedding over the whole control horizon is 6332.7 and 1.23 kWh, respectively, and the maximum deviation is 0.04%. Therefore, taking consideration of the dynamic characteristics of all air-conditioning load under its management, the control strategy determined by the optimisation model enables LA to maximise its profits and to successfully achieve its aggregation goal by coordinating all groups of air-conditioners without being penalised. At the same time, requirements of temperature range in the contract are satisfied, which guarantees the comfort level of all users.

In comparison, if traditional control strategy illustrated in Fig. 2 is carried out, the group of air-conditioners has to continuously be in ‘off’ for no more than 10 min (five time intervals), then in ‘on’ state for more than 4 min (two time intervals) and so on in cycle along the timeline, which limits the operational flexibility to some extent. In consequence, LAs will have to pay more to users, or discomfort will more likely to be brought to users, even above the temperature range in the contract, or even worse, LAs will be penalised for greater deviation between optimised load shedding and instructed load shedding.

Fig. 3 also illustrates the state of each air-conditioning group of LA 1 over the whole control horizon, which is corresponding to the solution sets $\{x_i\}$ of the optimisation model. In general, more groups of air-conditioners have to be turned off when more load reduction is instructed. Fig. 4 shows that the accumulative time duration of each group in ‘off’ state is relatively average instead of just turning off few groups, for each group get involved for more than 10 min.

7 Conclusion

With the increasing proportion of air-conditioning power consumption in total consumption, air-conditioning load aggregators play a significant role as an intermediary between ISO and common users in utilisation of air-conditioning load under demand response, which should be distinguished from other LAs. It is worth research on how air-conditioning load aggregators...
coordinate large groups of decentralised aid-conditioners after winning bids of load shedding amount from ISO based on its estimation of DR potential.

This paper researches on the bilayer interaction strategy for air-conditioning load aggregators. A bi-level optimisation model is set up based on a deregulated market architecture, where a dispatch method is provided for ISO to decide bid allocation, and a flexible direct load control strategy is employed by LA to exercise load control over groups of air-conditioning loads with or without ice storage system. The simulation results illustrate that ISO could allocate its desired load reduction amounts among various LAs while minimising its operational costs, and LA could maximise its own profits with limited deviation between optimised power and instructed power from ISO based on the flexible control strategy here. The feasibility and efficiency of the proposed bilayer interaction strategy is verified, and the role of LAs in a demand response market is investigated.

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