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Collaborative voltage regulation by increasing/decreasing the operating power of aggregated air conditioners considering participation priority

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ABSTRACT

The development of renewable energy sources can help optimise energy structures and alleviate environmental problems. However, the integration of large-scale distributed renewable energy sources into power distribution systems may lead to reverse power flows and over-voltage. In addition, the simultaneous charging of numerous electric vehicles may result in under-voltage. To address this issue, a collaborative voltage regulation algorithm for regulating the operating power of aggregated air conditioners is developed in this study. First, a thermal model of a room is developed for analysing the dynamic operation processes of an air conditioner. Based on the thermal model, the regulation power provided by the aggregated air conditioners can be calculated, by temporarily resetting the set temperatures. Furthermore, the node voltages can be regulated by increasing/decreasing the operating power of the air conditioners. In addition, a participation priority algorithm is proposed for selecting the most suitable air conditioners for regulation. The numerical test results show that the proposed method can control the node voltage fluctuation within the permissible limits, and can maintain the room temperature within a suitable range. Thus, using thermal modelling and the proposed collaborative algorithm, voltage regulation services can be provided by utilizing the air conditioners, without affecting occupant comfort.

1. Introduction

The integration of renewable energy sources (RES) into the power grid is an important approach to address the issues of global warming and fossil fuels reduction. However, as the output of RESs is intermittent and random, the power system will be disturbed when large-scale RESs are integrated. In a power distribution system, the power flow becomes inverse when the power generation of the RES exceeds the load demand, which may cause an over-voltage problem [1]. Moreover, the intermittent power output of a RES causes more fluctuations of voltage in power distribution systems. Furthermore, extremely high load demands, such as during simultaneous charging of electric vehicles, may cause an under-voltage problem [2]. Several methods have been proposed for managing the voltage regulation problem. Among the traditional voltage regulation methods, the on-load tap changer (OLTC), step voltage regulator (SVR), and capacitor switch banks have been installed to mitigate the voltage problem. However, the power fluctuations of distributed generators (DGs) will cause the OLTC or the feeder SVR to operate frequently [3], and excessive actions in those equipment will reduce their lifetimes and increase maintenance costs [4][5]. In addition, owing to the naturally intermittent varying output of DGs and dynamic behaviour of loads, the voltage variations can occur so rapidly that traditional regulation equipment cannot regulate as fast as required [6]. Using reactive power is an effective approach for dealing with voltage regulation problems in transmission grids, owing to their inherent inductive nature [7]. However, the R/X ratio in a distribution system is much larger than that in a transmission system, making the compensation by reactive power less effective [8]. In addition, large reactive power flows in low-voltage distribution systems will increase the line congestion and power loss [9]. Therefore, active power regulation is more effective on the demand side [10]. With the development of information and communication technologies, an active and reactive power-coordinated control of DGs can be used to improve the voltage stability of distribution systems [11]. In addition to the DGs, flexible loads can also participate in voltage regulation, through demand

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Nomenclature

Acronyms

AC	air conditioner
COP	coefficient of the performance
DG	distributed generator
OLTC	on-load tap changer
RES	renewable energy source
SVR	step voltage regulator
PV	hotovoltaic

Variables and parameters

$\Delta P_{AC_k^i}$	voltage regulation power provided by the k^{th} AC at the node i
AC_k^i	the k^{th} AC at node i
c_{air}	heat capacity of the air
H_{AC}	heat generated by the AC
$H_{conduction}$	conductive heat losses
$H_{eq\&oc}$	heat generated by the electrical equipment and occupants
$H_{generate}$	heat generation
H_{loss}	heat loss
H_{solar}	heat generated by solar radiation
$H_{ventilative}$	ventilative heat losses
P_{AC^i}	operating power of i^{th} AC
P_{As}	power level after reset AC's set temperature
P_{As}'	power level before reset AC's set temperature
$P_{average}$	average solar intensity
P_{cool}	the power of AC in cooling state
$P^i_{current}$	current regulation power of node i
P^i_{NEPR}	the decrease of aggregated ACs' operating power for over-voltage regulation
P^i_{PEPR}	the increase of aggregated ACs' operating power for under-voltage regulation
$P_{standby}$	the power of AC in standby state
S_{wall}	total area of the wall
SW_{cool}	AC switches to the cooling state
S_{window}	total area of the window
$SW_{standby}$	AC switches to the standby state
t_{cool}	time when the AC operates in the cooling state
T_{hy}	maximum deviation between room temperature and set temperature
T_{in}	current room temperature
T_{in}'	previous time slot room temperature
T_k^{i-with}	the k^{th} room temperature with AC regulation waiting time of i^{th} node
$T_k^{i-without}$	the k^{th} room temperature without AC regulation waiting time of i^{th} node
Tr_{wall}	thermal transmittance of the wall
Tr_{window}	thermal transmittance of the window
T_{set}	set temperature of AC
$t_{standby}$	time when the AC operates in the standby state
U^i	voltage of node i
ρ_{air}	density of the air
ΔP^i	the sum of i^{th} node injection and outflow active power
ΔQ^i	the sum of i^{th} node injection and outflow reactive power
ΔT_{in}	room temperature variation in each time interval Delta-t
ΔH	variation of heat in the room
A	living area of the room
i	node number
k	number of AC
K	total number of ACs
num	air changing times
s(t)	solar intensity
t	time
V	room's volume
α	coefficients in the linear equation of COP
β	coefficients in the linear equation of COP
$\delta(t)$	elevation angle
ε_{eq}	coefficient of the heat generated by electrical equipment in the room
ε_{oc}	coefficient of the heat generated by occupants in the room

response [10]. Flexible loads are different from the traditional loads, because the power consumption can be changed in a specified interval or transferred between different periods [12]. Hence, the flexible loads can be employed in the operation and control of the power grid, by changing the operating power [13][14]. It has been proven that flexible loads have positive effects on system balances between generation and demand, to thereby maintain the safety and stability of the power grid [15][16]. Compared with traditional voltage regulation equipment, flexible loads can increase/decrease operating power rapidly, to participate in voltage regulation [17].

Among the wide range of flexible loads, the air conditioner (AC) has a large electric power consumption. The AC is one of the most common adjustable flexible loads in daily life. AC and heating systems account for approximately 20% of the global primary energy demand [18][19]. In addition, an air-conditioned room has a heat preservation property. In a certain period, the AC can increase/decrease the operating power without compromising occupants' thermal comfort. Therefore, the AC, as a flexible load, has great potential for participating in the regulation of a power grid. The participation of ACs in the regulation and control of power grids has become a popular research topic in recent years. The simplest regulation strategy is to change the switching state of the AC during the period of peak power consumption, as the AC can be temporarily switched off in a special state to achieve energy-saving purposes [20][21]. Furthermore, the AC can reset its set temperature to provide an operating reserve [22]. The operating reserve can be utilized to provide ancillary services, such as improving the static voltage stability [23][24][25], eliminating unbalance limit violation [26], and voltage regulation [27].

However, the existing researches on ACs for ancillary services are insufficient. Although references [23, 24] and [25] develop the AC load models to improving the static voltage, the influence on room temperature variation is not considered. Ref. [22] develops a simple first-order equivalent thermal parameters model to monitor the room temperature, and avoids the room temperature being out of the comfortable range. But the thermal model is simple and only considers room temperature and ambient environment temperature. The solar radiation, electrical appliance-emitted heat, and so on should also be considered in the model due to the negative impact on the AC's performance of voltage regulation. Ref. [26] employs ACs to tackle the voltage magnitude and unbalance limit violation, while the process of the regulation does not consider the working states of ACs. Ref. [27] proposed a control method considering occupants' set temperature to dispatch ACs for voltage regulation, while the process of the dispatch does not consider the selection of the ACs. The working states of the ACs and the room temperature have impacts on the performance of voltage regulation. For example, the working states may affect the response speed of voltage regulation, and the room temperature may affect the duration of voltage regulation. Therefore, in the process of selecting ACs to participate in voltage regulation, both the working states of the ACs and the room temperature should be taken into account to avoid resetting the AC's set

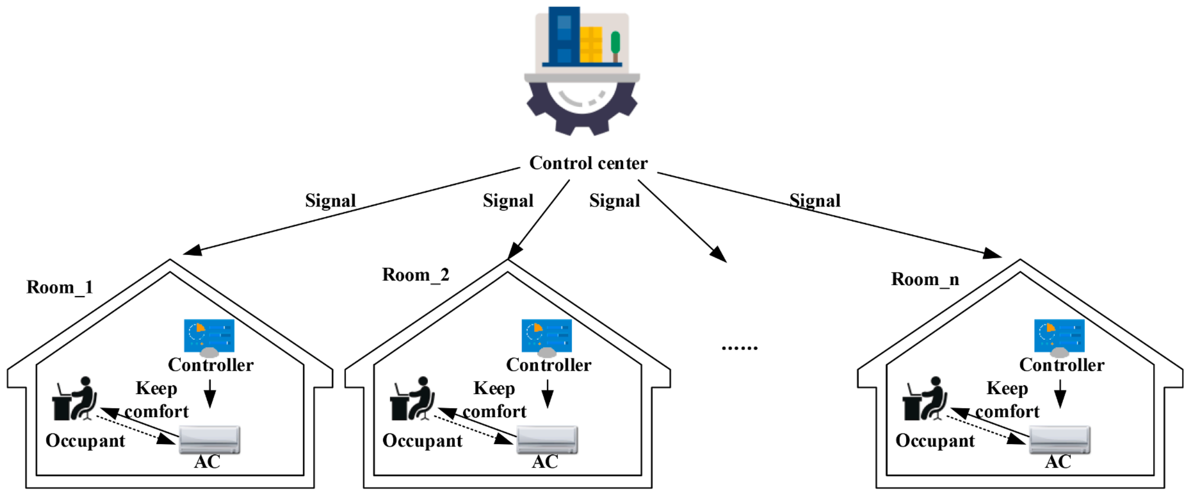

Fig. 1. The control structure of the aggregation model of air conditioners (ACs).

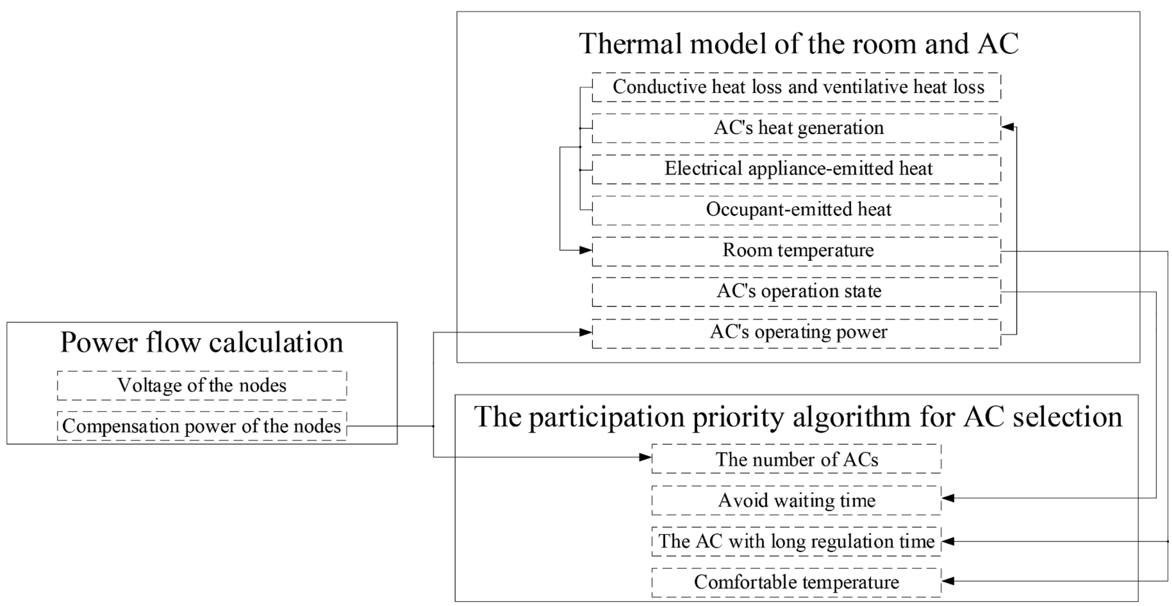

Fig. 2. The control strategy of the control center.

temperature too frequently and responding voltage regulation too slow.

To address the above-mentioned issues, this study develops a collaborative voltage regulation algorithm based on aggregated ACs, when the voltage fluctuation of the grid exceeds the permissible range (e.g. $>$ 1.1 p.u. or $<$ 0.9 p.u.). The set temperature of an AC during its participation in the grid's voltage regulation is controlled at 22–26 °C, because the comfortable temperature range for occupants is 24 ± 2 °C according to the findings of the British Council for Offices [28]. This range ensures no significant impact on the occupants when the AC participates in ancillary services. Detailed thermal models are established for a room and an AC to analyse the AC's dynamic operation process, making it more accessible for ACs to participate in voltage regulation. The main contributions of this study are summarised as follows:

1 The detailed thermal models for a room and an AC are established. On this basis, the aggregated ACs can be controlled to increase/decrease the operating power by resetting the ACs' set temperature.
2 A collaborative voltage regulation algorithm for increasing/decreasing the operating power of ACs is proposed. A detailed analysis of each AC's operation state and response time is conducted so that the operating power of the AC can be efficiently utilized in voltage regulation.
3 A participation priority algorithm is proposed to select the most effective ACs for participating in the voltage regulation service, according to the working states of the ACs and the room temperature. In this manner, the total participating number of ACs can be reduced, and occupant comfort can be guaranteed.

The remaining sections of this paper are as follows. Section 2 presents the control structure and operating characteristics of the aggregated ACs. Section 3 introduces the collaborative voltage regulation algorithm for voltage regulation. The experimental setup is introduced in Section 4. Case studies and discussions are provided in Section 5. Finally, Section 6 concludes this paper.

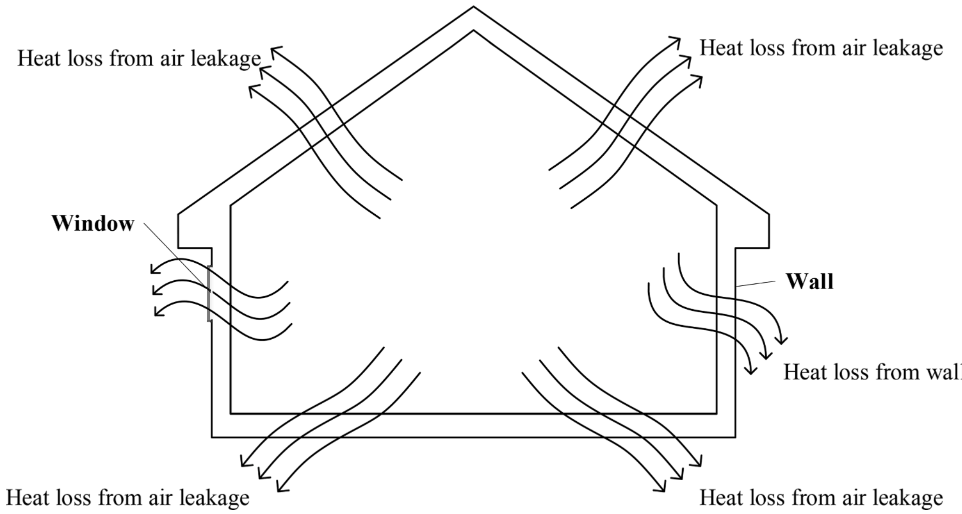

Fig. 3. The heat loss of the room, considering conductive heat loss and ventilative heat loss.

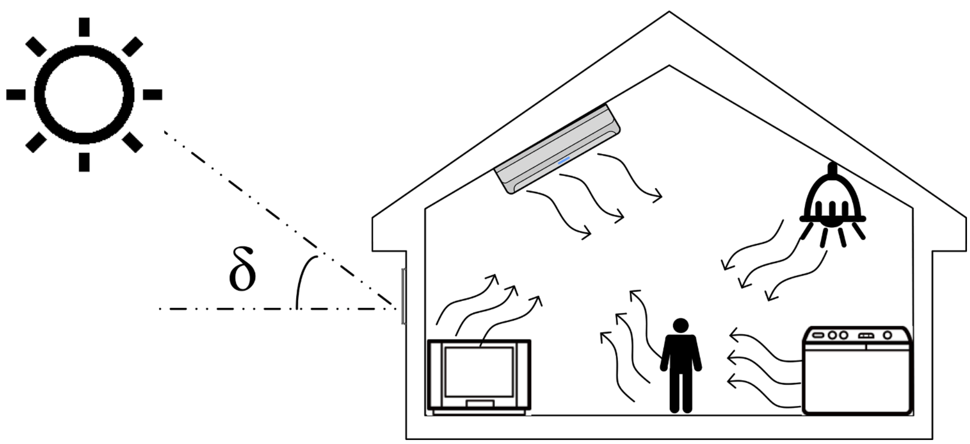

Fig. 4. The heat generation of the room considering the AC's heat generation, solar radiation, electrical appliance-emitted heat, and occupant-emitted heat.

2. Control structure and operating characteristics of aggregated air conditioners (ACs)

2.1. Control structure of aggregated ACs

The aggregated model for ACs proposed in this study is shown in Fig. 1. The occupants can set in advance the time when an AC will participate in the voltage regulation using the regulation controller. The control centre sends control signals to the participating regulation controllers based on the real-time information of the power grid. After a regulation controller receives the signal, it reduces or increases the set temperature of the corresponding AC(s) to regulate the operating power. During the regulation process, the room temperature is controlled within the permissible range to ensure occupant comfort.

The control center is responsible for receiving and processing the information of the distribution network, occupants' rooms and ACs. It controls the ACs to make the response to participate in voltage regulation. As shown in Fig. 2, the strategy of the control center consists of three parts. Firstly, the compensation power of each node is obtained from power flow calculation. Then the participation priority algorithm is adopted to select the most effective ACs to adjust their operating power for voltage regulation. In the regulation process, the room temperatures change due to the ACs operating state and operating power. To avoid affecting the comfort of occupants, the room temperatures should be controlled within a comfortable range.

2.2. Thermal model of a room

It is crucial to understand the dynamics of the room's energy generation and loss before developing a control strategy for utilizing the ACs in the grid's voltage regulation. Therefore, a thermal model of the room is built to link the heat flow with the room temperature change. The heat flow in a room is caused by heat losses and heat generation. The rate of change in heat can be expressed as follows:

$$\frac{dH(t)}{dt} = H_{generate}(t) - H_{loss}(t) \tag{1}$$

Here, ΔH denotes the variation of heat during each time interval Δt in the room; and $H_{loss}(t)$ and $H_{generate}(t)$ encompass all heat loss and heat generation, respectively [29]. Both $H_{loss}(t)$ and $H_{generate}(t)$ are related to time, as well as the inside and ambient temperature. The room can be regarded as a space full of air. According to the heat capacity of the air, $H_{loss}(t)$ and $H_{generate}(t)$ are related to the variations of the room temperature. The room temperature can be expressed as follows:

$$c_{air} \cdot \rho_{air} \cdot V \cdot \frac{dT_{in}(t)}{dt} = H_{generate}(t) - H_{loss}(t) \tag{2}$$

$$T_{in}(t) = T_{in}(t-1) + \Delta T_{in}(t) \tag{3}$$

Here, $\Delta T_{in}(t)$ is the room temperature variation during each time interval, in Δt; c_{air} is the heat capacity of the air [30]; ρ_{air} is the density of the air [31]; V is the room's volume; and $T_{in}(t)$ and $T_{in}(t-1)$ are the

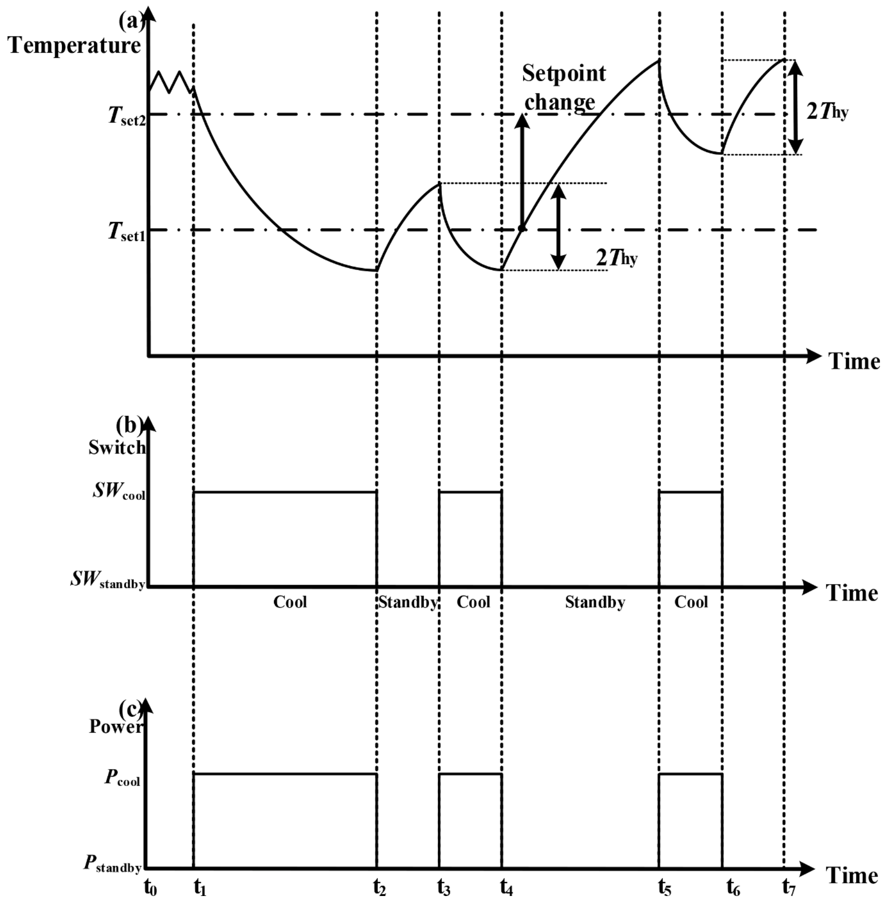

Fig. 5. The operation characteristics of the AC: (a) the variation curve of the room temperature, (b) the state variation curve of the AC, and (c) the operating power variation curve of the AC.

current and the previous time slot's room temperatures, respectively.

Heat losses can be generally categorised into two forms, i.e. conductive heat loss and ventilative heat loss, as described in Fig. 3. The conductive heat loss of the thermal model considers the flow through windows, walls, and roof of the room, caused by the difference between the inside and ambient temperature. Ventilative heat losses are caused by the movement of hot air from a hot region to a cold region through cracks, gaps, and deliberate ventilation. The heat losses, including conductive heat loss and ventilative heat loss, are expressed as follows:

$$H_{loss}(t) = H_{conduction}(t) + H_{ventilative}(t) \tag{4}$$

$$H_{conduction}(t) = Tr_{window} \cdot S_{window} \cdot (T_{in}(t) - T_{out}(t)) + Tr_{wall} \cdot S_{wall} \cdot (T_{in}(t) - T_{out}(t)) \tag{5}$$

$$H_{ventilation}(t) = c_{air} \cdot \rho_{air} \cdot V \cdot num \cdot (T_{in}(t) - T_{out}(t)) \tag{6}$$

In the above equations, $H_{conduction}(t)$ and $H_{ventilative}(t)$ are the conductive and ventilative heat losses, respectively [32]. Tr_{window} and Tr_{wall} represent the thermal transmittance of the window and wall, respectively. S_{window} and S_{wall} indicate the total area of the window and wall, respectively. $T_{in}(t)$ and $T_{out}(t)$ are the room temperature and ambient temperature, respectively. num denotes the number of time that the air changes.

The heat generation of the room is from various heat sources, as shown in Fig. 4. Among all of the heat sources, ACs have the greatest impact on the room temperature. In this study, positive heat generation is used to indicate that the AC is heating, whereas negative heat generation is used to indicate that the AC is cooling. The AC's coefficient of performance (*COP*) indicates the relationship between the AC's operating power and its heat generation [32]. The value of *COP*(t) is related to the performance of the AC's compressor and electric expansion valve, cooling load, and temperature difference between the room temperature $T_{in}(t)$ and the ambient temperature $T_{out}(t)$ [16]. When the difference is within a certain range ($|T_{in}(t) - T_{out}(t)| \leq 20$), the *COP* can be expressed as follows:

$$COP(t) = -\alpha \cdot (T_{in}(t) - T_{out}(t)) + \beta \tag{7}$$

The *COP*(t) has a linear relationship with the difference between the room and ambient temperature. α and β are the coefficients of the linear equation. Therefore, the AC has better performance when the temperature difference between the room and ambient temperature is larger. In addition to the heat generation, occupants and all operating electrical appliances emit heat into a room. In addition, solar radiation shines through the window(s) into the room, generating more heat in the room. The heat generation by solar radiation changes in real-time, and is related to the area of the window, the elevation angle δ of the sunlight, and the solar intensity $s(t)$ [32]. The heat generated by the AC, electrical equipment, occupants and solar radiation can be expressed as follows:

$$H_{generation}(t) = H_{AC}(t) + H_{eq\&oc} + H_{solar}(t) \tag{8}$$

$$H_{AC}(t) = COP(t) \cdot P_{AC_k^i}(t) \tag{9}$$

$$H_{eq\&oc} = \varepsilon_{eq} \cdot A + \varepsilon_{oc} \cdot N_{oc} \tag{10}$$

$$H_{solar}(t) = P_{average} \cdot \cos\delta(t) \cdot s(t) \tag{11}$$

Here, $H_{eq\&oc}$ is the heat generated by the electrical equipment and occupants. $H_{AC}(t)$ and $H_{solar}(t)$ are the heat generated by the AC and solar radiation, respectively. $P_{AC_k^i}(t)$ is the power consumed by the k^{th} AC at node *i*. $COP(t)$ is the AC's COP. *A* is the living area of the room. ε_{eq} is the coefficient of the heat generated by the electrical equipment [33]. *A* is the living area of the room. ε_{oc} is the heat generated by each occupant. N_{oc} is the number of occupants in the room. $P_{average}$ is the average solar intensity. $\delta(t)$ and $s(t)$ are time-varying parameters, which express the elevation angle and solar intensity, respectively [32].

2.3. The operating power and characteristics of an AC

The increase/decrease of the operating power ($\sum \Delta P_{AC_k^i}(t)$) of the aggregated ACs is related to their operating characteristics. Therefore, it is crucial to analyse the operating characteristics of the ACs. Fig. 5 shows the operation characteristics of an AC in summer. Fig. 5(a) illustrates a variation curve of the room temperature with the AC; Fig. 5(b) illustrates the operation state of the AC; and Fig. 5(c) illustrates the power consumption of the AC. This study only considers the cooling state of the AC. Fig. 5(a) shows two operation states of the AC in summer: cooling state and standby state.

Fig. 5(a) also describes the room temperature variation when the AC is operated in the two states, i.e. the cooling state and standby state. Conventionally, the AC can be considered as a thermostatically controlled on/off device [34]. When the AC works in the standby state, the power consumption is nearly zero ($P_{standby}$=0). In Fig. 5(a), the initial set temperature of the AC is T_{set1}, but the room temperature finally fluctuates between $T_{set1} - T_{hy}$ and $T_{set1} + T_{hy}$. The reason is that there is a dead zone in the temperature variation (T_{hy}), which expresses the maximum deviation between the room temperature and set temperature [16]. Owing to the different types of ACs and the structures of air-conditioned rooms, the temperature variation cannot be a fixed value. In this study, the T_{hy} is set to 1 °C. The operating state and power consumption of the AC are shown in Fig. 5(b) and Fig. 5(c), respectively. Once the room temperature is lower than $T_{set1} - T_{hy}$, the AC switches to the standby state $S_{standby}$. When the room temperature is higher than $T_{set1} + T_{hy}$, the AC switches to the cooling state S_{cool}. The operating state and the actual operating power can be expressed as follows:

$$S(t) = \begin{cases} S_{cool}, T_{in}(t) < T_{set1} - T_{hy} \\ S_{standby}, T_{in}(t) > T_{set1} + T_{hy} \end{cases} \tag{12}$$

$$P = \begin{cases} P_{cool}, SW_{cool} \\ P_{standby}, SW_{standby} \end{cases} \tag{13}$$

In this paper, the phrase 'power level' is used to describe an AC's power consumption within a certain period of time. The power level is the average power of two adjacent cooling and standby states [35], and can be expressed as follows:

$$P_{As}(t) = \frac{P_{cool}\cdot t_{cool} + P_{standby}\cdot t_{standby}}{t_{cool} + t_{standby}} = \frac{P_{cool}\cdot t_{cool}}{t_{cool} + t_{standby}} \tag{14}$$

In the above, t_{cool} and $t_{standby}$ are the two consecutive periods of time when the AC operates in the standby state and cooling state, respectively.

According to the above operation characteristics of the AC, the increase/decrease of the operating power for voltage regulation is related to the AC's power level. When the AC is in the cooling state, if the set temperature is decreased, the duration of the AC cooling state will be increased. Meanwhile, the operating power of AC is P_{cool}, which is greater than the operating power before regulating. If the set temperature is increased, the duration of the AC standby state will be increased. In the meantime, the operating power of AC is $P_{standby}$, which is lower than the operating power before regulating. The variation of the AC's operating power can be expressed as

$$\Delta P_{AC_k^i}(t) = \begin{cases} P_{cool} - P_{As}(t), \text{ increase the set temperature} \\ -P_{As}(t), \text{ decrease the set temperature} \end{cases} \tag{15}$$

Here, $P_{As}(t)$ is the power levels before resetting the AC's set temperature, respectively.

3. Proposed collaborative voltage regulation algorithm

This section proposes the collaborative voltage regulation algorithm for the ACs' participation in voltage regulation services. The collaborative voltage regulation algorithm includes processes of determining the required voltage regulation power, determining the ACs' operating power, and selecting ACs.

3.1. Determination of required voltage regulation power

In power distribution systems, regulating one node's voltage has a non-linear effect on the other nodes. A voltage sensitivity coefficient analysis can effectively obtain the active and reactive power required for regulating the grid voltage [36]. The voltage sensitivity matrix S can be expressed by the inverse matrix of a Jacobian Matrix.

$$S = \text{Jacobian Matrix}^{-1} = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{UP} & S_{UQ} \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = S \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{17}$$

The voltage angle ($\Delta\theta$) and amplitude (ΔU) are decoupled in (17). In addition, the reactive power regulation can be ignored, and $\Delta Q = 0$. When the ACs only provide active power, ΔU can be expressed as follows:

$$\Delta U(t) = S_{UP}\cdot\Delta P(t) \tag{18}$$

The regulation power can be expressed as follows:

$$\Delta P(t) = S_{UP}^{-1}(t)\cdot\Delta U(t) \tag{19}$$

In the above, $\Delta P(t) = [\Delta P^1(t), \Delta P^2(t)\ldots, \Delta P^i(t)]^T$, which expresses the required voltage regulation power of each node; and $\Delta U(t) = [\Delta U^1(t), \Delta U^2(t),\ldots, \Delta U^i(t)]^T$, which expresses the difference of each node's voltage between the upper and lower limits.

$$\Delta U^i(t) = \begin{cases} U^i(t) - V_{max}, \; U^i(t) > V_{max} \\ U^i(t) - V_{min}, \; U^i(t) < V_{min} \\ 0, \text{ other} \end{cases} \tag{20}$$

The IEEE 1159-2009 Standard categorises voltage increments and drops, and an under-/over-voltage indicates that the voltage is between 0.8 p.u. and 0.9 p.u./1.1 p.u. and 1.2 p.u., respectively, and that its duration is more than 1 min [37]. Therefore, the normal voltage area is 0.9–1.1 p.u., and V_{max} and V_{min} are 1.1 p.u. and 0.9 p.u., respectively. The node voltage being above 1.2 p.u. or below 0.8 p.u. is regarded as a system fault. Owing to the limited regulation capacity of the aggregated ACs, the aggregated ACs cannot increase/decrease the operating power sufficiently to recover the node's voltage to the normal area. Therefore, ACs will not participate in voltage regulation when the node voltage is above 1.2 p.u. or below 0.8 p.u..

Based on the node voltage calculated in the power flow equation, the required voltage regulation power $\Delta P(t)$ can be determined. After that, the aggregated ACs change their operating state to increase/decrease the operating power. The required voltage regulation power provided by aggregated ACs can be expressed as follows:

$$\begin{cases} \Delta P^i(t) = P_{NEPR}^i(t) = \sum \Delta P_{AC_k^i}(t), \text{ exist } 1.1\text{p.u.} < U^i(t) < 1.2\text{p.u.} \\ \Delta P^i(t) = P_{PEPR}^i(t) = \sum \Delta P_{AC_k^i}(t), \text{ exist } 0.8\text{p.u.} < U^i(t) < 0.9\text{p.u.} \end{cases} \tag{21}$$

Here, $P_{NEPR}^i(t)$ and $P_{PEPR}^i(t)$ denote the increase/ decrease of the aggregated ACs' operating power at node *i* for over- and under-voltage regulation, respectively. $U^i(t)$ is voltage of the node *i* in the power grid. $\Delta P_{AC_k^i}(t)$ denotes the increase/decrease of the k^{th} AC's operating power at the node *i* for voltage regulation. $\Delta P^i(t)$ is the required voltage

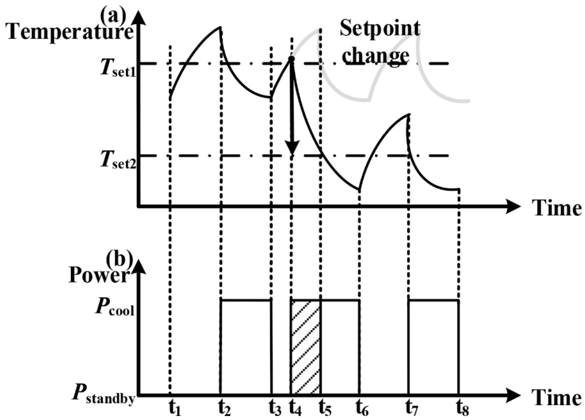

Fig. 6. AC increases operating power in standby state: (a) the variation curve of the temperature of the room and (b) the operating power variation curve of the AC.

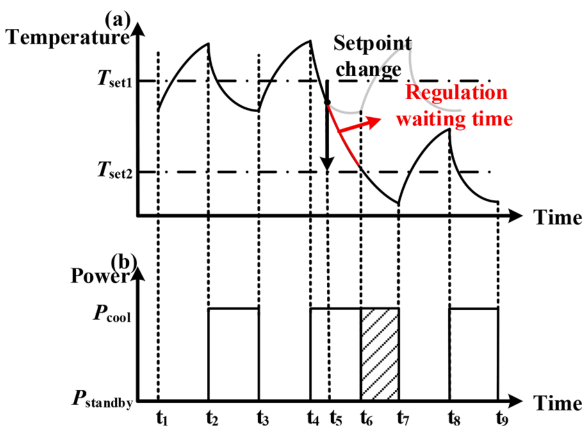

Fig. 7. AC increases operating power in cooling state: (a) the variation curve of the temperature of the room and (b) the operating power variation curve of the AC.

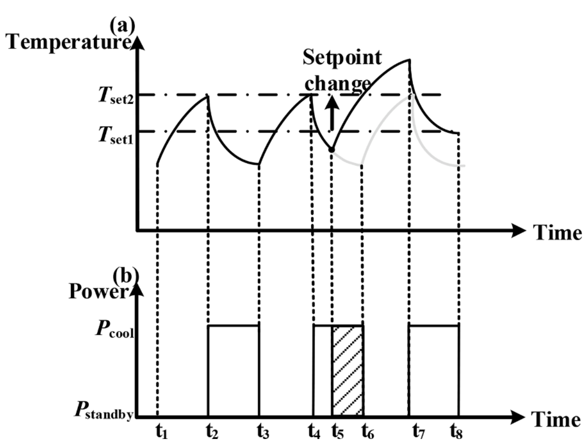

Fig. 8. AC decreases operating power in cooling state: (a) the variation curve of the temperature of the room and (b) the operating power variation curve of the AC.

regulation power of node *i*.

A sudden changing of numerous ACs' operating states may result in severe load variety, which may lead to load rebound [38]. In order to avoid the load rebound, the aggregated ACs' operating power should be increased/decreased gradually and reach the $\Delta P^i(t)$ in a period of time [39]. During this period of time, the voltage regulation power provided by aggregated ACs can be expressed as follows:

$$P_{injection}(t) = \left(1 - \frac{t}{\tau}\right) \cdot \Delta P^i(t) \tag{22}$$

Here, $P_{injection}(t)$ is the active power provided by aggregated ACs for voltage regulation, and τ is the length of the period. In addition, in order to avoid an AC continually selected to participate in regulation service, this AC will not participate in over-voltage regulation service if it just exits the regulation, unless the room temperature has risen 0.5 °C. Similarly, after an AC exits under-voltage regulation, the AC will not participate in under-voltage regulation service until the room temperature declines 0.5 °C.

3.2. ACs' operating power determination

In the voltage regulation, increasing the operating power of the ACs can drop an over-voltage, whereas decreasing the operating power of the ACs can raise an under-voltage. The increase/decrease of the ACs' operating power depends on the operation state of the ACs. It is crucial to analyse the detailed status of the ACs when utilizing the ACs' operating power in the voltage regulation service. This study divides the operation of the ACs into four states by considering ACs' operating power 'increase/decrease', and ACs' response time of 'with/without waiting time'.

1) *Increase operating power without waiting time*

Fig. 6 illustrates the increase of the AC's operating power when the AC works in the standby state. The set temperature of the AC during t_1–t_4 is T_{set1}, and the AC is in standby state during t_3–t_4. At the time of t_4, the power generation of the grid is excessive, and the AC receives a signal from the control centre to increase the operating power by decreasing the set temperature. At this time, the set temperature of the AC decreases from T_{set1} to T_{set2}. Because the room temperature at this time is higher than $T_{set2} + T_{hy}$, the AC immediately switches to the cooling state from the standby state, and the operating power of the AC increases immediately. The power level and increase of operating power can be expressed as follows:

$$P_{t_2--t_5} = \frac{(t_5 - t_3) \cdot P_{cool}}{t_5 - t_2} \tag{23}$$

$$\Delta P_{AC_k^i} = P_{cool} - \frac{(t_5 - t_3) \cdot P_{cool}}{t_5 - t_2} \tag{24}$$

$P_{t_2--t_5}$ is the power level of the AC before participating the voltage regulation. Because the cooling time of the AC is prolonged, the operating power of the AC increases. The shaded part t_4–t_5 represents the increase of the operating power by extending the cooling time. When the AC works in the standby state, it can increase operating power without waiting time.

1) *Increase operating power with waiting time*

Fig. 7 illustrates the increase of the AC's operating power when the AC works in the cooling state. The set temperature of the AC during t_1–t_5 is T_{set1}, and the AC is cooling during t_4–t_5. At the time of t_5, the power generation of the grid is excessive, and the AC receives the signal from the control centre to increase the operating power by decreasing the set temperature. At this time, the set temperature of the AC decreases from T_{set1} to T_{set2}. Because the room temperature at this time is higher than $T_{set2} + T_{hy}$, the AC remains in the cooling state for some time after t_5. During t_5–t_6, regardless of whether the AC's set temperature changes from T_{set1} to T_{set2}, the working state of AC is the cooling state, and the AC's power level does not change until t_6. Compared with the ACs with no change in the set temperature, lowering the ACs' set temperatures at

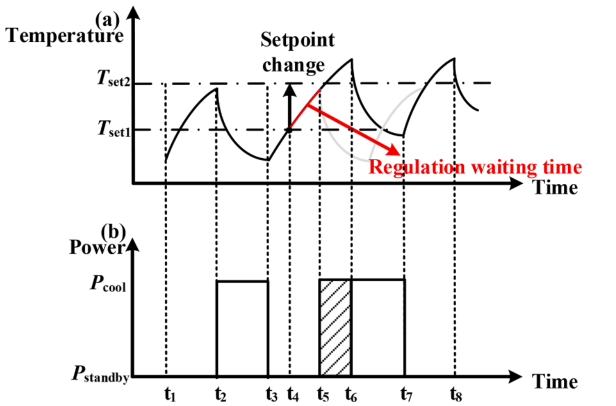

Fig. 9. AC decreases operating power in standby state: (a) the variation curve of the temperature of the room and (b) the operating power variation curve of the AC.

t_5 will prolong their cooling time, and increase the operating power during t_6–t_7. The power level and the increase in operating power during this period can be expressed as follows:

$$P_{t_3--t_6} = \frac{(t_6 - t_4)\cdot P_{cool}}{t_6 - t_3} \tag{25}$$

$$\Delta P_{AC_k^i} = P_{cool} - \frac{(t_6 - t_4)\cdot P_{cool}}{t_6 - t_3} \tag{26}$$

$P_{t_3--t_6}$ is the power level of the AC before participating the voltage regulation. After receiving the signal from the control centre, ACs' set temperature decreases. However, there is no change in operation state until t_6. The ACs do not change their operating power for the voltage regulation during t_5–t_6. Therefore, there is a waiting time of t_5–t_6 in the regulation service, which is expressed in solid red line in Fig. 7. The shaded part t_6–t_7 represents the increase of operating power by prolonging the cooling time. When the AC works in the cooling state, it can increase the operating power within the waiting time.

1) *Decrease operating power without waiting time*

Fig. 8 illustrates the decrease in the operating power of the ACs when they operate in the cooling state. The set temperature of the AC during t_1–t_5 is T_{set1}, and the AC is in the cooling state during t_4–t_5. At t_5, the power generation of the grid is inadequate, and the AC receives the signal from the control centre to decrease its operating power by increasing the set temperature. At this instant, the set temperature of the AC increases from T_{set1} to T_{set2}. Because the room temperature at this time is lower than $T_{set2} - T_{hy}$, the AC immediately switches to the standby state from the cooling state. The power level and reduction in operating power can be expressed as follows:

$$P_{t_3--t_6} = \frac{(t_6 - t_4)\cdot P_{cool}}{t_6 - t_3} \tag{27}$$

$$\Delta P_{AC_k^i} = -\frac{(t_6 - t_4)\cdot P_{cool}}{t_6 - t_3} \tag{28}$$

$P_{t_3--t_6}$ is the power level of the AC before participating the voltage regulation. Because the standby time of the AC is prolonged, the operating power of the AC decreases. The shaded part t_5–t_6 represents the decrease of operating power by the reduction of cooling time. When the AC works in the cooling state, it can decrease the operating power without waiting time.

1) *Decrease operating power with waiting time*

Fig. 9 illustrates the decrease of the AC's operating power when the AC works in the standby state. The set temperature of the AC during t_1–t_4 is T_{set1}, and the AC is in the standby state during t_3–t_4. At the time of t_4, the power generation of the grid is inadequate, and the AC receives the signal from the control centre to reduce the operating power by increasing the set temperature. At this time, the set temperature of the AC increases from T_{set1} to T_{set2}. Because the room temperature at this time is lower than $T_{set2} - T_{hy}$, the AC remains in the standby state for some time after t_5. During t_4–t_5, regardless of whether the AC's set temperature changes from T_{set1} to T_{set2}, the working state of AC is the standby state, and the AC's power level does not change until t_5. Compared with the ACs with no change in the set temperature, increasing the AC's set temperature at t_4 will prolong the standby time, and reduce the operating power during t_5–t_6. The power level and the decrease of operating power can be expressed as follows:

$$P_{t_2--t_5} = \frac{(t_3 - t_2)\cdot P_{cool}}{t_5 - t_2} \tag{29}$$

$$\Delta P_{AC_k^i} = -\frac{(t_3 - t_2)\cdot P_{cool}}{t_5 - t_2} \tag{30}$$

$P_{t_2--t_5}$ is the power level of the AC before participating the voltage regulation. After receiving the signal from the control centre, ACs' set temperature increases. However, there is no change in operation state until t_5. The ACs do not change their operating power for the voltage regulation during t_4–t_5. Hence, there is a waiting time of t_4–t_5 in the regulation service, which is expressed by the solid red line in Fig. 9. The shaded part t_5–t_6 represents the decrease in operating power by prolonging the standby time. When the AC works in the standby state, it can decrease the operating power within the waiting time.

3.3. ACs selection

When an AC participates in the voltage regulation service, the following factors need to be considered: the waiting time for AC regulation, and the room temperature. The waiting time for AC regulation determines the response speed of participating in the voltage regulation service, whereas the room temperature determines the duration of the increase/decrease of the AC's operating power. To enable ACs to participate in the voltage regulation service as soon as possible, the proposed collaborative algorithm preferentially chooses ACs without waiting time to participate in voltage regulation. In addition, the longer the duration of the increase/decrease in the ACs' operating power that can be provided by the ACs, the fewer ACs required to participate in voltage regulation. Therefore, besides considering the regulation waiting time, the room temperature should also be considered. When the voltage regulation needs to increase the operating power, an AC in a room with a high room temperature will have higher priority to participate in the regulation. When the voltage regulation needs to decrease the operating power, an AC in a room with a low room temperature will have higher priority to participate in the regulation. The participation priority algorithm for AC selection is illustrated in Fig. 10. When a node's voltage is an over-voltage, the participation priority algorithm selects ACs in the standby state, and sorts them by the room temperature from high to low ($AC_{k\_T}^{i\_without} = [AC_{k\_T\_max\_1}^{i\_without}, AC_{k\_T\_max\_2}^{i\_without}, AC_{k\_T\_max\_3}^{i\_without}, \ldots]$). It should be noted that $AC_{k\_T\_max\_1}^{i\_without}$ indicates that the AC is without a regulation waiting time and that the room temperature of this AC is the highest. This AC will be first selected to participate in the voltage regulation, and then the other ACs without regulation waiting time will be selected in order depending on the room temperatures ($AC_{k\_T\_max\_2}^{i\_without}, AC_{k\_T\_max\_3}^{i\_without}, \ldots$). ACs in rooms with higher room temperatures will take priority in over-voltage regulation. The ACs with regulation waiting time ($AC_k^{i\_with} = [AC_{k\_WT\_min\_1}^{i\_with}, AC_{k\_WT\_min\_2}^{i\_with}, AC_{k\_WT\_min\_3}^{i\_with}, \ldots]$) will be selected to participate in voltage regulation, when the regulation power is not enough. The order of participation is also based on waiting time

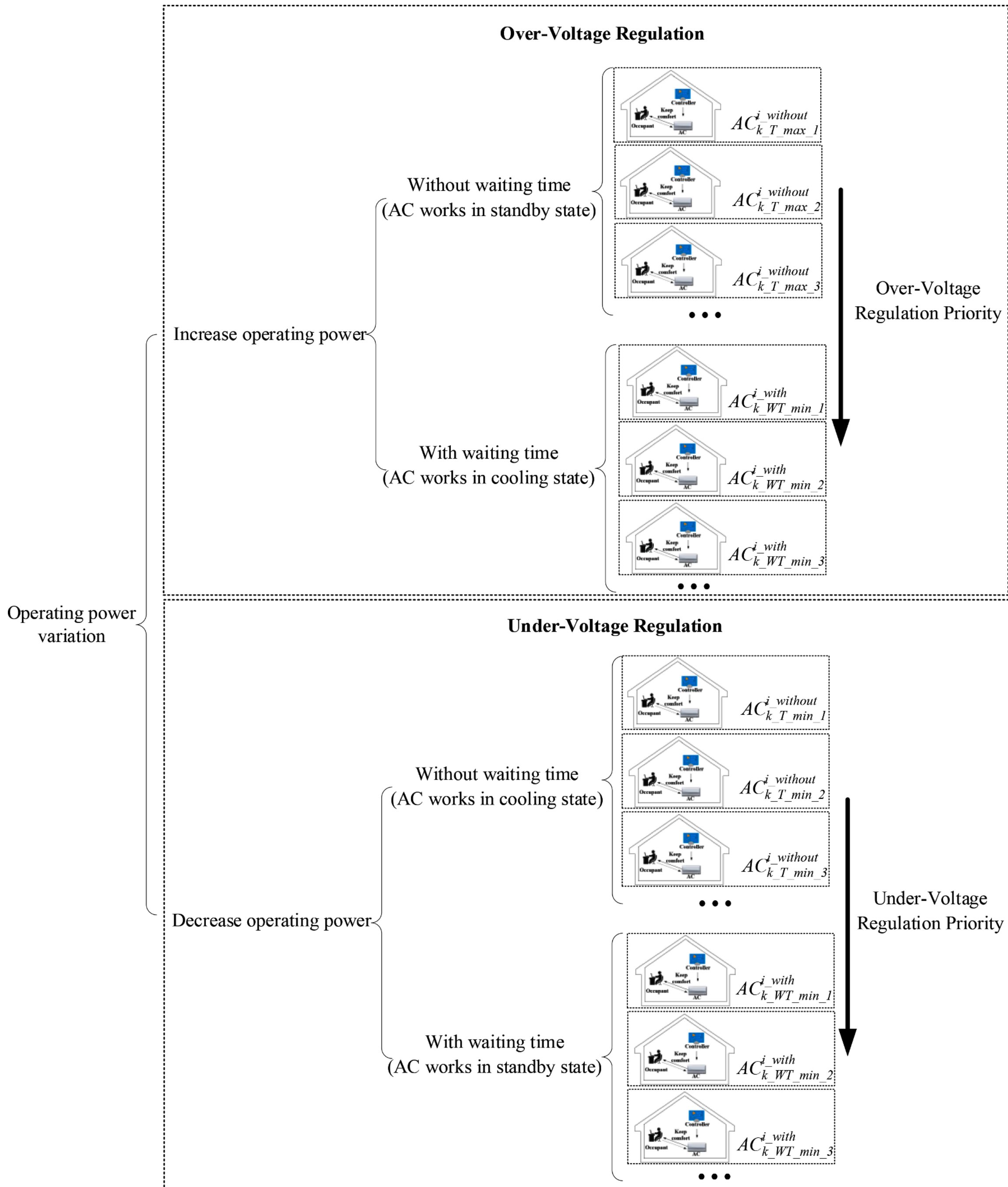

Fig. 10. The participation priority algorithm for AC selection.

in the regulation service ($AC_{k\_WT\_min\_1}^{i\_with}, AC_{k\_WT\_min\_2}^{i\_with}, AC_{k\_WT\_min\_3}^{i\_with}, \ldots$). According to Eq. (2), the waiting time in the regulation service can be expressed as follows:

$$\begin{cases} \mathrm{WD}(t) = \dfrac{c_{air}\cdot\rho_{air}\cdot V\cdot\left(T_{set} + T_{hy} - T_{in}(t)\right)}{H_{generate}(t) - H_{loss}(t)}, & \text{increase the set temperature} \\ \mathrm{WD}(t) = \dfrac{c_{air}\cdot\rho_{air}\cdot V\cdot\left(T_{in}(t) - T_{set} + T_{hy}\right)}{H_{generate}(t) - H_{loss}(t)}, & \text{decrease the set temperature} \end{cases} \tag{31}$$

The same procedure is adapted to manage under-voltage regulation. When ACs work in heating mode, the collaborative voltage regulation algorithm also is effective but based on room temperature. The participation priority is the opposite.

3.4. Specific regulation process of collaborative voltage regulation algorithm

The flowchart of the proposed collaborative voltage regulation algorithm is shown in Fig. 11. It consists of the processes of determining the required voltage regulation power (Part A), determining the ACs' operating power (Part B), and selecting ACs (Part C).

Part A is the determination of the required voltage regulation power. At the beginning of the regulation, the node voltage, nodes' states, and the regulation power are obtained using a power flow calculation. According to the IEEE 1159-2009 Standard [37], nodes' states are classified into four categories. When the voltage is $0.9\ \text{p.u.} < U^i(t) < 1.1\ \text{p.u.}$, the node's state is in a normal area, and voltage regulation is not needed. When the voltage

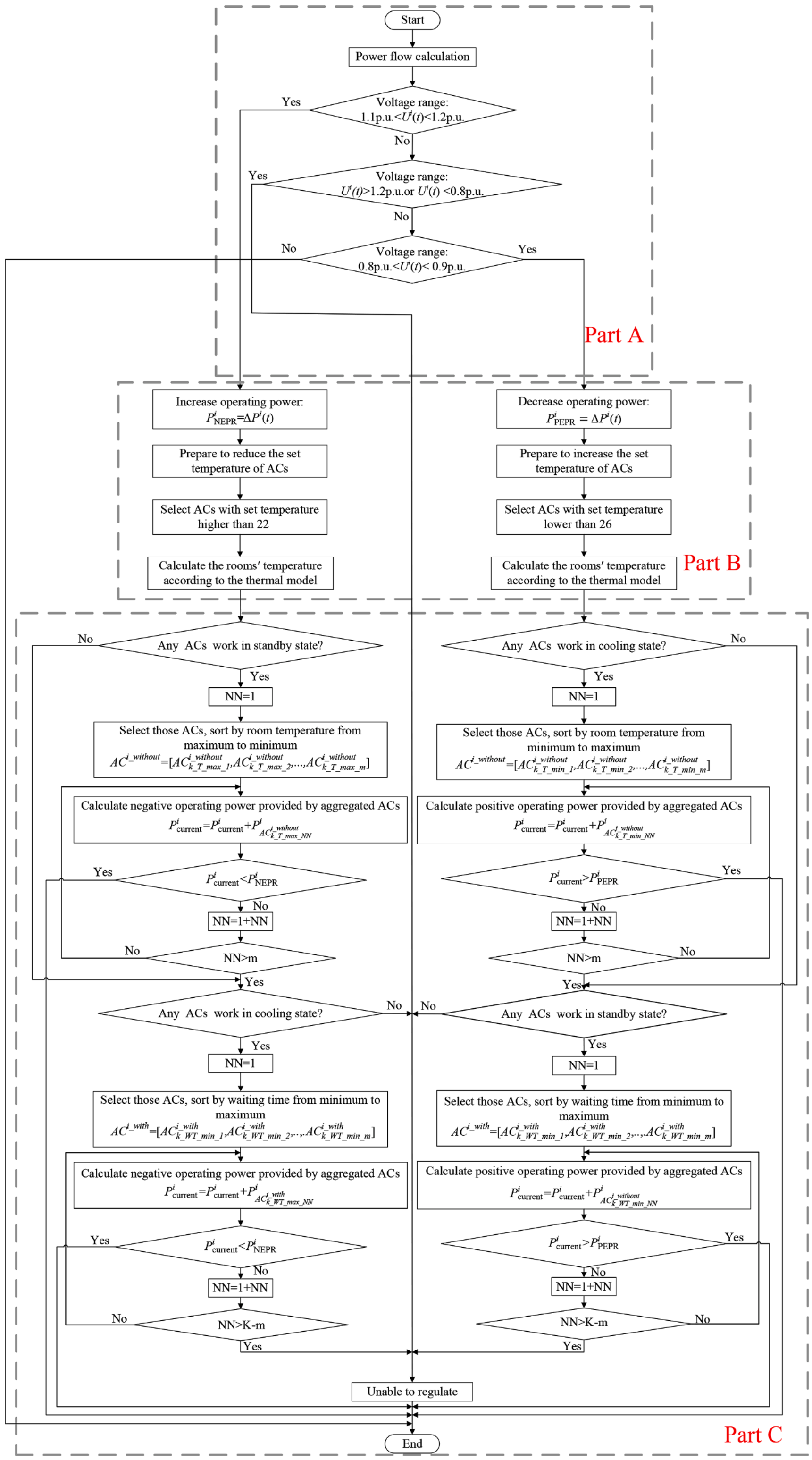

Fig. 11. The flowchart of the proposed collaborative voltage regulation algorithm.

is $U^i(t) > 1.2$ p.u. or $U^i(t) < 0.8$ p.u., it is regarded as a system fault, and the aggregated ACs will not participate the regulation. When the voltage is 1.1 p.u. $< U^i(t) < 1.2$ p.u., the node's state is an over-voltage, and the aggregated ACs participate in the regulation by increasing the operating power. When the voltage is 0.8 p.u. $< U^i(t) < 0.9$ p.u., node's state is an under-voltage, and the aggregated ACs participate in the regulation by decreasing the operating power.

Part B is the process of determining the ACs' operating power when the voltage of a node is an over- or an under-voltage. The aggregated ACs need to increase/decrease their operating power to force the node voltage to return to a permissible range. When node is in over-voltage, the ACs reduce their set temperatures and increase their operating power. The set temperatures of the selected aggregated ACs should be

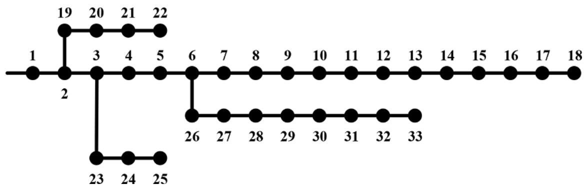

Fig. 12. IEEE 33-node power distribution system.

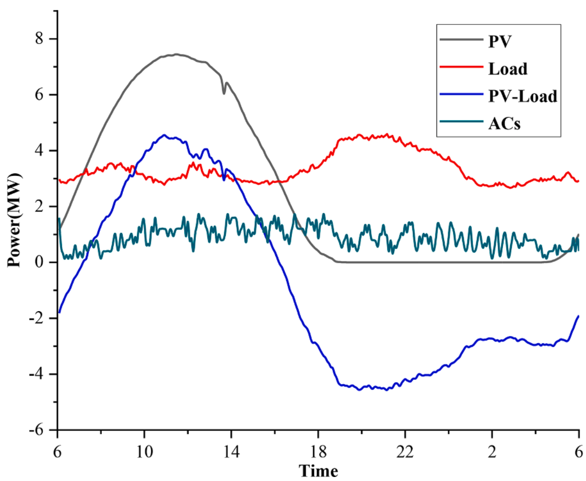

Fig. 13. Aggregated data of photovoltaics (PVs) and base load.

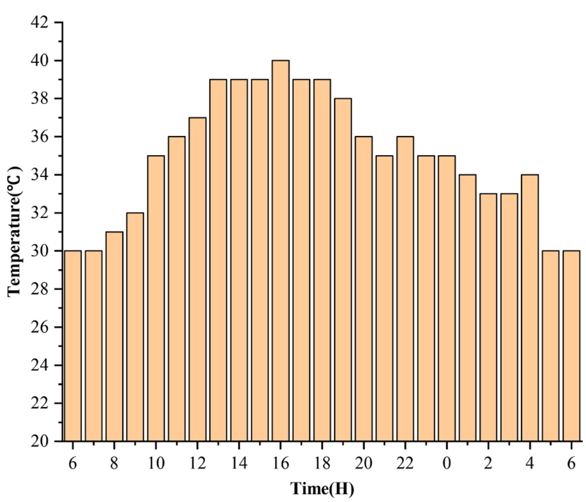

Fig. 14. The ambient temperature of Hangzhou on August 11, 2015 [41].

higher than 22 °C. When a node is in under-voltage, the ACs increase their set temperatures and decrease the operating power. The set temperatures of the selected aggregated ACs should be lower than 26 °C.

Part C is the process of selecting ACs by using the participation priority algorithm. If increased operating power is needed, according to the regulation priority algorithm, the ACs in a standby state (without regulation waiting time) with higher room temperatures will be selected first. When those ACs cannot increase enough operating power for managing the over-voltage problem, then the ACs working in a cooling state will be considered to join in the regulation. In detail, the ACs in the standby state (without regulation waiting time) will be selected and sorted by the room temperature from high to low ($AC_k^{i\_without} = [AC_{k\_T\_max\_1}^{i\_without}, AC_{k\_T\_max\_2}^{i\_without}, \ldots, AC_{k\_T\_max\_m}^{i\_without}]$). Each AC will be selected to participate in the regulation service in order until the power provided by the aggregated ACs ($P_{current}^{i}$) is sufficient (i.e. $P_{current}^{i} \geq P_{NEPR}^{i}$). If the ACs in the standby state (without regulation waiting time) cannot provide sufficient regulation power, the ACs in the cooling state (with regulation waiting time) will be selected with the sequence ($AC_k^{i\_with} = [AC_{k\_WT\_min\_1}^{i\_with}, AC_{k\_WT\_min\_2}^{i\_with}, \ldots, AC_{k\_WT\_min\_K-m}^{i\_with}]$). Those ACs also participate in the regulation service, and provide voltage regulation power in order until the regulation power is sufficient. If all of the ACs are selected and the regulation power is insufficient (i.e. $P_{current}^{i} < P_{NEPR}^{i}$), it indicates that the over-voltage problem is too serious, and that the aggregated ACs will not participate in the voltage regulation.

If decreased operating power is needed, according to the regulation priority algorithm, the ACs in the cooling state (without waiting time) with low room temperatures will be selected first. When those ACs cannot decrease enough operating power for managing the under-voltage problem, then the ACs working in the standby state will be considered to join in the regulation. The process of under-voltage regulation is similar to that of over-voltage regulation. The ACs in the cooling state (without regulation waiting time) will be selected and sorted by the room temperature from low to high ($AC_k^{i\_without} = [AC_{k\_T\_min\_1}^{i\_without}, AC_{k\_T\_min\_2}^{i\_without}, \ldots, AC_{k\_T\_min\_m}^{i\_without}]$). Each AC will be selected to participate in voltage regulation in order until the power provided by the aggregated ACs ($P_{current}^{i}$) is sufficient (i.e. $P_{current}^{i} \geq P_{PEPR}^{i}$). If the ACs in the cooling state (without regulation waiting time) cannot provide sufficient regulation power, then the ACs in the standby state (with regulation waiting time) will be selected and sorted ($AC_k^{i\_with} = [AC_{k\_WT\_min\_1}^{i\_with}, AC_{k\_WT\_min\_2}^{i\_with}, \ldots, AC_{k\_WT\_min\_K-m}^{i\_with}]$).

Table 1
The capacity values of ACs in the different scenarios.

Scenario	Voltage	Capacity(kW·H)	Number of the ACs
PV·1.00 Load·1.00	$U_{max} = 1.1024$	92.27	119
	$U_{min} = 0.8973$	107.32	126
PV·1.12 Load·1.12	$U_{max} = 1.1192$	675.96	868
	$U_{min} = 0.8805$	711.00	833
PV·1.35 Load·1.35	$U_{max} = 1.1408$	1161.78	1492
	$U_{min} = 0.8516$	1090.32	1278
PV·1.55 Load·1.55	$U_{max} = 1.1591$	1488.72	1912
	$U_{min} = 0.8245$	1568.58	1839
PV·1.78 Load·1.78	$U_{max} = 1.1794$	1853.20	2379
	$U_{min} = 0.7908$	2226.61	2610
PV·1.95 Load·1.95	$U_{max} = 1.2010$	2321.84	2981
	$U_{min} = 0.7908$	2223.35	2606

Table 2
Constant parameter initialization of the air conditioner (AC) and air-conditioned room.

Symbols	Definition or description	Value	Units
h	Height of the room	2.5	m
α	Fitted coefficient of COP	0.0384	N/A
β	Fitted coefficient of COP	3.9051	N/A
K	Heat transfer coefficient	7.69	W/(°C·m²)
c_{air}	Heat capacity of air	1.005	kJ/(kg·°C)
ρ_{air}	Density of air	1.205	kg/m³
ε	Coefficient of heat release by appliances and occupants [16]	4.3	W/m³
num	Air exchange times	1/7200	Hz
N_{room}	Number of rooms per node	100	N/A
N_{AC}	Number of ACs per room	1	N/A
T_{hy}	Hysteresis band of temperature control	1	°C

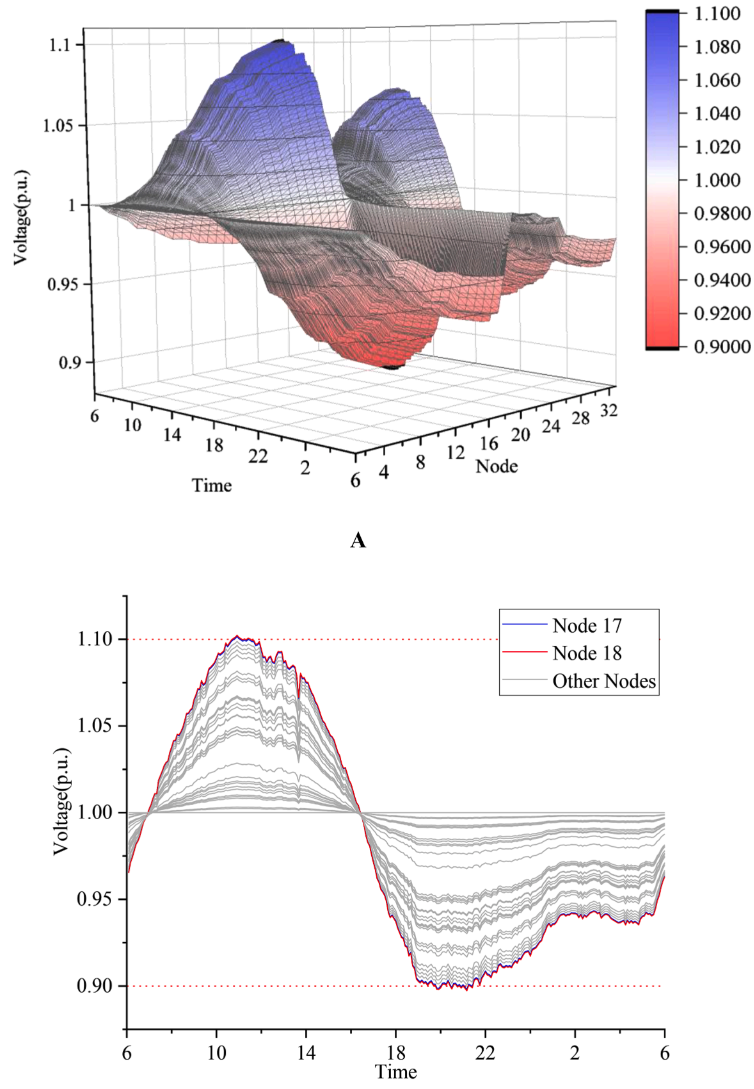

Fig. 15. The voltages of nodes before regulation.

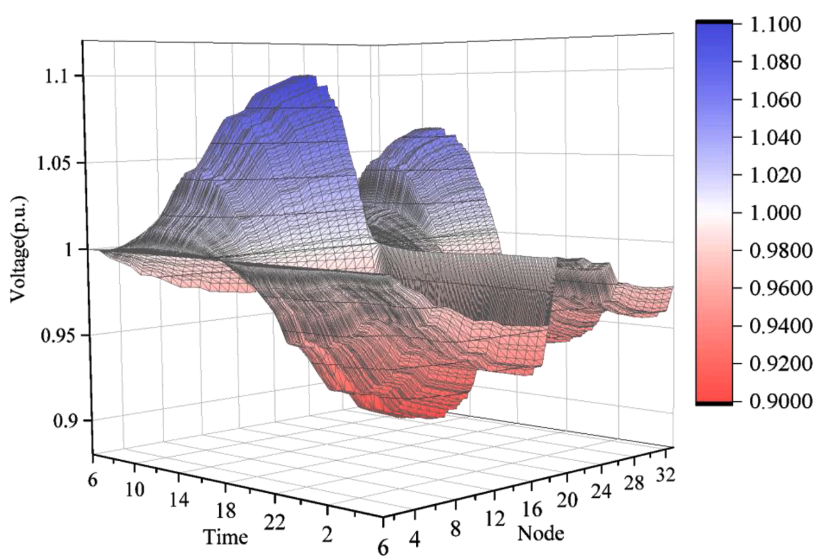

Fig. 16. The voltages of nodes after regulation by aggregated ACs.

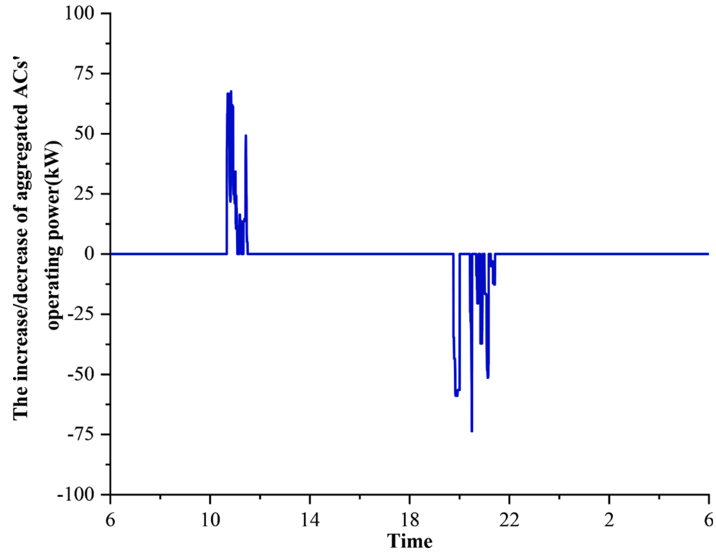

Fig. 17. The increase/decrease of aggregated ACs' operating power, when aggregated ACs participate in voltage regulation.

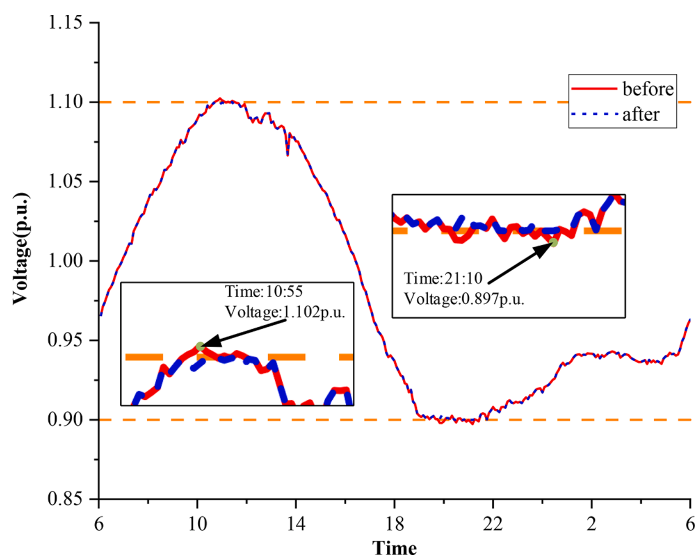

Fig. 18. The voltage curves of Node 18 before/after regulation.

Those ACs will also participate in regulation service, to provide voltage regulation power in order until the power is sufficient. If all of the ACs are selected and the regulation power is insufficient (i.e. $P^i_{current} < P^i_{PEPR}$), it indicates that the under-voltage problem is too serious, and that the aggregated ACs will not participate in the voltage regulation.

4. Experiment setup

The simulation is performed using MATLAB software on a computer with a central processing unit of Intel(R) Core(TM) i7-7820 @ 2.90GHz and 32 GB memory. To analyse the effects of the ACs participating in the voltage regulation, this study adopts the IEEE 33-node power distribution system, as shown in Fig. 12, to validate the effectiveness of the proposed collaborative algorithm. Node 1 is the reference node of the system, and the initial voltage is 1.0 p.u.. The remaining nodes are all 'PQ' nodes, and the permissible range of voltage is -10–10%. The simulation time is from 6:00 a.m. on a given day to 6:00 a.m. of the following day. There are 288 time nodes, and the duration of each slot is 5 min. At the beginning of each slot, a power flow calculation is performed to obtain the regulation power of each node. In the process of regulation, the room temperature is sampled every 30 s. When the room temperature reaches $(T_{set} - T_{hy})$or$(T_{set} + T_{hy})$, T_{set} will increase/decrease by 1 °C until it becomes lower/higher than 22/26 °C, respectively. Therefore, when a node is in over-voltage, the selected AC will decrease the set temperature and remain in the cooling state to increase the operating power. Conversely, when a node is in under-voltage, the selected AC will increase the set temperature and remain in the standby state to decrease the operating power.

In the IEEE 33-node power distribution system, 100 customers are assumed in each node. The penetration of photovoltaic (PV) generation and ACs are 85% and 100%, respectively. The data of the PV generation and load are from [40]. Fig. 13 shows the aggregated data of the load and PV generation. During the period of 5:00–11:30, PV generation increases gradually, and the highest PV power generation is 7.45 MW at 11:25. From 11:30–19:00, the PV power generation decreases gradually, and tends to 0. The aggregated load fluctuates between 2.67 MW and 4.59 MW. The ambient temperature is from real and monitored data of Hangzhou on August 11, 2015 [41], as shown in Fig. 14.

When the over-voltage or under-voltage problem occurs, the suffi-

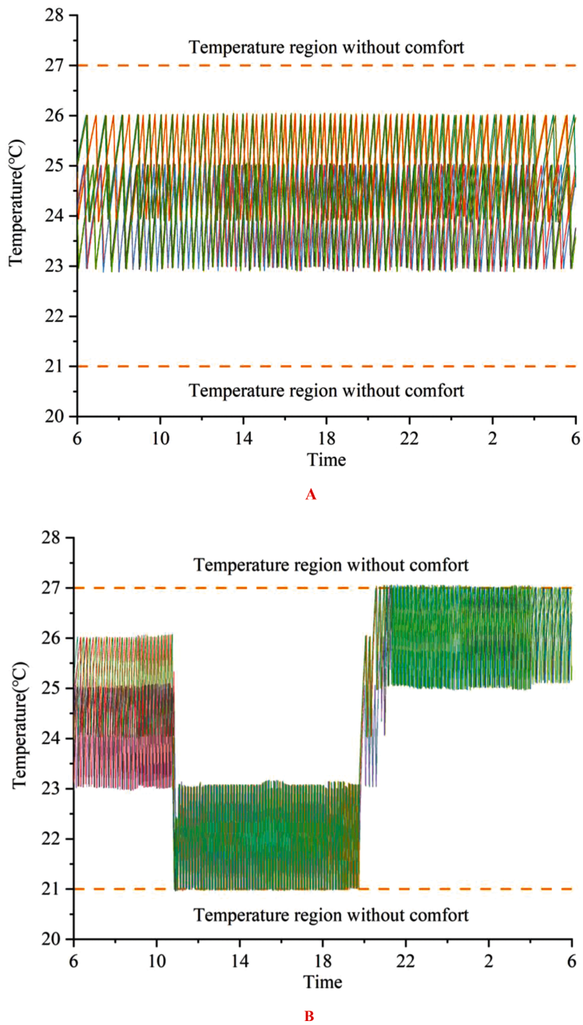

Fig. 19. The rooms' temperature curve of Node 18: (A) The rooms' temperature curve of Node 18 before regulation, (B) The rooms' temperature curve of Node 18 after regulation.

cient capacity and the number of ACs should be provided for voltage regulation. According to the duration of voltage problem and the power used for voltage regulation, the required capacity and the number of ACs can be calculated using (32).

$$\text{Storage} = \int_{T_{end}}^{T_{start}} \Delta P(t) \cdot \Delta t \tag{32}$$

Here, T_{start}, T_{end} are the start time and the end time of voltage regulation. According to (19) and (32), the capacity of ACs used to solve the voltage problem caused by the different penetration of PV is obtained and shown in Table 1:

It can be seen from Table 1, when the voltage of the node reaches 1.12 p.u. or 0.88 p.u., the capacity turns to be huge. It is not feasible to utilize such huge capacity of ACs to solve the severe voltage problem. However, ACs can participate in voltage regulation with the cooperation of other flexible loads (e.g., electric vehicles and heaters) and voltage regulation resources (e.g., OLTC and SVR).

In the process of the simulation, some parameters of the air-conditioned room were considered variable, to ensure the credibility of the simulation. The areas of the rooms were set in the normal distribution. The mean value was 15 m^2, and the standard deviation was 4 m^2. The initial room temperatures and ACs' set temperatures were set between 24 °C and 25 °C, randomly. The rated power of each AC was

Table 3
The voltage regulation process of Node 18 in the collaborative voltage regulation algorithm.

Time	Voltage before→after regulation(Increase operating power)	The number of the ACs without waiting time (The number of ACs exit during regulating)	The number of the ACs with waiting time
Over-voltage regulation			
10:45–10:50	1.1005 p.u.→1.0979~1.0967 p.u. (66.86 kW ~44.75kW)	67	33
10:50–10:55	1.1011 p.u.→1.0975~1.0999 p.u. (66.86kW~10.82 kW)	100(68)	0
10:55–11:00	1.1024 p.u.→1.0986 ~1.0999p.u. (36.44kW~5.12kW)	68(68)	32
11:00–11:05	1.1012 p.u.→1.0994~1.0999 p.u. (32.46kW~7.97 kW)	59(59)	41
Under-voltage regulation			
19:45–19:50	0.8977 p.u.→0.9006~0.9028 p.u. (-27.78~-47.78 kW)	52	33
19:50–19:55	0.8989 p.u.→0.9027 p.u. (-56.56~-56.56 kW)	100	0
19:55–20:00	0.8976 p.u.→0.9037 p.u. (-56.56~-56.56 kW)	100	0
20:25–20:30	0.8961 p.u.→0.9000~0.9046 p.u. (-5.97~-34.54 kW)	15	70

proportional to the area of the room. Thus, a larger room was installed with ACs of larger-rated power. The rated power's proportional coefficient was distributed between 70 and 80, again randomly. In addition, some room parameters were fixed, as shown in Table 2.

5. Numeric test and result analysis

This section evaluates the voltage regulation performance of the aggregated ACs using representative cases. The node's voltage and room temperature are analysed before/after voltage regulation by the aggregated ACs, based on the IEEE 33-node power distribution system. Furthermore, a detailed collaborative voltage regulation process during the daytime at Node 18 is analysed.

5.1. The node voltage before regulation

Fig. 15A shows the voltage fluctuations of 32 nodes in a day. The colour mapping of the voltage magnitude is shown on the right, and a black part represents that a node's voltage exceeds a permissible range. When the load and PV generation of the grid fluctuate, the voltage of nodes 16–18 will be significantly affected.

In Fig. 15B, each line represents the voltage curve of a node. Continuously increasing the PV power generation or continuously decreasing the load causes the node voltage to rise. From 10:30 to 11:50, the PV generation continues to increase, whereas the load shows a downward trend; as a result, the voltage rises. The voltages of Node 17 and Node 18 exceed 1.1 p.u., and the maximum voltage of Node 18 reaches 1.102 p.u.. When the PV continues to decrease, or the load continues to increase, the voltage drops. During the period of 19:20–21:50, the PV generation no longer generates power and the load continues to increase; thus, the grid's voltage begins to drop. The voltages of Node 16, Node 17, and Node 18 become less than 0.9 p.u., and the minimum voltage of Node 18 is 0.897 p.u..

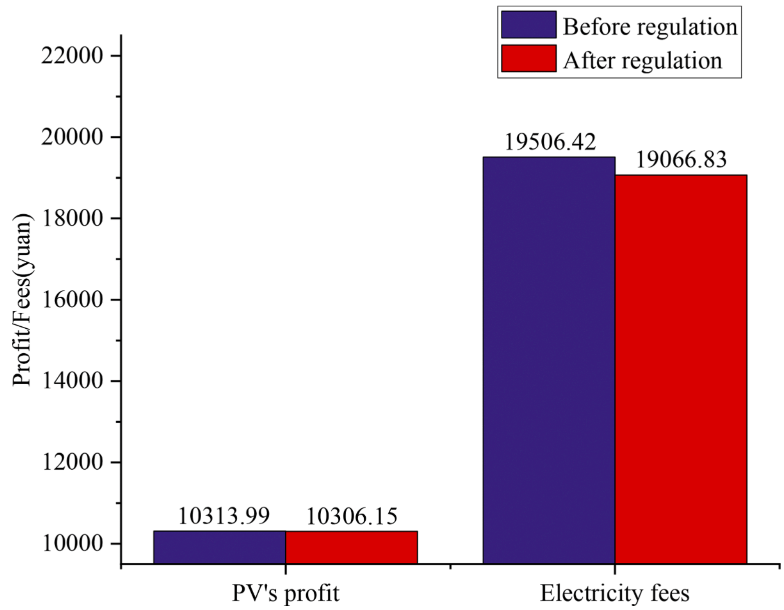

Fig. 20. The PV's profits and occupants' electricity fees before and after regulating ACs.

5.2. The node voltage after regulating by aggregated ACs

The 32-node voltage curves after regulation by the aggregated ACs are shown in Fig. 16. The voltages of the 32 nodes are all within [0.9,1.1] p.u.. During the over-voltage period, the highest voltage of node18 decreases from 1.102 p.u. to 1.098 p.u.. In addition, during the under-voltage period, the lowest voltage rises from 0.897 p.u. to 0.900 p.u.. All nodes' voltages return to the permissible range after the regulation utilizing the aggregated ACs.

The aggregated ACs increase/decrease their operating power when participating in voltage regulation, as shown in Fig. 17. The aggregated ACs' operating power incrementally reaches its highest point from 10:45 to 11:30. The operating power increment reaches 72.73 kW. The aggregated ACs' operating power reduction reaches its highest point during 19:45–21:25. The operating power reduction reaches -83.06 kW.

5.4. Room temperature before and after regulation of Node 18

From Fig. 15, it can be seen that the voltage of Node 18 is the most significantly affected by the PV generation and load. The voltage curve of Node 18 before and after voltage regulation is shown in Fig. 18. The initial T_{set} of the ACs are 24 °C or 25 °C, and the temperatures of the rooms are in the range of 24 °C–25 °C. When the ACs do not participate in the voltage regulation, the room temperature fluctuates in the range of [23, 25] °C and [24, 26] °C. The ACs reduce the set temperature to increase the operating power when participating in the voltage regulation from 10:45 to 11:30. The ACs increase the set temperature to decrease the operating power from 19:45–21:25. The rooms' temperature curves of Node 18 before and after regulation are shown in Fig. 19. During the periods when the ACs participate in voltage regulation, the room temperature remains within a comfortable range.

5.4. The detailed collaborative voltage regulation process of Node 18 during noon

Table 3 illustrates the detailed process of the ACs when they participate in the voltage regulation of Node18 during 10:45–11:05 and 19:45–20:30.

At 10:45, the voltage of Node 18 exceeds 1.1 p.u. and reaches 1.1005 p.u.. According to the voltage sensitivity method, the aggregated ACs should raise 126.03 kW of operating power for over-voltage regulation. During 10:45–10:50, sixty-seven ACs participate in the voltage regulation and raise 44.75 kW of operating power for the voltage regulation. In addition, another 33 ACs with waiting time are selected to participate in the regulation, which have 30 s–2 min waiting time. As a result, the voltage of Node 18 decreases from 1.1005 p.u. to 1.0967 p.u..

At 19:45, the voltage of Node 18 falls to 0.8981 p.u., and the ACs reset their operating power to provide voltage regulation service. According to the voltage sensitivity method, the aggregated ACs should decrease 142.22 kW of operating power for under-voltage regulation. During 19:45–19:50, fifty-two ACs participate in the voltage regulation and raise 27.78 kW of operating power for the voltage regulation. In addition, another 33 ACs with waiting time are selected to participate in the regulation, which have 2 min waiting time. As a result, the voltage of Node 18 increases from 0.8977 p.u. to 0.9028 p.u..

5.5. The differences of fees before and after regulating ACs

Fig. 20 illustrates the differences of PV's profits and occupants' electricity fees before and after regulating ACs, according to the realistic power system policy in Hangzhou, China. The electricity price in Hangzhou is classified as the peak-load price and valley-load price according to different time periods. The period of peak-load is 8:00–22:00, and the electricity price is 0.568 RMB/kWh. The rest period is valley-load and the corresponding electricity price is 0.288 RMB/kWh [42]. In addition, the Hangzhou Electric Power Company purchases PV output for 0.3997 RMB/kWh [43]. Before ACs participating in voltage regulation, the occupants can get 10313.99 RMB profits by PVs and pay 19506.42 RMB fees to electric power company. Therefore, the final electricity cost is 9192.43 RMB. After ACs participating in voltage regulation, the profit by PV generation is 10306.15 RMB, which is decreased 0.076% compared with the value before regulation. Besides, the electricity fees are 19066.83 RMB, which is decreased 2.25% compared with the value before regulation. Therefore, the final electricity cost decreases to 8760.68 RMB, which is 95.3% of the cost before participating in voltage regulation.

6. Conclusions

Air conditioners have massive potential for becoming regulation resources for power grids. Increasing and decreasing the operating power of aggregated air conditioners can help balance demand and supply. This paper proposes a collaborative voltage regulation algorithm for increasing/decreasing the operating power of aggregated air conditioners. First, a thermal model is established to obtain the room temperatures during the regulation process, avoiding the influence of too high or too low of room temperatures on occupant comfort. The detailed operation statuses of the air conditioners are analysed, and then the regulation power provided by the aggregated air conditioners is calculated by temporarily resetting the air conditioners' set temperatures based on the thermal model. Meanwhile, the node voltages in distribution systems can be regulated by increasing/decreasing the operating power of the air conditioners. Moreover, an algorithm for air conditioners participation priority in the voltage regulation is proposed, to select the most effective air conditioners for quickly responding to voltage regulation and extending the duration of voltage regulation. Finally, the simulation results show that the grid's voltage can be maintained between [0.9, 1.1] p.u. by increasing/decreasing the operating power of the aggregated air conditioner, which ensures that the grid can provide qualified voltage. Furthermore, the set temperatures of air conditioners are maintained between [22, 26] °C, ensuring the occupants' comfort. The simulation result verified that air conditioners can participate in a voltage regulation service and guarantee the quality of a power supply. Based on the collaborative voltage regulation algorithm, increasing/decreasing the operating power of aggregated air conditioners can provide a new method for voltage regulation.

CRediT authorship contribution statement

Yongzhu Hua: Conceptualization, Methodology, Data curation, Writing - original draft. **Qiangqiang Xie:** Writing - review & editing, Supervision, Project administration, Funding acquisition. **Hongxun Hui:** Writing - review & editing. **Yi Ding:** Writing - review & editing. **Weiran Wang:** Formal analysis, Investigation. **Huibin Qin:** Writing - review & editing. **Xiangrong Shentu:** Formal analysis, Investigation. **Jiadong Cui:** Formal analysis, Investigation.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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