Applied Energy 196 (2017) 218–228

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Operating reserve evaluation of aggregated air conditioners

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HIGHLIGHTS

- A novel control strategy for the aggregation model of air conditioners (AC) is proposed.
- A series of indexes are proposed to evaluate the operating reserve performance provided by ACs.
- Operating reserve performance provided by both individual AC and aggregated ACs are analysed quantitatively.
- Operating reserve from demand-side can be dispatched by the system operator similar as conventional generating units.

ARTICLE INFO

Article history:
Received 3 October 2016
Received in revised form 21 November 2016
Accepted 2 December 2016
Available online 21 December 2016

Keywords:
Air conditioner
Aggregation model
Operating reserve
Control strategy
Quantitative evaluation

ABSTRACT

The penetration of renewable energy sources (RES) in power system is increasing around the world. However, the severe intermittency and variability characteristics of RES make the operating reserve become more and more important for the electric power system to maintain balance between supply and demand. Moreover, the flexible loads, especially for air conditioners (AC), are growing so rapidly that they account for an increasingly large share in power consumption. With the development of information and communication technologies (ICT), ACs can be monitored and controlled remotely to provide operating reserve and respond actively when needed by the electric power system operation. In this paper, a novel control strategy for the aggregation model of ACs based on the thermal model of the room is proposed. By resetting the temperature of each AC, the operation state is adjusted temporarily without affecting customers' satisfaction. The operation characteristics of both individual AC and the aggregation model of ACs are analysed. Furthermore, several indexes are put forward to evaluate the operating reserve performance, including reserve capacity, response time, duration time and ramp rate. The effectiveness of the proposed control strategy is illustrated in the numerical studies.

1. Introduction

The utilization of renewable energy sources (RES) is burgeoning to deal with the rapidly increasing energy consumption and environment deterioration [1]. However, the large fluctuation and severe intermittence of RES make the power generation less predictable and controllable. Furthermore, the high penetration of RES, such as wind power and photovoltaic power, has posed a great challenge to the security and reliability of the power system operation [2]. Therefore, more operating reserve is required for the system to maintain balance between power supply and demand [3]. Operating reserve is the generating capacity available in a short period of time to avoid power shortage that results from emergencies, such as random failures of the generator and load fluctuations [4]. Operating reserve is mainly provided by conventional large generators, especially thermal power generating units and hydro turbines. However, thermal power generation may be phased out in the future. Moreover, the fluctuation brought by the growing share of RES will continuously increase, while the conventional operating reserve providers may not be able to satisfy the requirements of the system with burgeoning RES in the future. Therefore, the shortage of operating reserve has become an urgent issue for both power system operation and planning [5,6].

The development of information and communication technologies (ICT) has made the remote control of flexible loads much easier [7]. Thus it is possible for small end-customers to provide operating reserve to support power system's operation. Studies in [8,9] have illustrated that flexible loads have positive effects on maintaining system balance between supply and demand. Small end-customers can serve as balancing resources through the application of smart controllers and smart meters [10]. By

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http://dx.doi.org/10.1016/j.apenergy.2016.12.004
0306-2619/

Nomenclature

Acronyms

RES	renewable energy sources
AC	air conditioner
ICT	information and communication technologies
HVAC	heating, ventilating and air-conditioning loads
RC	reserve capacity
RT	response time
DT	duration time
RR	ramp rate
COP	coefficient of performance
PER	simulation period

Variables and parameters

H_{gain}	total heat gains of the room
H_{loss}	total heat losses of the room
H_{AC}	heating/cooling generated by AC
$H_{internal}$	heat gain from appliances and occupants
H_{solar}	solar radiation received by the room
c_A	heat capacity of air
ρ_A	density of air
T_A	temperature in the room
T_O	ambient temperature
$T_{set}^{(k)}$	set temperature of the kth AC
$T_{set2}^{(k)}$	reset temperature of the kth AC
ΔT_{set}	temperature adjustment
$T_{hy}^{(k)}$	hysteresis band control of temperature
A	living area of the room
h	height of the room
A_S	surface area of the room envelope
V	volume of the room
ε	coefficient of heat release by appliances and occupants
$P_{incident}$	time-varying coefficient of heat absorbed from the sun
S	operation state of AC
S_{cool}	cooling state of AC
S_{heat}	heating state of AC
S_{styb}	standby state of AC
P	power of AC
$P_{cool}^{(k)}$	power of the kth AC in cooling state
$P_{styb}^{(k)}$	power of the kth AC in standby state
$PD_{cool}^{(k)}$	length of time in cooling state
$PD_{styb}^{(k)}$	length of time in standby state
k	serial number of ACs
N	total number of ACs
t	time
t_{ds}	start moment of duration time
t_{de}	end moment of duration time
α	valid interval of providing operating reserve
P_{max}	maximum power before receiving the control signal
P_{min}	minimum power after receiving the control signal
SS	send control signal
SR	receive control signal
t_{SS}	the moment of sending control signal
t_{SR}	the moment of receiving control signal

utilizing the communication infrastructure of the smart grid, small end-customers are able to control their daily energy consumption and adapt their electricity bills to their actual economic conditions [11].

As one of the most popular and easily controlled flexible loads, air conditioners (AC) account for a large share in power consumption due to the mass application across the world [12]. According to a study carried out in Spain, electricity consumption of residential ACs accounts for about one third of the peak electricity consumption in large cities during the summer [13]. Therefore, ACs have yielded enormous potential in serving as energy storage devices, which can provide operating reserve by reducing power consumption temporarily. In this field, some researches have been conducted. For example, heating, ventilating and air-conditioning (HVAC) loads are controlled to adjust their demand profiles in response to the electricity price [7,14,15]. The potential for providing intra-hour load balancing services using aggregated HVAC loads has been investigated in [16]. Meanwhile, inconvenience to customers should be reduced as much as possible when ACs are controlled to provide operating reserve for power system [17–21]. Fuzzy logic-based approaches have been used in [17–19] to optimize both customer's satisfaction and utility savings. The AC's on/off control time is considered in [20], which introduces a dynamic programming approach to minimize the load reduction in order to reduce the customers' discomfort. Ref. [21] combines the advantages of linear and dynamic programming approaches to enable an acceptable level of services. Moreover, some field demonstration projects in [22–26] have shown the benefits of the demand response. For example, Con Edison, an energy company in New York City, provides customers with free *smart air-conditioning kits*, which help customers control their ACs remotely while earning rewards [25]. Several countries in Europe, e.g. England, Germany and Denmark, have started smart heat pump projects to help balance generation and demand [26].

However, all the above control strategies are based on the on/off control strategy, which comes into effect only by making the ACs switch between the mode of on and off. The on/off control strategy is a rough control method that sheds load directly, which will cause a sudden change in the power, bring a disturbance to the customers involved in demand response programs, and have a negative impact on the operation and performance of ACs. With the development and reform of the electric utility industry, customers' satisfaction with electric services will be increasingly more important.

Furthermore, several unified indexes, including the minimum/-maximum generating capability, the start-up/shut-down time, the minimum/maximum reserve capacity, and the ramp-up/ramp-down rate limit, have been developed for evaluating the operating reserve performance provided by conventional power generating units [27,28]. However, there are few researches which evaluate the performance of operating reserve provided by ACs for maintaining system balance. Only one index, the load-shedding capacity or load reduction, is defined to evaluate the performance of reserves for ancillary services in [16,29–31]. This index may not be comprehensive to evaluate the performance of operating reserve provided by ACs, since it is not clear whether the ACs can meet the requirements of providing operating reserve for the power system, how long the response time of the aggregated ACs is, and how long the load-shedding state of ACs can last. Therefore, the evaluation indexes for operating reserve provided by ACs are not sufficient. Consequently, the operating reserve provided by generation-side and demand-side cannot be dispatched collaboratively. Moreover, the lack of unified evaluation indexes makes it difficult to optimize the control of aggregated ACs, and increases the risk of unpredictable load fluctuations caused by the ACs' control.

This paper proposes a new control strategy based on the aggregation model of ACs, as shown in Fig. 1. The customers, who participate in the demand response program, have signed the contract with the agreement on providing load-shedding when needed. Their houses are installed with the terminal controllers, and the customers can set the controllers' parameters, such as a target comfortable temperature and a maximum adjustable temperature deviated from the target. Accordingly, the householders can get more benefits with a larger adjustable temperature range. When power reduction is needed, the control centre sends control signals (SR) to each participated terminal controller. The SR may contain: the adjustment amount of ACs' set temperature, the beginning time and the ending time of demand response. After receiving the control signal, the ACs will change the operation state, which results in reducing power consumption and providing operating reserve for that moment. Here, the adjustment amount of ACs' set temperature will be within the maximum acceptable range, which is set in advance by the customers. In this way, the customers' satisfaction can be guaranteed. Similar to the operating reserve provided by conventional generating units [4], several indexes are defined to evaluate the performance of operating reserve provided by individual AC and aggregated ACs, including reserve capacity (RC), response time (RT), duration time (DT) and ramp rate (RR). These indexes can provide an effective and efficient measurement of the maximum load-shedding capacity, the response time, the duration time, and the regulation rate.

The contributions of this paper can be described as follows:

(1) Compared with the on/off control strategy, resetting the temperature of ACs is a softer approach to influence customers' comfort, especially when the time interval is short before adjusting to the original set temperature.
(2) Resetting the temperature of ACs will not bring a sharp drop of the power which may be adverse to the safety of the power system operation. Moreover, the ACs will be less worn and get a longer operation life by adjusting their set temperature rather than turning them on/off repeatedly.
(3) The operating reserve performance provided by individual AC and aggregated ACs is evaluated quantitatively. Several indexes are defined, including RC, RT, DT and RR, which makes up the gap of evaluating the performance of operating reserve provided by HVAC loads.
(4) Based on the proposed evaluation indexes, the operating reserve from demand-side can be dispatched by the system operator similar as conventional generating units, which will contribute to the improvement of power system's economic performance [10].
(5) The proposed evaluation indexes are calculated and analysed by simulations and case studies in this paper. Results have shown the effectiveness of the proposed control strategy and evaluation indexes.

The remaining of this paper is organized as follows. Section 2 analyses the thermal model of the room and the operating reserve characteristics of an individual AC. Section 3 presents the performance of operating reserve provided by aggregated ACs and the corresponding evaluation indexes. The numerical studies are presented in Section 4. Finally, Section 5 concludes the paper.

2. Operating reserve provided by individual AC

2.1. Thermal model of the room

To study the control strategy for ACs and evaluate the performance of operating reserve provided by ACs, it is important to develop the thermal model of the room [32–34]. The heat variation in the room is calculated by subtracting heat gains H_{gain} from heat losses H_{loss}. The temperature in the room T_A can be represented as a function of time:

$$c_A \rho_A V \frac{dT_A}{dt} = H_{gain} - H_{loss} \quad (1)$$

where c_A, ρ_A and V denote the heat capacity of air, the density of air and the volume of the room, respectively; dT_A/dt is the temperature variation during each time interval.

The heat gains, from the AC H_{AC}, internal appliances and occupants $H_{internal}$ and the sun H_{solar}, can be expressed as

$$H_{gain} = H_{AC} + H_{internal} + H_{solar} = P \cdot COP + \varepsilon A + P_{incident}(t)A \quad (2)$$

where P and COP correspond to the operating power and coefficient of performance of AC, respectively; ε represents the coefficient of heat release by appliances and occupants; A is the living area of the room; $P_{incident}(t)$ is the time-varying coefficient of heat absorbed from the sun [34]. Note that H_{AC} is a positive value in the heating state and a negative value in the cooling state.

COP is an important factor for AC, which expresses the relationship between the heat supply (cooling or heating) and the power input [35]. The value of COP is related to the performance of AC's compressor, electric expansion valve, cooling load, and temperature difference between T_A and the ambient temperature T_O [36–38]. For the air-source ACs studied in this paper, COP varies mainly with the temperature difference between T_A and T_O. Based on the data in [39], COP will be lower with a larger temperature difference, and it can be fitted to a straight line approximately, which can be expressed as

$$COP = -\theta \cdot |T_A - T_O| + \delta \quad (3)$$

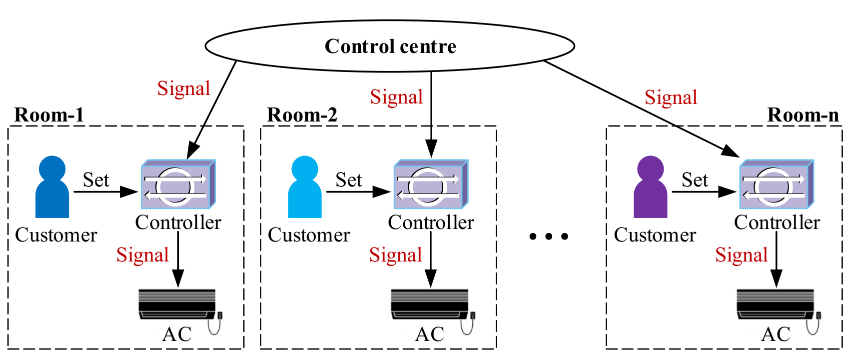

Fig. 1. The control structure of the aggregation model of ACs.

where θ and δ are the fitted coefficients of the linear relationship between COP and $|T_A - T_O|$.

The heat losses are estimated by calculating losses through the building envelope and air leakages [34], which can be expressed as

$$H_{loss} = KA_S(T_A - T_O) + c_A\rho_A V(T_A - T_O)n \quad (4)$$

where K denotes the heat transfer coefficient; A_S is the surface area of the envelope; T_O denotes the ambient temperature; n is the air exchange times.

2.2. Operation characteristics of individual AC

Based on the thermal model as shown above, the operation characteristics of individual AC are analysed in this subsection. It is assumed that the ACs are turned on and operated in cooling mode. The general operation characteristics of the kth individual AC are shown in Fig. 2, where three typical curves are presented: (a) the variation curve of the temperature in the room, (b) the state variation curve of AC and (c) the operating power variation curve of AC.

Fig. 2(a) describes the variation curve of the temperature in the room, where $T_A^{(k)}$ is the temperature within the kth room. $T_{set}^{(k)}$ represents the set temperature, which is set by the customers. $T_{hy}^{(k)}$ is the hysteresis band of temperature, which describes the maximum absolute difference between the room temperature and the set temperature. Therefore, the temperature in the room varies in the range $[T_{set}^{(k)} - T_{hy}^{(k)}, T_{set}^{(k)} + T_{hy}^{(k)}]$.

The operation state of the kth AC is shown in Fig. 2(b). ACs in summer have two operation states: cooling state $S_{cool}^{(k)}$ and standby state $S_{styb}^{(k)}$. When the temperature in the room is not higher than the lower limit value $(T_{set}^{(k)} - T_{hy}^{(k)})$, the AC is turned to standby state. Conversely, when the temperature in the room is equal to or higher than the upper limit value $(T_{set}^{(k)} + T_{hy}^{(k)})$, the AC is turned to cooling state. Therefore, the operation state $S^{(k)}$ can be expressed as

$$S^{(k)} = \begin{cases} S_{cool}^{(k)}, T_A^{(k)} \geqslant T_{set}^{(k)} + T_{hy}^{(k)} \\ S_{styb}^{(k)}, T_A^{(k)} \leqslant T_{set}^{(k)} - T_{hy}^{(k)} \end{cases} \quad (5)$$

The operating power variation curve of the kth AC is similar to the state variation curve, as shown in Fig. 2(c), where $P^{(k)}$, $P_{cool}^{(k)}$ and $P_{styb}^{(k)}$ respectively correspond to the actual operating power, the power in cooling state and the power in standby state. Therefore, it can be expressed as

$$P^{(k)} = \begin{cases} P_{cool}^{(k)}, S_{cool}^{(k)} \\ P_{styb}^{(k)}, S_{styb}^{(k)} \end{cases} \quad (6)$$

Conventionally, AC belongs to thermostatically controlled on/off device [27–29], which is considered as consuming constant power in cooling state and zero power in standby state.

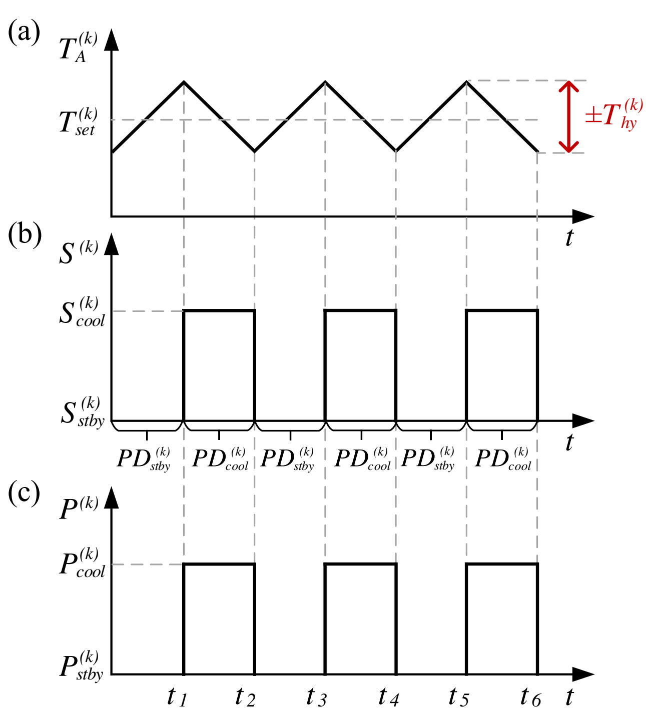

Fig. 2. Operation characteristics of the kth AC: (a) the variation curve of the temperature in the room, (b) the state variation curve of AC and (c) the operating power variation curve of AC.

2.3. Operating reserve provided by individual AC

Based on the operation characteristics of individual AC as shown above, this subsection analyses the operating reserve performance of individual AC. The control strategy is to reduce the power consumption by resetting AC's temperature. For instance, the set temperature of ACs in cooling state can be adjusted to a higher level to reduce power consumption, thus providing operating reserve.

The buildings which participate in the demand response program have been installed terminal controllers, and customers can set the controllers' parameters such as a comfortable temperature and a maximum adjustable temperature. Once power reduction is needed, the control centre will send control signals, including the adjustment amount of ACs' set temperature, the beginning time and the ending time of demand response, to each terminal controller. Upon receipt of the control signal, the ACs will adjust the set temperature, which results in reducing power consumption and providing operating reserve for system operation. Here, the adjustment amount of ACs' set temperature will be in the maximum acceptable range, which is set in advance by the customers. In this way, the customers' satisfaction can be guaranteed. If before the instructed ending time, the system operator decides that the power reduction is no longer needed, a recall of the deployment can be sent and ACs can be tuned back to their original set temperature earlier than scheduled. Otherwise, original set temperature will be brought back after the instructed ending time. Compared with the on/off control strategy, resetting the temperature of ACs is a softer approach within customers' comfort zone, especially when the time interval is short before adjusting to the original set temperature.

According to the ACs' operation state when receiving the control signal, ACs' operating reserve performance can be divided into two categories: operating reserve provided by ACs in cooling state (Fig. 3), and in standby state (Fig. 4).

(1) Operating reserve provided by ACs in cooling state

Fig. 3 illustrates individual AC's operating reserve performance when receiving the control signal in cooling state. Fig. 3(a) shows the temperature variation curve in the kth room and Fig. 3(b) shows the operating power variation curve of the kth AC. The solid line is the actual operating curve and the dashed line is the original operating curve if the set temperature is not adjusted. When the control signal is received by AC at the time t_{SR}, the set temperature

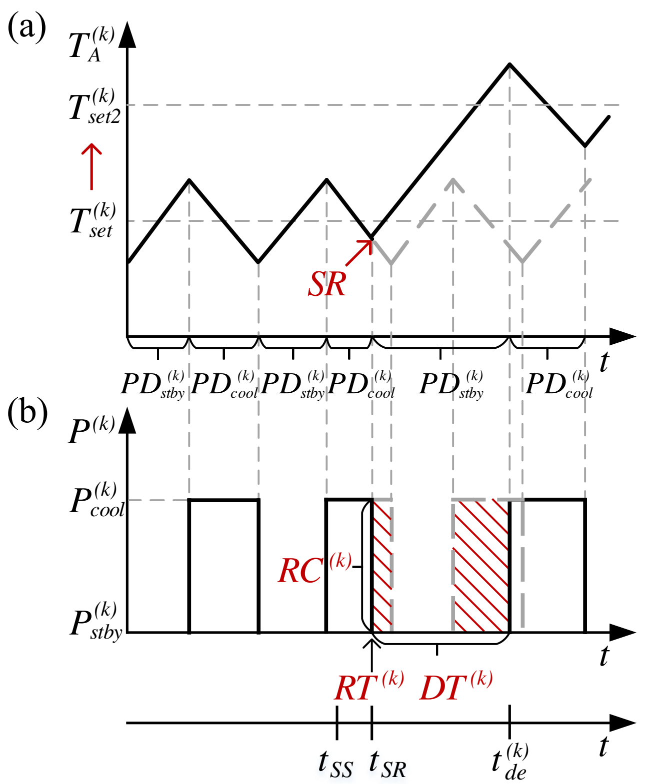

Fig. 3. Operating reserve provided by the kth AC when receiving the control signal in cooling state: (a) the variation curve of the temperature in the room and (b) the operating power variation curve of AC.

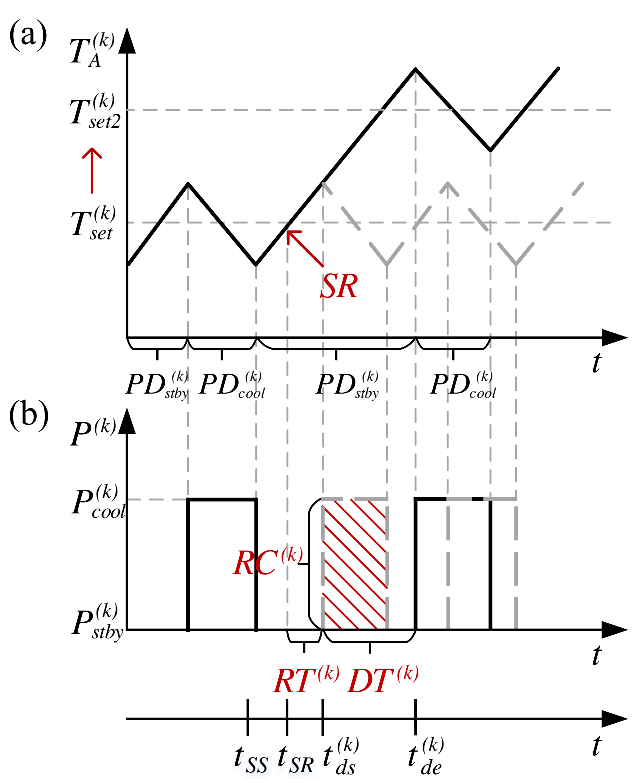

Fig. 4. Operating reserve provided by the kth AC when receiving the control signal in standby state: (a) the variation curve of the temperature in the room and (b) the operating power variation curve of AC.

of the AC is reset from $T_{set}^{(k)}$ to $T_{set2}^{(k)}$. Then the AC turns to standby state and keeps in that state until the temperature in the room rises to the upper limit value of $(T_{set2}^{(k)} + T_{hy}^{(k)})$. Therefore, ACs in cooling state can reduce power consumption and provide operating reserve in a fast response manner.

(2) Operating reserve provided by ACs in standby state

Fig. 4 illustrates individual AC's operating reserve performance when receiving the control signal in standby state. Fig. 4(a) is the temperature variation curve in the kth room and Fig. 4(b) is the operating power variation curve of the kth AC. Although the ACs in standby state have no power loads, these ACs will also reset the temperature from $T_{set}^{(k)}$ to $T_{set2}^{(k)}$ after receiving the control signal. Then the standby time will be extended to the time $t_{de}^{(k)}$. If the set temperature is not adjusted, the AC will turn to cooling state at the time $t_{ds}^{(k)}$. It is equivalent that ACs in standby state start to provide reserve capacity at the time $t_{ds}^{(k)}$ when the AC is supposed to work.

In order to evaluate the performance of operating reserve provided by individual AC, several indexes are defined, including reserve capacity (RC), response time (RT) and duration time (DT). RC is the maximum reserve capacity provided by the AC, which is equal to its cooling power. Therefore, the reserve capacity provided by ACs in both states can be expressed as

$$RC^{(k)} = P_{cool}^{(k)} \tag{7}$$

where $RC^{(k)}$ and $P_{cool}^{(k)}$ represents the reserve capacity and the cooling power of the kth AC, respectively.

Response time (RT) is the time delay before the AC starts to provide operating reserve after the control signal is sent. For ACs in cooling state, RT is the control signal communication time. While for ACs in standby state, RT has to add the original standby time, which can be expressed as

$$RT^{(k)} = \begin{cases} t_{SR} - t_{SS}, t_{SR} \in PD_{cool}^{(k)} \\ t_{ds}^{(k)} - t_{SS}, t_{SR} \in PD_{styb}^{(k)} \end{cases} \tag{8}$$

where $PD_{cool}^{(k)}$ and $PD_{styb}^{(k)}$ are the time periods of cooling state and standby state, respectively.

Duration time (DT) is the length of time that the AC keeps in standby state until it restarts to refrigerate. DT of ACs in both states can be defined as

$$DT^{(k)} = \begin{cases} t_{de}^{(k)} - t_{SR}, t_{SR} \in PD_{cool}^{(k)} \\ t_{de}^{(k)} - t_{ds}^{(k)}, t_{SR} \in PD_{styb}^{(k)} \end{cases} \tag{9}$$

3. Operating reserve provided by aggregated ACs

Based on the operating reserve performance of individual AC as shown above, the operating reserve provided by the aggregated ACs is analysed in this section. The aggregated model contains multi-ACs, which have different rated powers and different coefficients of performance. The set temperature and operation state of these ACs are also different. Thus the reserve capacity provided by aggregated ACs is time-varying as the result of different response time and capacity of each AC.

Typical operating reserve provided by the aggregated ACs is shown in Fig. 5, where P_{max} and P_{min} correspond to the maximum power and minimum power of the aggregated ACs, respectively. The control signal is sent by the control centre at the time t_{SS}. Because of the different response time, the ACs start to respond

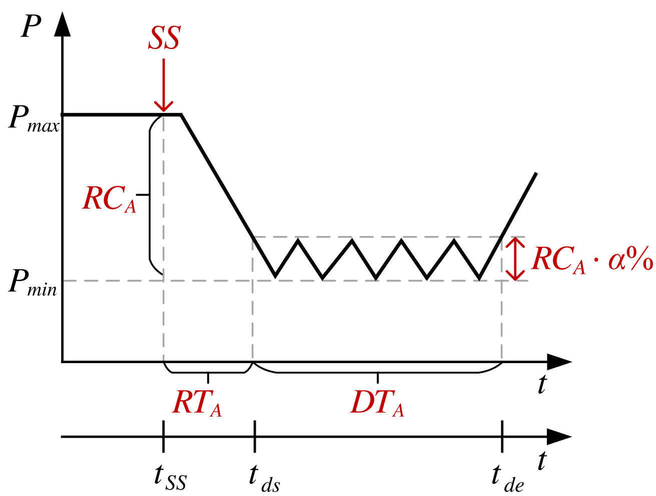

Fig. 5. Operating reserve provided by aggregated ACs.

and provide reserve one by one rather than all at once. The aggregated ACs have the minimum power consumption at the time t_{ds} and start to provide operating reserve. The aggregated ACs finish providing operating reserve at the time t_{de} when the power consumption of the aggregated ACs are rising. Because the minimum power is not a strict horizontal line, $\alpha\%$ is a valid interval from the maximum load-shedding capacity to a certain range, and $(RC_A \cdot \alpha\%)$ is regarded as the valid range in which the aggregated ACs provide operating reserve. And $(t_{de} - t_{ds})$ is regarded as the duration time of providing operating reserve.

3.1. Performance of operating reserve provided by aggregated ACs

Several indexes are proposed in this paper to evaluate the performance of operating reserve provided by aggregated ACs, including reserve capacity (RC_A), response time (RT_A), duration time (DT_A) and ramp rate (RR_A).

(1) Reserve capacity

Different from the reserve capacity provided by individual AC, RC_A is defined as a valid range around the maximum reserve capacity, since the total power of aggregated ACs is fluctuating, even when it has reached the maximum shedding capacity.

It is assumed that the operating power of ACs at the time t_{SS} is P_{max}, and the minimum operating power is P_{min}. Therefore, the reserve capacity of the aggregated ACs can be represented as

$$RC_A = P_{max} - P_{min} \tag{10}$$

(2) Response time and duration time

RT_A is the length of time from the moment when the control signal is sent to the moment when valid reserve capacity is achieved. DT_A is the length of time when the reserve capacity is within the valid range of RC_A.

As shown in Fig. 5, t_{ds} and t_{de} can be evaluated according to the intersections of the operating power curve $P(t)$ and the upper boundary of the reserve capacity's valid range $(P_{min} + RC_A \cdot \alpha\%)$. The intersections can be achieved by

$$P(t) = P_{min} + RC_A \cdot \alpha\% \tag{11}$$

Based on the two solutions t_{ds} and t_{de}, the response time and duration time can be calculated as

$$RT_A = t_{ds} - t_{SS} \tag{12}$$

$$DT_A = t_{de} - t_{ds} \tag{13}$$

(3) Ramp rate

RR_A is the ratio of RC_A and RT_A, which reflects the rate of providing reserve capacity by aggregated ACs. According to the reserve capacity and response time, the ramp rate can be calculated as

$$RR_A = RC_A \cdot (1 - \alpha\%)/RT_A \tag{14}$$

3.2. Simulation framework for evaluating operating reserve performance

Based on the thermal model of the room and the control strategy of AC, the operating reserve performance of the aggregated ACs can also be simulated. Fig. 6 shows the detailed flow chart of the simulation, which can be described by the following steps:

(a) Initialize the parameters, including AC parameters (such as rated powers, set temperatures and *COP*), room parameters (such as living areas and specific heat transfer coefficients of the building envelop) and ambient temperature.
(b) Determine whether ACs have been turned on. The turned off ACs are not available, and the program jumps to step g.
(c) Search for the control signal. The ACs will reset the set temperature from $T_{set}^{(k)}$ to $T_{set2}^{(k)}$ after receiving the signal. Otherwise, the set temperature will remain unchanged.
(d) Calculate the power of the *k*th AC and the corresponding heat flow produced by the AC.
(e) Based on the thermal model of the room, calculate the *k*th room's temperature $T_A^{(k)}$ at the time *t*.
(f) Compare $T_A^{(k)}$ with the set temperature. The AC will either turn to cooling state if $T_A^{(k)} \geqslant T_{set}^{(k)} + T_{hy}^{(k)}$, or turn to standby state if $T_A^{(k)} \leqslant T_{set}^{(k)} - T_{hy}^{(k)}$. And the operation state remains unchanged in other cases.
(g) Determine whether all the ACs have been considered. If some ACs have not been calculated, the program will loop from step b to step g. Otherwise, the program jumps to step h.
(h) Calculate the total power at the time *t*.
(i) Determine whether the simulation period *PER* has been finished. If the time *t* is smaller than PER, the program will loop from step b to step i. Otherwise, the program jumps to step j.
(j) Output all the results.

4. Case studies and discussion

This section evaluates the operating reserve performance of aggregated ACs by representative cases. It is organized as parameter initialization, operating reserve performance with different temperature adjustments, operating reserve performance with different numbers of ACs, analysis of aggregated ACs returning to original set temperature and analysis of demand response in actual case studies.

4.1. Parameter initialization

Some fixed parameters are shown in Table 1 [39–41]. The variable parameters are set as follows.

- The number of ACs is *N*, which is equal to the number of corresponding rooms.
- The living area of the *N* rooms are generated in the normal distribution by using the mean value of 100 m^2 and the standard deviation of 40 m^2.

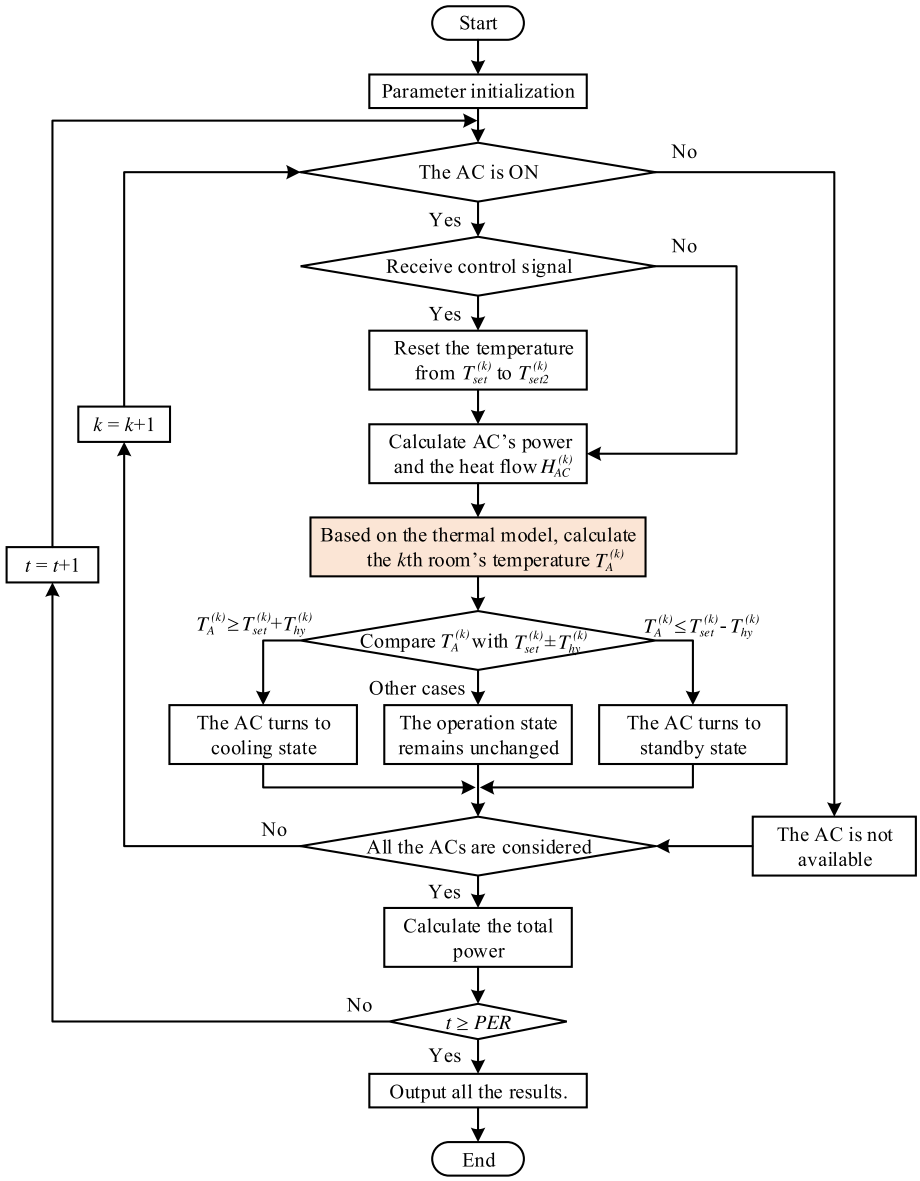

Fig. 6. The flow chart of simulation method for calculating operating reserve.

Table 1
Fixed parameter initialization [39–41].

Symbols	Definitions or descriptions	Values	Units
h	Height of the room	2.5	m
θ	Fitted coefficient of *COP*	0.0384 [39]	N/A
δ	Fitted coefficient of *COP*	3.9051 [39]	N/A
K	Heat transfer coefficient	7.69 [39]	$W/(^\circ C \cdot m^2)$
c_A	Heat capacity of air	1.005 [40]	$kJ/(kg \cdot ^\circ C)$
ρ_A	Density of air	1.205 [40]	kg/m^3
ε	Coefficient of heat release by appliances and occupants	4.3 [41]	W/m^2
n	Air exchange times	0.5	1/h
$T_{hy}^{(k)}$	Hysteresis band of temperature control	± 1	$^\circ C$
$\alpha\%$	Valid interval of providing operating reserve	10%	N/A

- The initial set temperatures of ACs distribute randomly between 23 °C and 26 °C.
- The rated power of each AC is related to the living area of the corresponding room. In general, the rated power will be higher in a bigger room. Here it is assumed that each rated power equals to sixtyfold living area. For example, the rated power is 1800W if the room area is 30 m^2.

The ambient temperature is the actual monitored data of a city, on August 1, 2015 [42], as shown in Fig. 7. And the control signal sending time is 12:00 AM.

4.2. Operating reserve performance with different temperature adjustments

This section will analyse the operating reserve performance with different temperature adjustments. The number of ACs is set to 100 and three conditions of different adjustment amounts of the set temperature ΔT_{set} are considered: $\Delta T_{set} = 1\,^\circ C$, $\Delta T_{set} = 2\,^\circ C$ and $\Delta T_{set} = 3\,^\circ C$.

To directly demonstrate the operating process of the aggregated ACs, the temperature and power variation processes of 100 aggregated ACs with different temperature adjustments are shown in Figs. 8 and 9, respectively. Fig. 8 indicates that the temperature

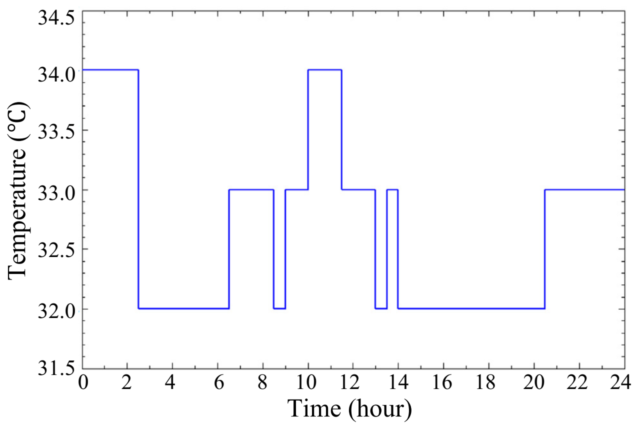

Fig. 7. The ambient temperature [42].

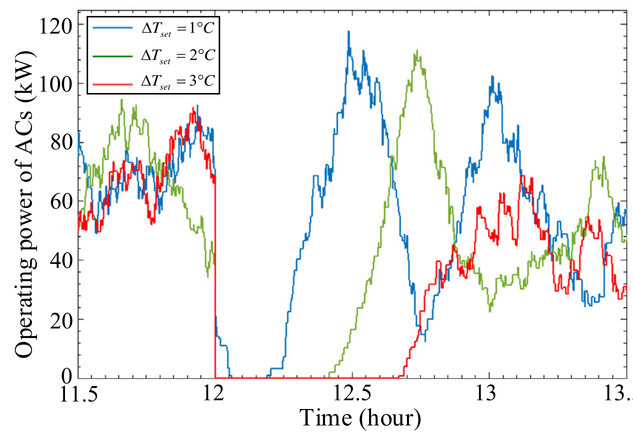

Fig. 9. Operating power curves with different temperature adjustments.

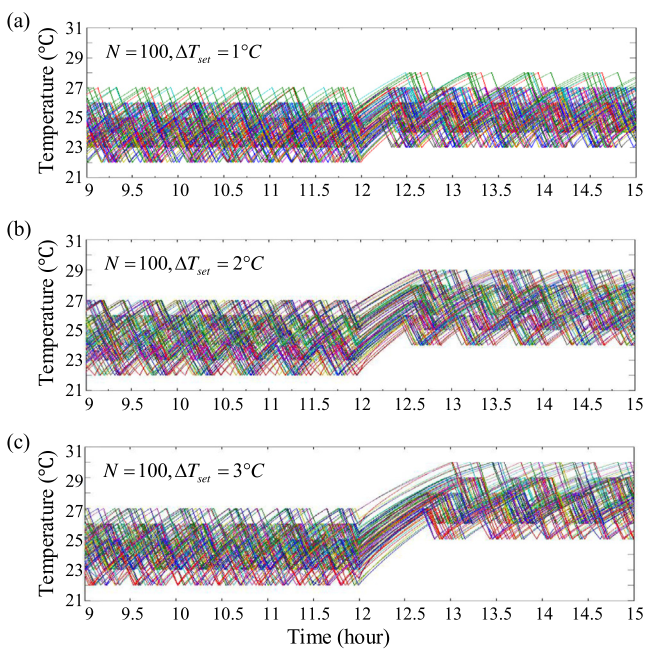

Fig. 8. Temperature variation curves of 100 ACs with different temperature adjustments, (a) 1 °C, (b) 2 °C and (c) 3 °C.

of the 100 aggregated ACs are time-varying after adjusting the set temperature. The power curve in Fig. 9 is similar to the theoretical power curve shown in Fig. 5, which validates the effectiveness of the control strategy of the aggregated ACs.

The proposed indexes, reserve capacity (RC_A), response time (RT_A), duration time (DT_A) and ramp rate (RR_A), are calculated and shown in Table 2.

Several observations can be made from above simulation results:

- AC aggregation can provide operating reserve, and the maximum reserve capacity can be reached in a short time.
- Reserve capacities in the three cases are almost the same. When the number of ACs remains the same, the total installed power capacity will be roughly similar. Therefore, although the temperature adjustments are different, reserve capacities which AC aggregation can achieve are almost the same.
- Response time in the three cases are all within 5 min, and the time will decrease along with the increase of the temperature adjustments. Especially, when the adjustment amount of temperature is more than 2 °C, the response can be accomplished instantaneously. Response time will be a little longer in practice, due to the fact that the communication time of control signal is neglected in the simulation. However, the communication technology is able to achieve second-level communication nowadays. Therefore, the communication impact on response time is not significant.
- Ramp rate is the ratio of reserve capacity to the response time. The value will be very large when the response time is relatively small. For example, ramp rate is 575.06 kW/min when the temperature adjustment is 3 °C.
- Duration time in the three cases are extended along with the increase of the temperature adjustments. The more set temperatures are adjusted, the longer standby time will last, hence leading to a longer duration time. The relationship between duration time and the adjustment amount of the set temperatures can be fitted as a linear function, as shown in Fig. 10.

4.3. Operating reserve performance with different numbers of ACs

This subsection will analyse the operating reserve performance under different numbers of ACs. The number is set to 100, 500, 1000 and 2000. The adjustment amount of the set temperature ΔT_{set} is 1 °C. The temperature and power variation processes of aggregated ACs are shown in Figs. 11 and 12, respectively.

The proposed four indexes can be calculated, as shown in Table 3.

Compared with the results in Section 4.2, the simulation illustrates that the response time (RT_A) and duration time (DT_A) are most dependent on temperature adjustment, not on the number of ACs. However, reserve capacity (RC_A) and ramp rate (RR_A) will increase along with the number of ACs. The variation tendency of the two indexes with the number N can be described in Fig. 13.

The curve-fitting solid line and dashed line respectively correspond to the reserve capacity and ramp rate, which are directly proportional to the number of ACs.

4.4. Analysis of aggregated ACs returning to original set temperature

This subsection will analyse the operating performance of aggregated ACs returning to original set temperature. The studied number of ACs is 1000 and the adjustment amount of the set temperature ΔT_{set} is set to 1 °C. Demand response ends at 16:00, and each AC returns to their original set temperature from $T_{set2}^{(k)}$ to $T_{set}^{(k)}$. The temperature and power variation processes of aggregated ACs are shown in Figs. 14 and 15, respectively.

Table 2
Four indexes in three kinds of temperature adjustments.

Indexes	$\Delta T_{set} = 1\,^{\circ}\mathrm{C}$	$\Delta T_{set} = 2\,^{\circ}\mathrm{C}$	$\Delta T_{set} = 3\,^{\circ}\mathrm{C}$	Units
RC_A	92.63	96.06	92.01	kW
RT_A	2.83	0.21	0.16	min
RR_A	32.73	457.43	575.06	kW/min
DT_A	12.67	28.25	40.42	min

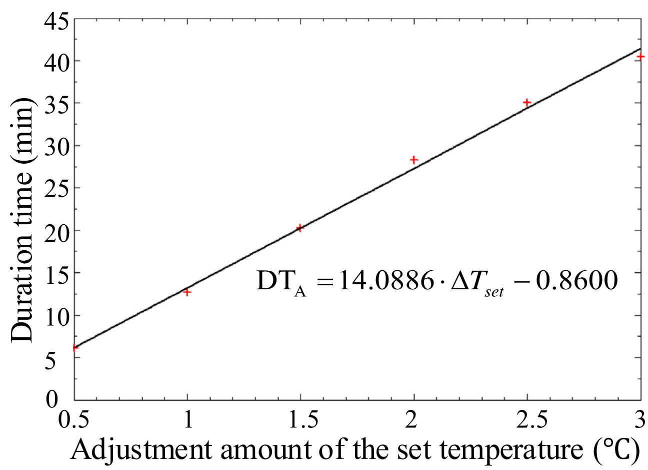

Fig. 10. Fitted curve of duration time and temperature adjustments.

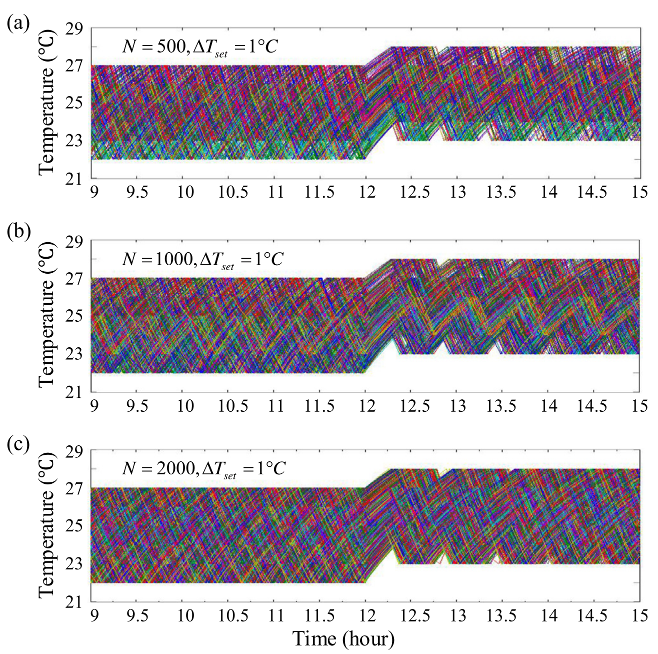

Fig. 11. Temperature variation curves with different numbers of ACs, (a) 500, (b) 1000 and (c) 2000.

There are two cases in Fig. 15. In Case 1, all the aggregated ACs return to original set temperature at 16:00. A power rebound occurs, because all the ACs will turn to cooling state at almost the same time. Due to the thermal insulation properties of each building are with little difference in the same region, the duration time of each AC in cooling state or standby state is similar. Therefore, the power oscillation lasts for a lengthy period of time in this simulation [43].

In order to reduce the sharp rebound of power, a batch returning method is simulated in Case 2. ACs are divided into five groups.

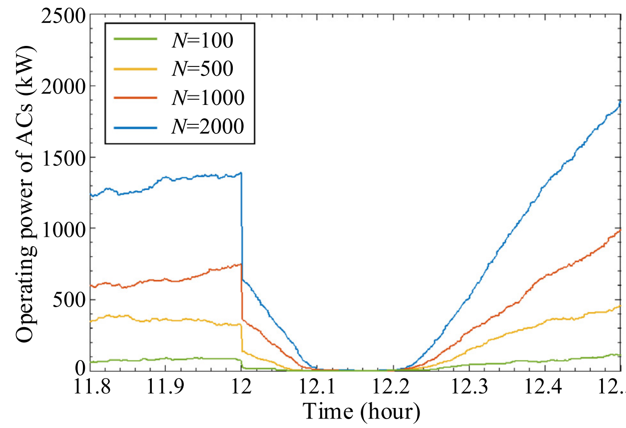

Fig. 12. Operating power curves with different numbers of ACs.

Every half an hour, a group of ACs returns to original set temperature. The second curve in Fig. 15 shows that power oscillation is confined to a certain range.

4.5. Analysis of demand response in actual case studies

ACs can lead to the load peak and cause stress on the power system especially in hot days. Moreover, the increasing penetration of RES, such as wind power and photovoltaic power, brings more fluctuation and intermittence to the power generation. In order to testify the effectiveness of the proposed control strategy and evaluate the reserve capacity performance of residential ACs, a case study has been carried out by applying the proposed control strategy to real-recorded household demand through a demonstration project in a province of China, where the number of ACs rises rapidly, and their electricity consumption has accounted for more than 30 percent in summer. Each household participating in the project is equipped with a smart meter and a terminal energy controller. In addition, the householders sign the contract regarding how many times that they agree to be controlled in a year and how they will be compensated after demand response event.

There are 522 households participating in the demand response program, whose electricity consumption are collected every 15 min for two weeks. Two cases are considered:

Case 1: There is no demand response signal sent to the customers' terminal controller in the first week. The original power consumption curve is calculated by the average of the seven days' electricity consumption data.

Case 2: There is a beginning signal of demand response sent to the terminal controllers at 14:00 and an ending signal at 15:00 every day during the second week. Similarly, the second power consumption curve is calculated by the average of the seven days' electricity consumption data.

The weather condition is similar during the selected two weeks. And it is assumed that these customers' electric-equipment do not change. The results are shown in Fig. 16.

It can be seen that the demand response program performed in the second week causes peak load shifting: the load begins to

Table 3
Four indexes with different number of ACs.

Indexes	$N = 100$	$N = 500$	$N = 1000$	$N = 2000$	Units
RC_A	92.63	388.89	789.10	1578.00	kW
RT_A	2.83	3.00	4.08	4.33	min
RR_A	32.73	129.63	193.41	364.43	kW/min
DT_A	12.67	12.42	11.17	10.58	min

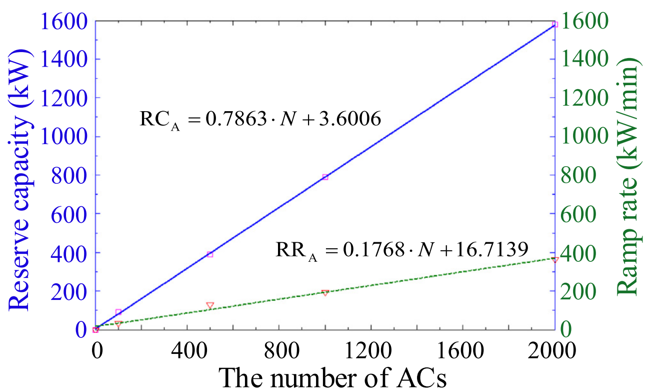

Fig. 13. Fitted curve of reserve capacity and ramp rate with different numbers of ACs.

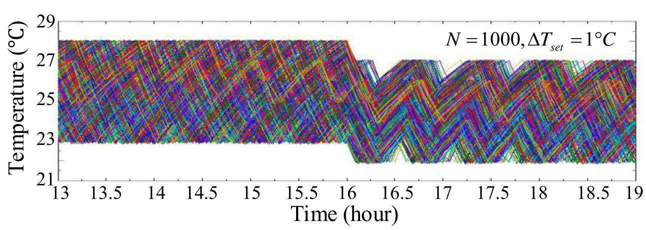

Fig. 14. Temperature variation curves of aggregated ACs returning to original set temperature.

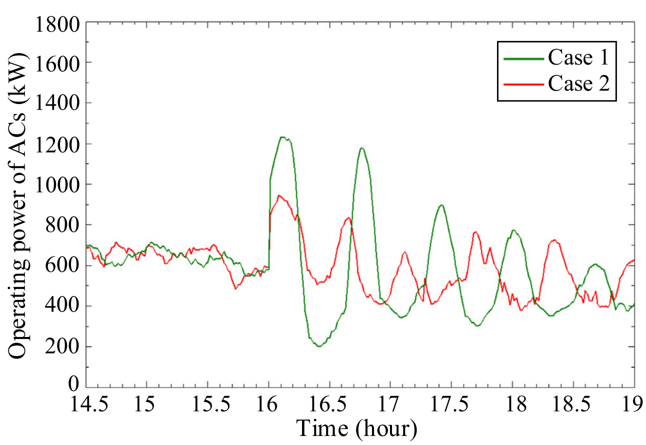

Fig. 15. Operating power curves of aggregated ACs returning to original set temperature.

decrease at 14:00 and reaches the lowest point at 14:56. The maximum power reduction is 1218.12 kW, which is the reserve capacity (RC_A). The power begins to rebound at 15:17 and returns to the normal level at 15:45. Base on the evaluation method of operating reserve, the other three indexes can be calculated. The response time (RT_A), ramp rate (RR_A) and duration time (DT_A) are around 33 min, 40.61 kW/min and 48 min, respectively. It demonstrates

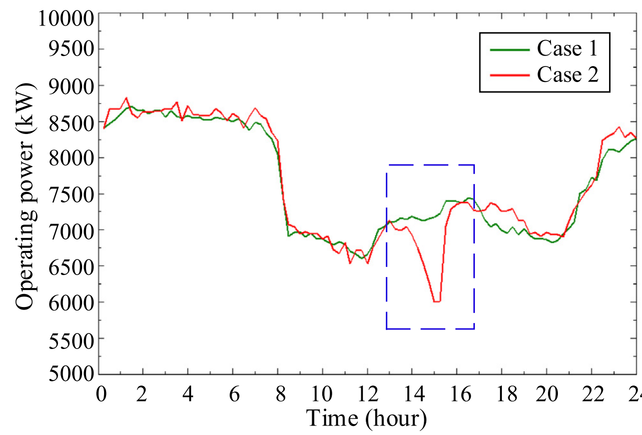

Fig. 16. Operating power curves in actual case studies.

that demand response can provide operating reserve by reducing power consumption.

5. Conclusions

This paper proposes a method to quantitatively analyse the operating reserve performance of the aggregated ACs. First, a softer control method on ACs is proposed and several indexes on the performance of operating reserve provided by AC aggregation are defined. These indexes, including reserve capacity, response time, duration time and ramp rate, are similar to the evaluation indexes of conventional power generations. Moreover, a simulation method on evaluating these indexes is proposed. The case study results show that AC aggregation can reach the maximum load-shedding within 5 min, and meet the requirements for providing operating reserve. The simulation results and the demonstration program validate the effectiveness of the proposed evaluation indexes for operating reserve provided by aggregated ACs.

Operating reserve capacity provided by ACs mainly relates to two factors, acceptable temperature adjustments and the number of ACs. Response time and duration time are mainly affected by temperature adjustments. Response time will be shorter or even instantaneous, when the temperature adjustment is large enough. Duration time will extend significantly along with the increase of the temperature adjustment. However, the other two indexes, reserve capacity and ramp rate will increase in direct proportion with the ACs' number. Furthermore, customer's comfort will be affected by a larger temperature adjustment. Therefore, in order to improve the potential of operating reserve, promoting more customers to participate in the demand response program is important.

This paper has made up the gap of evaluating the performance of operating reserve provided by HVAC loads. Based on the indexes proposed in this paper, the operating reserve from demand-side can be dispatched by the system operator as conventional generating units, which is a novel and meaningful practice for the power system. Moreover, this research can guide the demand response program and improve power system's economy.

Acknowledgements

This work is supported by the National Key Research and Development Program of China under Grant 2016YFB0901103, the China NSFC under Grant 51577167 and the State Grid Corporation of China (52110416001T).

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