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A Compound HVAC-Based Demand Response Method for Urgent Responses of Commercial Buildings Towards Smart Grids

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Abstract. As the major electricity consumers worldwide, buildings can play an important role for power balance of smart grid through demand response (DR). Demand side-based control and supply side-based control are two typical types of DR measures when using centralized building air-conditioning systems for DR. For demand side-based control, the major disadvantage is that the response speed is generally too slow to allow buildings providing an immediate power reduction for the smart grid. For supply side-based control, the response speed is fast enough while it may cause control disorder to the whole system and uneven indoor temperature increase among different zones. In order to overcome above disadvantages, we proposed a novel DR method for building air-conditioning systems, which combines both the demand side-based and supply side-based control simultaneously. It consists of two major steps. First, some running chillers will be shut down to provide an immediate power reduction once urgent power reduction requests from smart grids are received by buildings. Second, the indoor air temperature set-points will be adjusted stepwise based on an “incremental schedule” to achieve a uniformly indoor temperature rise among all concerned zones/rooms. By implementing such two steps, an immediate power reduction is achieved while minimizing the uneven sacrifice of thermal comfort among different occupants. Two new performance indexes are



proposed to evaluate the thermal comfort performance of DR methods. The proposed DR method is implemented and tested as case study in a virtual building dynamically simulated by TRNSYS. Five scenarios with different incremental steps for adjusting the temperature set-points are compared to determine the optimum “incremental schedule”. Results show that buildings can provide immediate power reduction and achieve a small and even thermal comfort sacrifice by implementing the proposed compound DR method.

1. Introduction

Sufficient and stable power supply is of great importance for smooth operation of the power grid, which is the cornerstone of economic development [1]. The balance between the electricity supply side and demand side must be achieved all the time. With the rapid development of economy, the electricity demand has been increasing dramatically, especially during peak hours in winter and summer when air-conditioning systems are used. A large amount of renewable energy generations is connected to the power grid, which has a great impact on the balance of the power grid. The peak load and power imbalance have become two critical issues in an electrical grid operation. Demand response (DR) has been considered as a promising solution to alleviate the peak demand and imbalance problem.

As a primary electricity consumer of the grid, buildings can play an important role in power demand response. Particularly the centralized air-conditioning system in commercial buildings, which has great flexibility or elasticity in changing their power demands, can provide a great potential for DR [2]. Currently, two kinds of demand response methods can be used in central air-conditioning systems [3]. One is the demand side-based DR control method. Room temperature resetting is a typical demand side-based strategy, which allows building operators to adjust the room temperature set-points, upon initiation of DR events, to reduce the cooling and electricity demand of air-conditioning systems [4]. Another is supply side-based control method. For instance, directly shutting down some operating chillers to response the DR event.

However, both abovementioned DR methods have inherent limitations when used in existing centralized air-conditioning systems. For demand side-based control, the major disadvantage is that the response speed is generally too slow to allow buildings providing an immediate power reduction for the smart grid. For supply side-based control, the response speed is fast enough while it may cause control disorders to the whole system and uneven indoor temperature increase among different zones [5]. Some measures, such as developing dedicated control strategies for chilled water distributions during DR periods, have been proposed to solve these problems [6]. However, such methods can only be applicable in a few advanced buildings with complete control and measurement systems. For most existing buildings, there are no hardware and/or software conditions for implementing these measures. In order to overcome above disadvantages, we propose a novel DR method for centralized air-conditioning systems,

which combines both the demand side-based and supply side-based DR control measures simultaneously.

2. Methodology

DR is designed to solve short-term power balance issues by inducing customers to reduce their electric usage at times of high electricity prices or when system reliability is under threat. For implementing DR in buildings, customers could benefit from lower electricity cost or direct incentives by sacrificing the thermal comfort of occupants to acceptable levels. In the meantime, the grid intends to achieve expected power reductions as soon as possible when DR event is triggered. In other words, a successful DR measure should ensure the power reduction to be achieved fast enough and meanwhile minimize the notice and complaints of building occupants. In this study, a compound building demand response method for urgent responses of smart grids is proposed.

2.1. Implementation of the proposed DR method

The proposed DR method consists of two critical actions/steps, which are to be taken on both the cooling supply side (i.e., chillers and pumps) and cooling demand side (i.e., room temperature) of a centralized air-conditioning system in commercial buildings. This method is applicable for building air-conditioning systems with multiple chillers. When receiving the incentive signals requested from the grid, building operators should carry out the following steps simultaneously, as shown in figure 1.

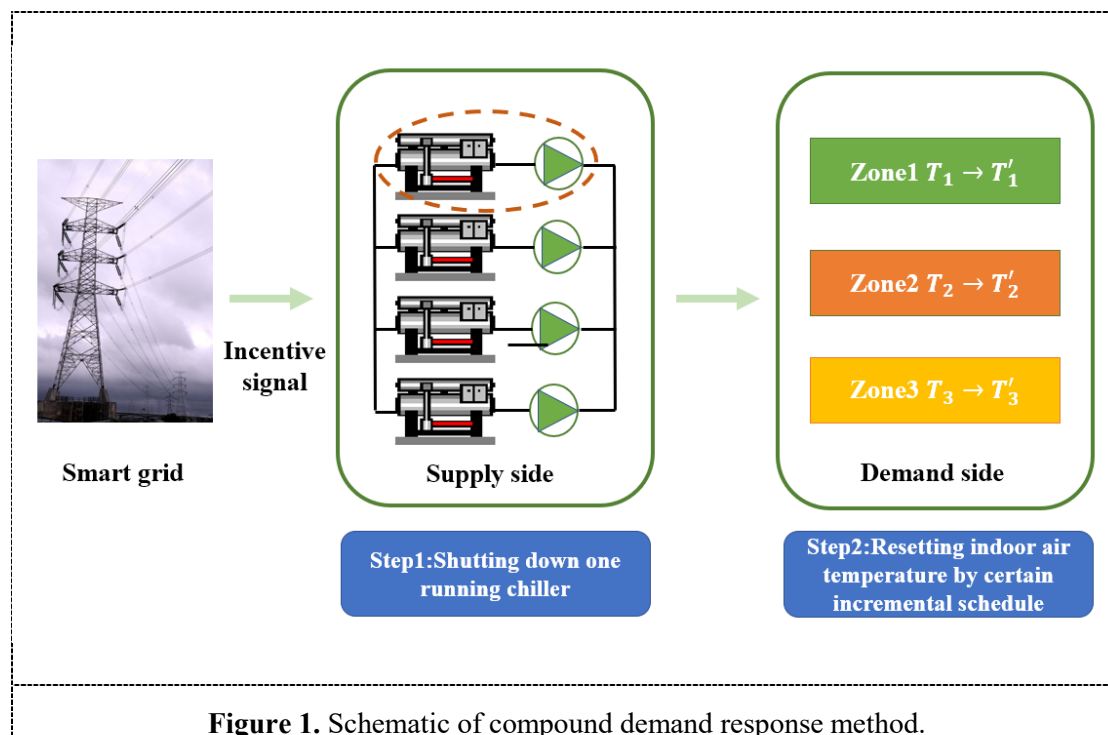


Figure 1. Schematic of compound demand response method.

On the supply side, one or two chillers in operation will be directly shut down to achieve an immediate power reduction. The number of chillers being shut off is determined by the amount of requested power reduction and the sacrifice level of thermal comfort [7]. As a result of cooling limiting, the cooling supply of the remaining chillers is insufficient to meet the cooling demand of the building. Attempting to maintain the set-point of indoor air temperature, all cooling terminals (e.g., AHUs and VAV boxes) would compete for the limited cooling supply by opening the modulating valves/dampers to the maximum openness. This means the feedback control system is completely out of control, which leads to serious unbalanced cooling distribution to different zones within the same air-conditioning system. The consequence is that the indoor environment in some zones/spaces sacrifices to unacceptable levels much more quickly than other zones/spaces. Uneven sacrifice should be avoided in DR events, which is addressed by the demand side actions.

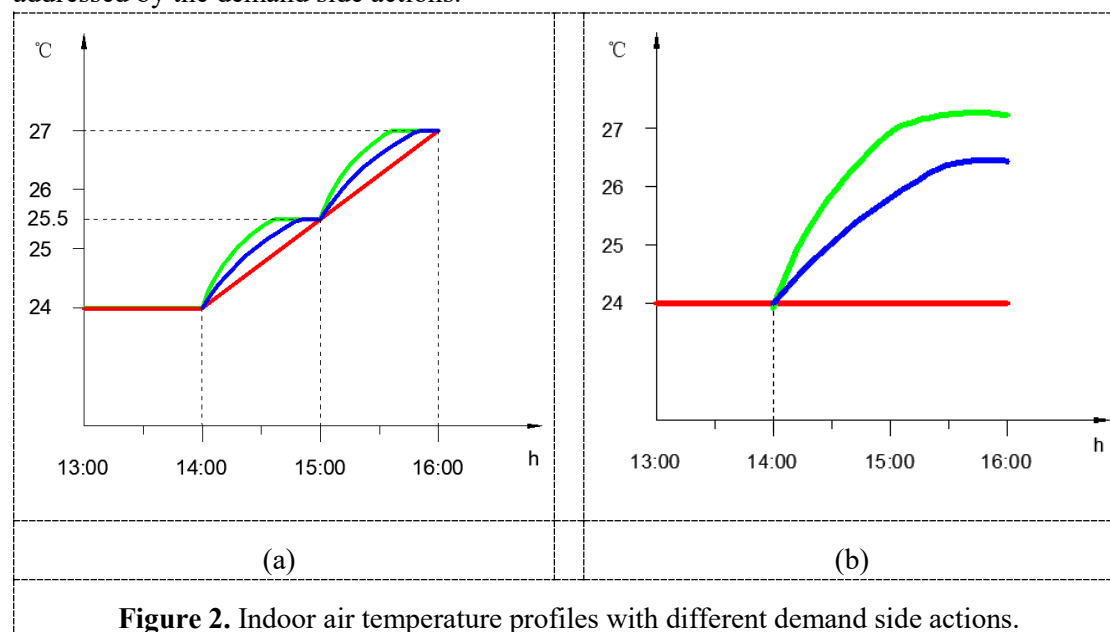


Figure 2. Indoor air temperature profiles with different demand side actions.

On the demand side, the set-points of indoor air temperatures will be adjusted stepwise based on an “incremental schedule” to achieve a uniform sacrifice of thermal comfort among all concerned zones. The pre-condition to ensure the feedback control loops work properly is that the total demand of the building is not more than what can be provided from the supply side. In order to satisfy this pre-condition, we propose to increase the indoor air temperatures of all zones according to a predetermined schedule. A conceptual incremental schedule is shown in Figure 2 (a). The set-point of indoor air temperature of all zones/rooms is adjusted with a certain increment, e.g., increase 1.5°C per hour. Due to the increase of set-points, the required total cooling demand is significantly reduced to be not more than the total cooling supply from remaining running chillers. This ensures the feedback control loops work normally to maintain the actual indoor temperature at set-point. Although the temperature profile of different zones/rooms may be different, the difference among them is significantly reduced comparing

with that of the temperature floating profile (i.e., control loops are under disorder when no action is taken in the demand side in figure 2 (b)).

2.2. Evaluation of thermal comfort sacrifice

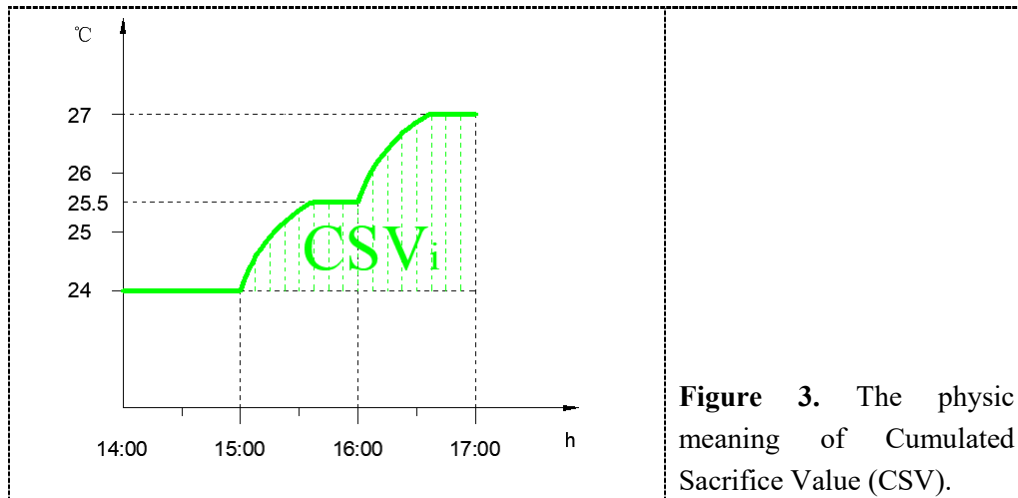
During the DR events, the power reduction is usually achieved at the expense of a certain degree sacrifice of the thermal comfort of building occupants. Generally, the indoor thermal comfort is evaluated by the indoor air temperature. The maximum accepted indoor air temperature increase during the DR event is assumed to be 3°C [6]. In previous studies, the sacrifice degree of thermal comfort is only measured by the value of indoor air temperature increase while the duration of temperature increase is ignored. In this study, a new index, i.e., Cumulated Sacrifice Value (CSV), is proposed for the first time to evaluate the thermal comfort sacrifice by taking into account both the amount and duration of temperature increase simultaneously.

The Cumulated Sacrifice Value (CSV) represents the area enclosed by the temperature profile and the time axis as shown in Figure 3. It can be calculated by integrating the temperature increase over time during DR event, as described in equation (1). The CSV of each individual zone/room then can be determined once the actual indoor air temperature profiles are obtained. The unevenness of thermal comfort sacrifice of the building can be evaluated by the relative difference (μ), as shown in equation (2), which represents the deviation of CSV of a certain zone/room from the average value of all zones/rooms.

$$CSV = \int_{start}^{end} \Delta T d\tau \quad (1)$$

$$\mu = \frac{CSV_i - CSV_{ave}}{CSV_{ave}} \times 100\% \quad (2)$$

where, ΔT is the value of temperature increase compared with the original room temperature before DR event; μ is the relative difference of comfort sacrifice compared with the average value of all zones/rooms. An even sacrifice of thermal comfort can be considered as achieved, when the maximum relative difference is small enough, e.g., less than 5% in this study. As a result, the CSV and μ can be used as effective indexes to evaluate the thermal comfort performance of a DR strategy.



3. Case study

To demonstrate the application and evaluate the effectiveness of the proposed compound DR method, a case study in a commercial building is carried out. We built the virtual model of this building in the transient simulation software TRNSYS. Six representative rooms with different thermal responsiveness and load conditions are selected for the test. The initial indoor air temperature and relative humidity of all rooms are 24°C and 50% respectively. Five incremental scenarios with different time intervals are investigated in this study. Scenario (a) represents that the set-point keeps at 24°C all the time and Scenario (e) represents that the set-point directly increases to 27° at the beginning of the DR event. For other three scenarios, the set-point is increased from 24°C to 27°C stepwise according to given incremental schedules. Taking Scenario (b) for example, the set-point is increased from 24°C to 27°C with the temperature increment of 0.375 °C and the time interval of 15 minute during the DR period of two hours.

The indoor air temperature profiles of four incremental scenarios are shown in Figure4. Due to the insufficient cooling supply, the indoor temperature definitely will increase while the increase profiles under different demand side actions are totally different. In scenario (a), some rooms (e.g., room6) can maintain the indoor temperature at 24°C while the temperature of other rooms increase rapidly. The unevenness of temperature increase among different rooms are too large to be accepted. Through adjusting the set-point proactively, the indoor air temperature of all six rooms can be well controlled, as shown in Figure.4 (b)-(d).

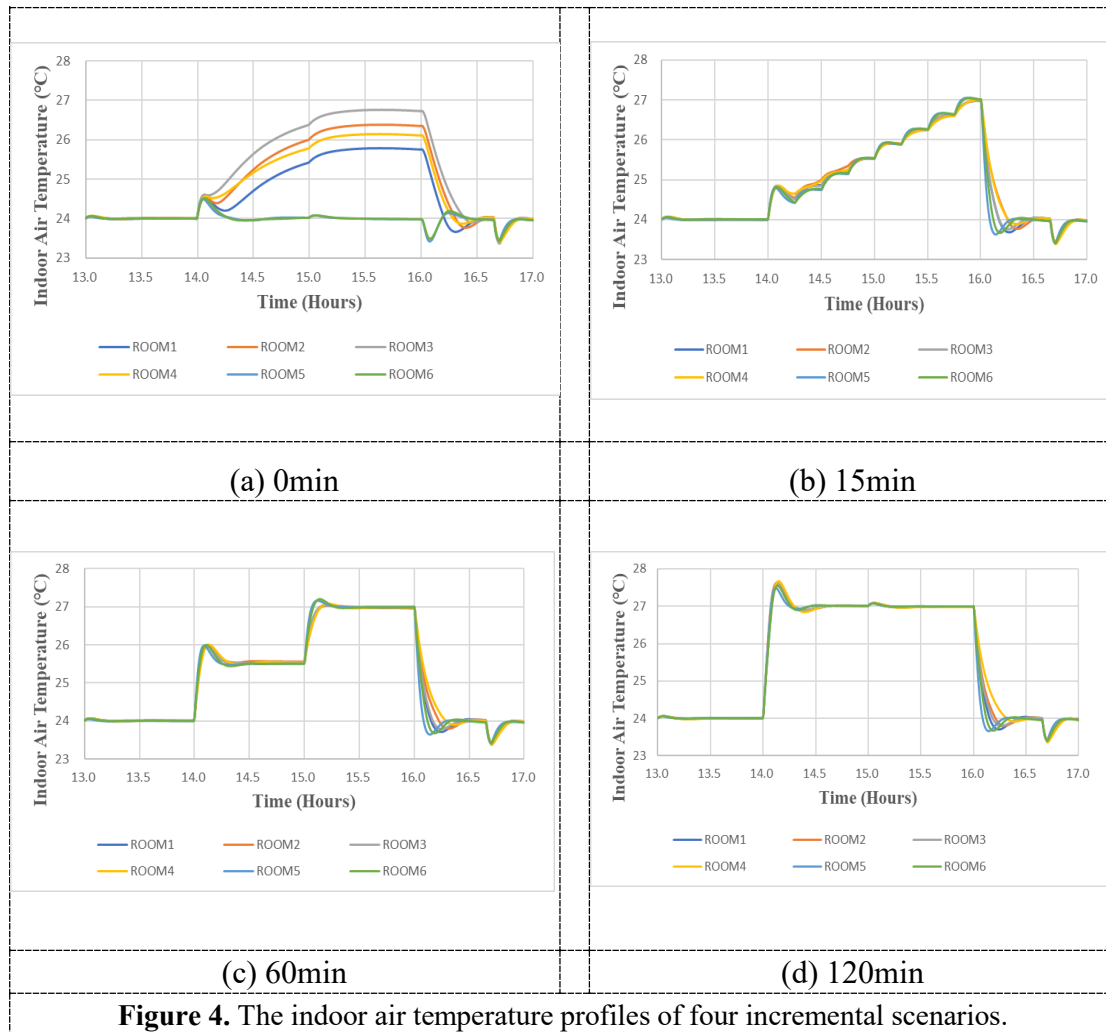


Figure 4. The indoor air temperature profiles of four incremental scenarios.

The thermal comfort performance of the DR under above five scenarios are compared in Table 1. The idealist DR should have the smallest CSV_{ave} to minimize the overall thermal comfort sacrifice and the smallest relative difference (μ) to minimize the unevenness among different rooms. Unfortunately, it is hard to achieve the minimum values for both indexes simultaneously. As an alternative, scenario (b) that has the minimum CSV_{ave} and acceptable μ can be considered as the optimum DR scenario.

Table 1. The performance of five different set-point incremental schedules.

Scenario No.	a	b	c	d	e
Time interval (min)	0	15	30	60	120
Temperature increment (°C)	0	0.375	0.75	1.5	3
CSV_{ave}	2.282	3.398	3.766	4.510	5.970
Max relative difference (μ)	-96.65%	0.95%	0.39%	-0.14%	-0.23%

4. Conclusions

A compound DR method, combining both the demand side-based and supply side-based DR control actions simultaneously, is developed for centralized air-conditioning systems. Two performance indexes, including the Cumulated Sacrifice Value (CSV) and relative difference (μ), are proposed to evaluate the thermal comfort sacrifice performance of DR methods. Five scenarios with different incremental steps for adjusting the temperature set-points are compared in a case study to demonstrate the effectiveness of the proposed method. Results show that it can provide immediate power reductions to the grid and achieve even indoor temperature increases among different zones by adjusting set-points properly. No additional measurement devices or dedicated control strategies are involved, which therefore may be a more generic and feasible HVAC-based DR method for most existing buildings.

Acknowledgements

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