Contents lists available at ScienceDirect

Energy

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

# Power-controllable variable refrigerant flow system with flexibility value for demand response

Peng Ren [a,1], Lunshu Chen [b,c,d,1], Hongxun Hui [b,c,d,*]

[a] Gree Electric Appliances, Inc. of Zhuhai, Guangdong, 519070, China
[b] State Key Laboratory of Internet of Things for Smart City, University of Macau, Macao, 999078, Macao Special Administrative Region of China
[c] Department of Electrical and Computer Engineering, University of Macau, Macao, 999078, Macao Special Administrative Region of China
[d] Zhuhai UM Science and Technology Research Institute, Guangdong, 519031, China

ARTICLE INFO

*Keywords:*
Demand response
Fuzzy control
Power regulation
Predicted mean vote
Variable refrigerant flow system

ABSTRACT

With the increase of renewable energy sources in the power supply, the issues of balancing power supply and demand are becoming severe. Demand response, by altering the demand-side load state, has been proven as a good method to solve the supply and demand balance problem. Variable refrigerant flow system has great potential in demand-side loads and is poised to become the mainstay of demand response. However, the traditional temperature or compressor state control of variable refrigerant flow systems does not allow for better power regulation for the power system. To address this problem, this paper proposes a power-controllable variable refrigerant flow system with demand response flexibility value for power regulation. The demand response flexibility value is designed as a subjective indicator to satisfy the heterogeneous customer comfort requirement. The predictive mean vote as an objective indicator of customer comfort coordinates with the demand response flexibility value. A fuzzy control strategy for variable refrigerant flow systems is designed to balance power system requirements and customer comfort requirements. The experiment result demonstrates that the power-controllable variable refrigerant flow system can provide power regulation service to the power system with a maximum power regulation deviation of 3.67%. By guaranteeing consumer comfort, the higher the flexibility value, the shorter the consumer's participation time in demand response. The demand response flexibility values can provide regulation configuration for demand response in practical engineering.

## 1. Introduction

### 1.1. Background and motivation

With global climate change, more countries are developing the construction of renewable energy resources (RESs) [1]. However, RESs have significant fluctuations and uncertainties which bring challenges for large-scale RESs access to the power system [2]. The fluctuation of RESs on the supply side will lead to the power supply and demand imbalance in the power system [3]. To cope with this challenge, power systems normally install operating reserves (e.g., thermal power units) on the supply side [4]. With the increasing of RESs in power systems, the operating reserves on the supply side are gradually hard to address the fluctuations from RESs [5]. Therefore, coordinating demand-side resources is important to address this challenge [6]. Demand response is a control technology that balances supply and demand in power systems by regulating demand-side load operating mode [7]. Demand-side loads include electric vehicles, energy storage systems, and air conditioners, which can flexibly adjust operating modes to provide power regulation services to power systems [8]. In all demand-side loads, the air conditioner (AC), accounting for 50% of the total demand-side loads, shows great potential in power regulation [9]. The function of the ACs at home is to provide a comfortable temperature environment for the customers [10]. The comfortable temperature environment resulting from AC has a time lag and is not immediately uncomfortable due to a change in the state of the AC [11]. Therefore, AC can provide power regulation services to power systems without affecting customer comfort [12]. With the development of the Internet of Things technology, the power system operator can allow ACs to participate in demand response through remote control [13]. In this setting, enhancing the efficiency of AC control to balance the power demands of power systems and customer comfort is crucial.

* Corresponding author at: State Key Laboratory of Internet of Things for Smart City, University of Macau, Macao, 999078, Macao Special Administrative Region of China.

*E-mail address:* hongxunhui@um.edu.mo (H. Hui).

[1] These authors contribute equally to this work and should be considered co-first authors.

https://doi.org/10.1016/j.energy.2024.133820
Received 1 August 2024; Received in revised form 3 November 2024; Accepted 11 November 2024

**Nomenclature**

**Abbreviation**

| | |
|---|---|
| AC | Air Conditioner |
| DR | Demand Response |
| ETP | Equivalent Thermal Parameter |
| IAC | Inverter Air Conditioner |
| PMV | Predicted Mean Vote |
| RESs | Renewable Energy Resources |
| VRFS | Variable Refrigerant Flow System |

**Parameter**

| | |
|---|---|
| $\kappa_1$ | The operating power coefficients of the VRFS |
| $\kappa_2$ | The cooling capacity coefficients of the VRFS |
| $b_1$ | The operating power coefficients of the VRFS |
| $b_2$ | The cooling capacity coefficients of the VRFS |
| $C$ | Equivalent air heat capacity of the room |
| $R$ | Equivalent thermal resistance of the room envelope |
| $f_{\mathrm{VRFS}}(t)$ | The operating frequency of VRFS at time $t$ |

**Set**

| | |
|---|---|
| $\mathcal{I}$ | The set of the VRFS |
| $\mathcal{K}$ | The set of the fuzzy rule |

**Variable**

| | |
|---|---|
| $\ell_i$ | The DR flexibility value of outdoor unit $i$ |
| $\overline{T}_{\mathrm{r}}$ | The mean radiant temperature |
| $\rho$ | The air density |
| $f_{\mathrm{cl}}$ | The clothing surface area factor |
| $i$ | The VRFS number |
| $N$ | The total VRFS number |
| $p_{\mathrm{a}}$ | The water vapor partial pressure |
| $P_{\mathrm{reg}}(t)$ | The regulation power of the total VRFS at time $t$ |
| $R_k$ | The $k$'th fuzzy rule |
| $v_{\mathrm{s}}$ | The wind speed from the VRFS |
| $W$ | The effective mechanical power |
| $f_{\mathrm{VRFS}}(t)$ | The operating frequency of VRFS at time $t$ |
| $h_{\mathrm{c}}$ | The convective heat transfer coefficient |
| $P_{\mathrm{VRFS}}(t)$ | The operating active power of VRFS at time $t$ |
| $Q_{\mathrm{VRFS}}(t)$ | The cooling capacity of the VRFS at time $t$ |
| $S_{\mathrm{fan}}$ | The VRFS fan leaf area |
| $T_{\mathrm{in}}(t)$ | The indoor temperature of the room at time $t$ |
| $T_{\mathrm{out}}(t)$ | The outdoor temperature of the room at time $t$ |
| $T_{\mathrm{cl}}$ | The clothing surface temperature |

### 1.2. Literature review

Recently, there have been many studies on developing and optimizing DR strategies to improve the flexibility and efficiency of the power system while facilitating the integration of RESs [14]. Mansouri et al. [15] propose a tri-level game-theoretic DR strategy for smart buildings and electric vehicles. The demand-side loads in the smart building can be aggregated by DR aggregators [16]. Nie et al. [17] propose a two-stage strategy for DR aggregators to exploit the potential of demand-side loads. These studies have demonstrated the potential for demand-side loads to participate in DR [18]. AC, as a key component in the demand-side loads, plays an essential role in the execution of DR [19]. Existing control methods of the AC participating in DR include temperature control and compressor state control. Chen et al. [20] use the temperature–power relationship of AC to estimate DR potential. Qi et al. [21] design the edge intelligent terminal to regulate the AC on/off according to the set temperature to participate in the DR. These studies realize that AC participates in the DR by temperature control. However, the temperature variation may be lagging in providing accurate power demand to the power system [22]. The temperature-based operating feature of AC ontology limits the flexibility of power regulation. The inverter air conditioner (IAC) is a type of AC with a frequency converter in the compressor [23]. Some scholars have proposed changing the compressor frequency to realize the regulation of power. Hong et al. [24] propose event-based distributed control to regulate the frequency of IAC compressors to participate in the DR. Dong et al. [25] propose an adaptive distributed regulation strategy to optimize the operation of the IAC cluster to realize DR. These studies demonstrate that IAC participates in the DR by compressor state control. However, the compressor frequency in the above research is assumed to be directly controlled without demonstrating how to change the compressor state. Zhou et al. [26] propose a state-switching control method for IAC participating in DR. The IAC state switching is demonstrated by controlling the output power of the inverter which affects the frequency of the compressor. This control method is still constrained by the IAC ontology. The traditional IAC is originally designed to meet the comfort requirements of the consumer [27]. The compressor of IAC usually works to meet certain temperature requirements to maintain the comfort requirements of the consumer [28]. Therefore, the traditional IAC is not convenient for DR through the above analysis. Although the above research has demonstrated the potential of AC in participating in DR to provide power regulation services. However, neither the temperature control nor the compressor state control is effective in controlling the AC power output.

It is necessary to improve the traditional AC to have a power-controllable function. Variable Refrigerant Flow System (VRFS) is the main type of AC and is widely used in commercial buildings [29]. According to statistics, the share of VRFS in the China AC market is 50.93% in the first half of 2023 [30]. The high market share of VRFS can provide sufficient regulation resources for DR. While promoting the VRFS in DR, it is important to balance the power system demand and the customer comfort [31]. Zhou et al. [32] propose a flexibility-oriented DR mechanism considering the customer satisfaction indicator. The customer satisfaction indicator demonstrates the global satisfaction of the customer for DR services. Specifically, the VRFS participating in the DR services also requires an indicator of the consumer's comfort level. Predicted Mean Vote (PMV) is an indicator for evaluating the thermal response of people and is often used to indicate the comfort level of the customer [33]. While the PMV is an objective indicator, the customer needs a subjective indicator that can be actively configured to satisfy the heterogeneous comfort requirements. Chen et al. [34] propose a proportional control based on the PMV indicator to better allow the consumer to participate in the DR. The recommended proportional control model can satisfy the heterogeneous requirements of customers. Therefore, when designing the VRFS control strategy to satisfy the power system demand and customer comfort, it is necessary to consider both objective and subjective indicators.

The intelligent control method for power-controllable VRFS is also required to consider both the power system requirements and the customer requirements. There are nonlinear relationships among the VRFS, power system requirements, and customer comfort. Therefore, it is difficult to find the functional expression of the power-controllable VRFS. The fuzzy control strategy is a flexible and intelligent control method for complex systems [35]. The fuzzy controller can simulate the inference behavior and decision-making processes of people, which makes the control more flexible and adaptive [36]. To this end, the fuzzy control strategy is designed in this study to coordinate the power system requirements and the customer requirements.

### 1.3. Research gaps and contributions

From the above analysis of recent research, the temperature or compressor state control of VRFS in recent research articles still faces challenges in efficiently integrating into DR. Fewer research have advocated the power-controlled VRFS for DR. Moreover, customer comfort needs to be guaranteed during the VRFS power regulation [37]. The literature review reflects that there are many gaps in releasing the power regulation potential of VRFS to improve the power system requirement and customer requirements. Both objective and subjective indicators need to be considered to satisfy the customer comfort.

The above research gaps have encouraged the authors of this study to propose a power-controllable VRFS with DR flexibility value. The subjective indicator (i.e., DR flexibility) is intricately coordinated with the objective indicator (i.e., PMV value) to explore the power regulation potential of VRFS. The contributions of the proposed power-controllable VRFS fulfill the limitations identified in the literature as follows:

- A power-controllable VRFS is designed to change the operating power of the VRFS directly. With this design, the VRFS only needs to focus on power regulation when participating in DR and does not need to establish relationships between temperature or compressor state with power like in previous studies.
- A DR flexibility value is designed as a subjective indicator to satisfy the heterogeneous customer comfort requirement. The DR flexibility value can guide the customer to adjust their power consumption behavior voluntarily. The PMV as an objective indicator of customer comfort coordinates with the DR flexibility value.
- A fuzzy control strategy considering PMV values, DR flexibility values, and power regulation requirements for the VRFS cluster is used to provide power regulation service to the power system. Through the fuzzy control strategy, VRFS can satisfy both the regulation requirements of the power system and the comfort requirements of the customer.

### 1.4. Paper organization

The remainder of this paper is organized as follows. Section 2 introduces the proposed power-controllable VRFS structure. Section 3 introduces the mathematical modeling of the power-controllable VRFS. Section 4 illustrates the experiments and analyzes the experiment results. Section 5 concludes this paper.

## 2. The proposed power-controllable variable refrigerant flow system

Fig. 1 shows the overall structural diagram of the power-controllable VRFS participating in the power regulation service for the power system. This structural diagram demonstrates how the power system interacts with the demand-side loads to realize DR. Traditional VRFS adjust the frequency of the compressor to meet the indoor temperature requirement of the customer. The power-controllable VRFS proposed in this study directly adjusts the compressor frequency to meet the power requirement. A demand response strategy based on incentives is employed. Power system operators develop corresponding incentive policies based on the operating status of the power system [38]. For instance, power system operators provide financial compensation to encourage customers to reduce and increase power consumption during peak and low periods, respectively. The power system operator monitors the operating status of the power system and sends the power regulation signal to demand-side loads (i.e., VRFS in this study). The aggregation controller of the demand-side loads controls the VRFS to regulate the power after receiving the regulation signals. The fuzzy controller in the aggregation controller is used to coordinate the power system regulation signals, PMV value, DR flexibility value, and compressor frequency of VRFS. After the fuzzy controller processing, the VRFS can adjust the power of the compressor to meet the power regulation requirements and the customer comfort.

## 3. Modeling and control method

In this section, the mathematical modeling of the proposed power-controllable VRFS is described. A fuzzy control strategy considering PMV values, DR flexibility values, and power regulation requirements for the VRFS cluster is designed to provide power regulation service to the power system.

### 3.1. Modeling of variable refrigerant flow system

The modeling of VRFS is very important in this study, which reveals the factors affecting the power of VRFS. The modeling of VRFS includes a thermal model, an electrical model, and an aggregated regulation model.

**(a) Thermal model:** The equivalent thermal parameter (ETP) model [39] can be used to describe the thermal dynamic characteristics of the VRFS, which can be expressed as follows:

$$\frac{dT_{\text{in}}}{dt} = \frac{1}{RC}(T_{\text{out}} - T_{\text{in}}) - \frac{Q_{\text{VRFS}}}{C}, \tag{1}$$

where $T_{\text{in}}(t)$ is the indoor temperature of the room at time $t$; $T_{\text{out}}(t)$ is the outdoor temperature of the room at time $t$; $R$ is the equivalent thermal resistance of the room envelope; $C$ is the equivalent air heat capacity of the room; $Q_{\text{VRFS}}(t)$ is the cooling capacity of the VRFS at time $t$.

**(b) Electrical and thermal conversion model:** The electrical and thermal conversion model [40] of VRFS is used to describe the relationship between the cooling capacity and the electrical power of the VRFS, which can be expressed as follows:

$$\begin{cases} P_{\text{VRFS}}(t) = \kappa_1 f_{\text{VRFS}}(t) + b_1, \\ Q_{\text{VRFS}}(t) = \kappa_2 f_{\text{VRFS}}(t) + b_2, \end{cases} \tag{2}$$

where $\kappa_1$ and $b_1$ are the operating power coefficients of the VRFS; $\kappa_2$ and $b_2$ are the cooling capacity coefficients of the VRFS; $P_{\text{VRFS}}(t)$ and $f_{\text{VRFS}}(t)$ are the operating active power and operating frequency of VRFS at time $t$, respectively.

In this study, the compressor of the VRFS is modified to enable power-controllable. The power-controllable VRFS provides power regulation service to the power system to participate in the DR. As shown in Fig. 1, when the outdoor unit receives the power regulation signal, the compressor frequency will be changed to meet the power requirements of the power system. The cooling capacity of VRFS will change with power, which can be expressed as follows:

$$Q_{\text{VRFS}}(t) = \frac{\kappa_2}{\kappa_1} P_{\text{VRFS}}(t) + \frac{\kappa_1 b_2 - \kappa_2 b_1}{\kappa_1}. \tag{3}$$

And the indoor temperature $T_{\text{in}}(t)$ will also change with the cooling capacity $Q_{\text{VRFS}}(t)$ according to Eq. (1).

**(c) Aggregated regulation model:** Since a single VRFS has limited regulation capability, it is necessary to aggregate multiple VRFSs as the cluster to provide power regulation capability to the power system. The VRFS cluster can be expressed as follows:

$$P_{\text{reg}}(t) = \sum_{i=1}^{N} P^{i}_{\text{VRFS}}(t), \tag{4}$$

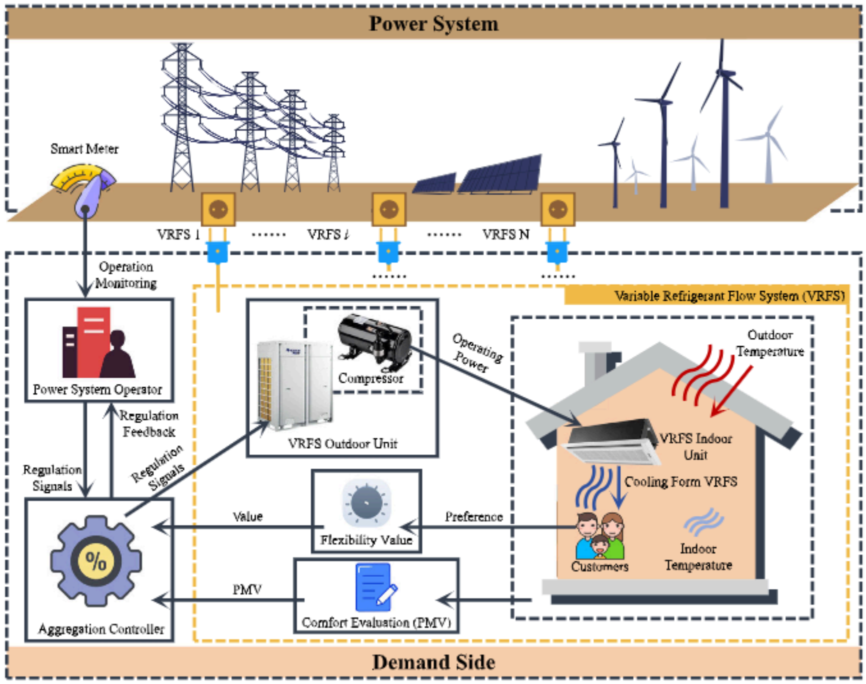



**Fig. 1.** The overall structural diagram of the VRFS participating in the power regulation service for the power system.

where $P_{\mathrm{reg}}(t)$ is the regulation power of the total VRFS at time $t$; $i$ is the VRFS number; $\forall i \in \mathcal{I}$; $\mathcal{I} = \{1, 2, 3, \ldots, N\}$ is the set of the VRFS; $N$ is the total VRFS number.

### 3.2. Modeling of demand response flexibility value

To guarantee customer comfort during the power regulation process, the DR flexibility value is designed as a subjective indicator to satisfy the heterogeneous customer comfort requirement. The DR flexibility value can guide the customer to adjust their power consumption behavior. Therefore, the total VRFS power with DR flexibility value $P_{\mathrm{reg}}(t)$ is expressed as follows:

$$P_{\mathrm{reg}}(t) = \sum_{i=1}^{N} \ell_i P_{\mathrm{VRFS}}^{i}(t), \tag{5}$$

where $\ell_i$ is the DR flexibility value of outdoor unit $i$; $\forall \ell_i = [0, 1]$; $\ell_i = 0$ indicates that the outdoor unit $i$ prioritizes the customer comfort and does not provide power regulation to the power system; $\ell_i = 1$ indicates that the outdoor unit $i$ prioritizes power regulation without guaranteeing the customer comfort.

### 3.3. Modeling of predicted mean vote

The PMV as an objective indicator coordinates with the DR flexibility value. The PMV value model is a comprehensive indicator [41], which can be expressed as follows:

$$PMV = \left[0.303e^{-0.036M} + 0.0275\right] L, \tag{6}$$

where $M$ is the metabolic rate; $L$ is the thermal load. The thermal load is influenced by internal heat production and the actual environment, which can be expressed as follows:

$$\begin{aligned} L = {} & (M - W) - 3.05[5.733 - 0.007(M - W) - p_{\mathrm{a}}] - \\ & 0.42[(M - W) - 58.15] - 0.0173M(5.876 - p_{\mathrm{a}}) - \\ & 0.0014M(34 - T_{\mathrm{in}}) - 3.96 \times 10^{-8} f_{\mathrm{cl}}[(T_{\mathrm{cl}} + 273)^4 - \\ & (\overline{T_{\mathrm{r}}} + 273)^4] - f_{\mathrm{cl}} h_{\mathrm{c}}(T_{\mathrm{cl}} - T_{\mathrm{in}}), \end{aligned} \tag{7}$$

where $W$ is the effective mechanical power; $p_{\mathrm{a}}$ is the water vapor partial pressure; $T_{\mathrm{in}}$ is the indoor temperature; $f_{\mathrm{cl}}$ is the clothing surface area factor; $T_{\mathrm{cl}}$ is the clothing surface temperature; $\overline{T_{\mathrm{r}}}$ is the mean radiant temperature; $h_{\mathrm{c}}$ is the convective heat transfer coefficient, which can be expressed as follows:

$$h_{\mathrm{c}} = \max(2.38|T_{\mathrm{cl}} - T_{\mathrm{in}}|^{0.25}, 12.1\sqrt{v_{\mathrm{s}}}), \tag{8}$$

where $v_{\mathrm{s}}$ is the wind speed from the VRFS. The power of the VRFS can affect the fan speed of the VRFS which changes the wind speed in the room. From Eq. (3), it can obtain the relationship between the VRFS operating power $P_{\mathrm{VRFS}}(t)$ and the VRFS cooling capacity $Q_{\mathrm{VRFS}}(t)$. The cooling capacity of VRFS is converted into wind energy to cool the room, which can be expressed as follows:

$$Q_{\mathrm{VRFS}} = \frac{1}{2}\rho {v_{\mathrm{s}}}^3 S_{\mathrm{fan}}, \tag{9}$$

where $\rho$ is the air density; $S_{\mathrm{fan}}$ is the VRFS fan leaf area.

This research focuses on the relationship between VRFS power and indoor temperature. Assuming that all other parameters in the PMV model are constants, the PMV model can be simplified as follows:

$$PMV = f_{PMV}(T_{\mathrm{in}}(t), P_{\mathrm{VRFS}}(t)). \tag{10}$$

### 3.4. Fuzzy control strategy

It is difficult to find the functional expression among the regulation signals of the power system $\Delta P_{\mathrm{Grid}}$, the DR flexibility value $\ell$ of the VRFS, the PMV value, and the compressor frequency $f_{\mathrm{VRFS}}$ of VRFS. However, the approximate relationship among these four factors is that the VRFS regulates the compressor frequency $f_{\mathrm{VRFS}}$ according to the regulation signal $\Delta P_{\mathrm{Grid}}$ from the power system. During this process, the DR flexibility value $\ell$ set by the customer is considered to maintain the PMV value within the appropriate range. The fuzzy control strategy is used in this study to coordinate these factors. Fig. 2 shows the architecture of the fuzzy controller. The fuzzy controller consists of the fuzzifier (Step 1), the rule base (Step 2), the inference engine (Step 3), and the defuzzifier (Step 4).

**Step 1:** The first step in the fuzzy controller processing is to fuzzify the inputs and outputs. As shown in Fig. 2, the inputs of this study are the regulation signals of the power system $\Delta P_{\mathrm{Grid}}$, the DR flexibility value of the VRFS $\ell$, and the PMV value. The output is the compressor frequency $f_{\mathrm{VRFS}}$.

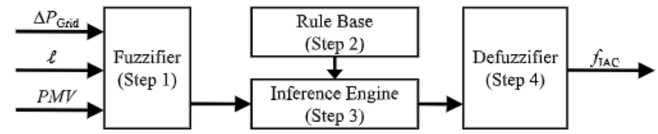



**Fig. 2.** The architecture of the fuzzy controller.

**Table 1**
The rule base of the fuzzy controller.

| $\ell$ | $PMV$ | $\Delta P_{Grid}$ | | |
|---|---|---|---|---|
| | | $p_1$ | $p_2$ | $p_3$ |
| | $r_1$ | $f_1$ | $f_2$ | $f_3$ |
| | $r_2$ | $f_1$ | $f_2$ | $f_3$ |
| $l_1$ | $r_3$ | $f_1$ | $f_2$ | $f_3$ |
| | $r_4$ | $f_1$ | $f_2$ | $f_3$ |
| | $r_5$ | $f_1$ | $f_2$ | $f_3$ |
| | $r_1$ | $f_1$ | $f_1$ | $f_2$ |
| | $r_2$ | $f_1$ | $f_2$ | $f_2$ |
| $l_2$ | $r_3$ | $f_1$ | $f_2$ | $f_3$ |
| | $r_4$ | $f_2$ | $f_2$ | $f_3$ |
| | $r_5$ | $f_2$ | $f_3$ | $f_3$ |
| | $r_1$ | $f_1$ | $f_1$ | $f_1$ |
| | $r_2$ | $f_1$ | $f_1$ | $f_1$ |
| $l_3$ | $r_3$ | $f_2$ | $f_2$ | $f_2$ |
| | $r_4$ | $f_3$ | $f_3$ | $f_3$ |
| | $r_5$ | $f_3$ | $f_3$ | $f_3$ |

The regulation signals of the power system $\Delta P_{\text{Grid}}$ can be fuzzified as the following fuzzy set:

$$\Delta P_{\text{Grid}} \in \left[p_1, p_2, p_3\right], \tag{11}$$

where $p_1$ denotes the power-down regulation; $p_2$ denotes that the power does not regulation; $p_3$ denotes the power-up regulation .

The DR flexibility value $\ell$ of the VRFS can be fuzzified as the following fuzzy set:

$$\ell \in \left[l_1, l_2, l_3\right], \tag{12}$$

where $l_1$ denotes high flexibility; $l_2$ denotes moderate flexibility; $l_3$ denotes low flexibility.

The PMV value can be fuzzified as the following fuzzy set:

$$PMV \in \left[r_1, r_2, r_3, r_4, r_5\right], \tag{13}$$

where $r_1 \sim r_5$ corresponds to the comfort level of the room as cold, cool, neutral, warm, and hot respectively.

The compressor frequency $\widetilde{f_{\text{VRFS}}}$ can be fuzzified as shown in the following fuzzy set:

$$\widetilde{f_{\text{VRFS}}} \in \left[f_1, f_2, f_3\right], \tag{14}$$

where $f_1$ denotes the frequency-down regulation; $f_2$ denotes that the frequency does not regulation; $f_3$ denotes the frequency-up regulation.

From the above fuzzy sets, the uniform triangle affiliation function for the fuzzy sets can be defined. The affiliation function can fuzzify the inputs and outputs.

**Step 2:** The second step in the fuzzy controller processing is to create the rule base. The rule base helps to clarify the relationship between inputs and outputs. The rule base is based on the relationship among the power system, the consumer, and the VRFS as shown in Table 1. The fuzzy rules between the input and output can be queried by the fuzzy base.

**Step 3:** The third step in the fuzzy controller processing is to design the inference engine. The function of the inference engine is to generate the corresponding fuzzy output from the fuzzy rules and fuzzy inputs through fuzzy logic operations. The fuzzy logic operations are based on the fuzzy rule base in *Step 2*, which can be expressed as follows:

$$\begin{aligned} R_1 \quad &: \quad \text{IF } (\ell \text{ is } l_1) \text{ and } (PMV \text{ is } r_1) \text{ and } (\Delta P_{\text{Grid}} \text{ is } p_1) \\ &\quad\;\; \text{THEN } (\widetilde{f_{\text{VRFS}}} \text{ is } f_1), \\ &\quad\;\; \ldots\ldots, \\ R_{45} \quad &: \quad \text{IF } (\ell \text{ is } l_3) \text{ and } (PMV \text{ is } r_5) \text{ and } (\Delta P_{\text{Grid}} \text{ is } p_3) \\ &\quad\;\; \text{THEN } (\widetilde{f_{\text{VRFS}}} \text{ is } f_3). \end{aligned} \tag{15}$$

The above fuzzy logic operations can be simplified and represented as follows:

$$\widetilde{f^k_{\text{VRFS}}} = R_k \circ (\ell_k, PMV_k, \Delta P^k_{\text{VRFS}}), \tag{16}$$

where $R_k$ is the $k$'th fuzzy rule; $\circ$ is a mapping of the fuzzy logic calculation rules; $k \in \mathcal{K}; \mathcal{K} = [1, 2, \ldots, 45]$.

**Step 4:** The fourth step in the fuzzy controller processing is to clarify the output result. Through the **Step 2**, the fuzzy output $\widetilde{f^k_{\text{VRFS}}}$ can be obtained. The area-centered method can clarify the fuzzy output. Therefore, an accurate output value $f_{\text{VRFS}}$ can be obtained.

## 4. Experiment

The experiment setup and experiment results for the power-controllable VRFS are discussed in the subsequent sections.

### *4.1. Experiment setup*

To verify the performance of the proposed method, the traditional VRFS needs to be modified. Gree company is one of the largest heating and air conditioning system manufacturers in the world. The traditional VRFS is modified the compressor by Gree company to make it have a power-controllable function. The testing building with the power-controllable VRFS for this research is located in Gree company, Zhuhai City, China. Fig. 3 shows the field demonstration of VRFS and the software platform of the VRFS control center. 4 VRFS outdoor units and 20 indoor units are developed to participate in this experiment. The VRFS control center can set the desired power and flexibility value of VRFS. The operating data of VRFS is collected in real time by the VRFS control center. The data update frequency is set to 1 min in these experiments.

### *4.2. Result analysis of power regulation*

To verify the power regulation capability of VRFS, the power down- and up-regulation experiments are designed. When VRFS runs in the stable state, a 400 W down-regulation command to VRFS is sent. After the VRFS runs in the stable state, a 300 W up-regulation command is sent to VRFS. Fig. 4 shows the experiment results of VRFS power regulation. It can be seen from Fig. 4(a) that the operating power of the VRFS can be followed by the expected power to regulate down and up. The maximum power regulation deviation is the maximum difference between the operating power and the expected power. By measuring the maximum power regulation deviation between the operating power and the expected power, the regulation accuracy and response speed of the system can be evaluated. The maximum power regulation deviation during the whole regulation process is 3.67%. The down and up-regulation process of the power can be completed in 1 min as shown in Fig. 4(b) and (c), respectively.

To verify the power regulation capability of the VRFS at different DR flexibility values, controlled experiments are designed. The DR flexibility values in the control experiments are selected to be 0.0, 0.5, and 1.0. During the period from 8:30 to 17:30, the same power regulation commands are sent and the power and energy variations of the VRFS are observed. Fig. 5(a)–(c) show the power regulation results of VRFS under different DR flexibility values. From the experiment results, it can be seen that the operating power of VRFS can follow the expected power under different DR flexibility values. Since the test building is an office, there are people in the office who can modify the

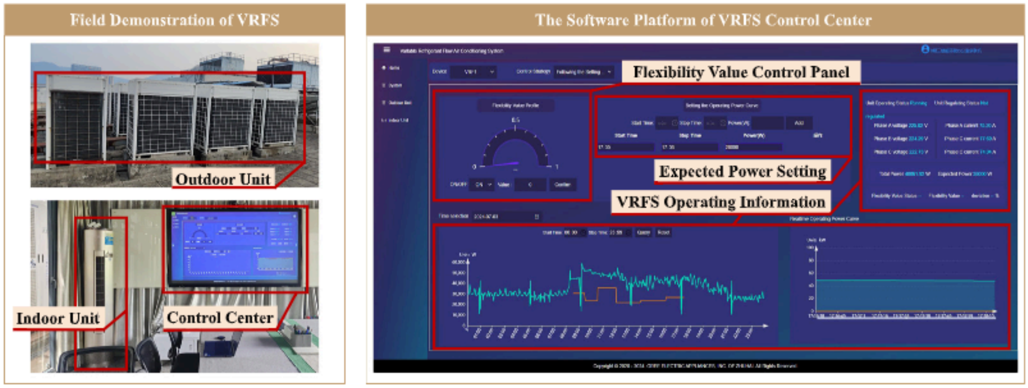



**Fig. 3.** The field demonstration of VRFS and the software platform of VRFS control center.

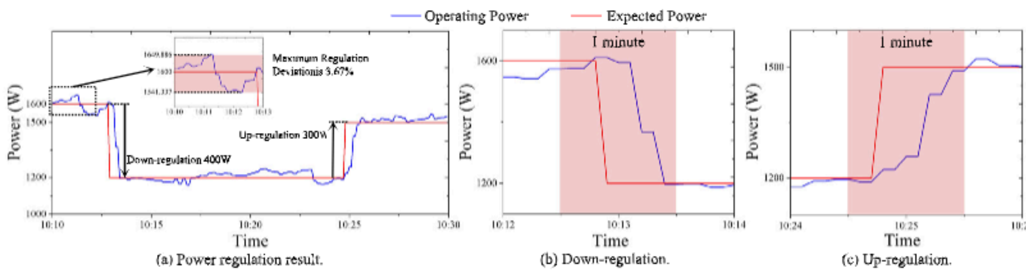



**Fig. 4.** The experiment results of VRFS power regulation capability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

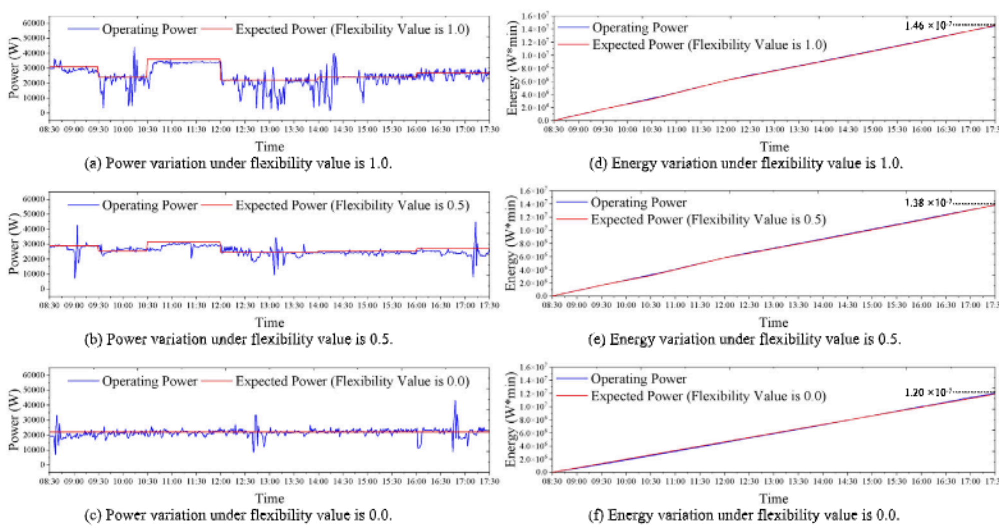
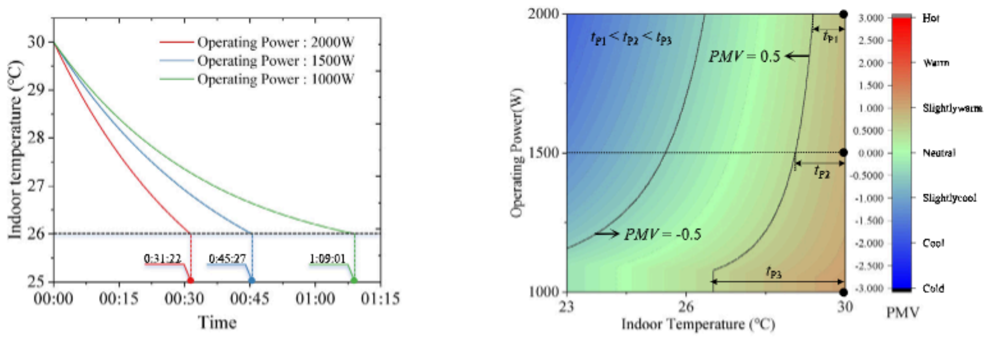



**Fig. 5.** The power regulation results of VRFS under different demand response flexibility values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

set temperature according to their preferences. The modification of the setting temperature by the people results in power changes. After the modification by the people, the VRFS controller automatically regulates the operating power of the VRFS to track the expected power. Therefore, there are some tiny fluctuations in the operating power of the VRFS during the experiment. Converting the experiment results into the energy (i.e., power multiplied by time) form, as shown in Fig. 5(d)–(f), it can be seen that the energy variation corresponding to the operating power of the VRFS can follow the energy variation corresponding to the expected power. The experiment result also demonstrates that the high DR flexibility value of the VRFS provides a large range of power regulation and the low DR flexibility value of the VRFS provides a low range of power regulation.

### 4.3. Result analysis of customer comfort

To verify customer comfort under the different operating powers of VRFS, the simulation has been carried out based on the Python tool. Fig. 6(a) shows the variation of indoor temperature at different operating power of VRFS. From Fig. 6(a), it can be found that the time of indoor temperature from the same temperature (i.e., 30 °C) to the desired temperature (i.e., 26 °C) is different under different VRFS operating power. The VRFS running at high power has a shorter time for the room to reach the desired temperature, while the VRFS running at low power has a longer time. The process of varying indoor temperature can lead to different comfort feelings for the consumer. Therefore, it is worth considering that the variation in indoor temperature during




(a) Temperature variation.

(b) PMV value variation.

**Fig. 6.** The indoor temperature and PMV value variation under different operating power of VRFS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

power regulation brings different comfort to the customer. Fig. 6(b) shows the variation of PMV value at different operating power of VRFS according to the Eq. (10). The PMV value between −0.5 and 0.5 is defined as the comfort zone of the customer. From Fig. 6(b), it can be found that the time of the PMV value from the start temperature (i.e., 30 °C) to the comfort zone is different under different VRFS operating power. The VRFS running at high power has a shorter time for the room to the comfort zone, while the VRFS running at low power has a longer time. Therefore, it is worth considering the PMV value during power regulation to guarantee customer comfort.

To verify customer comfort at different DR flexibility values, controlled experiments are designed. The DR flexibility values in the control experiments are selected to be 0.0, 0.5, and 1.0. The experiment controls the VRFS operating power from 35 000 W to 24 000 W at 8 : 30. Fig. 7(a) and (b) show the experiment result of the temperature variation and PMV value variation under different DR flexibility values, respectively. From the experiment results, it can be observed that the indoor temperature variation and PMV value variation are different with different DR flexibility values. In the case of DR flexibility value of 0, the indoor temperature variation is not significant and the PMV value remains within the comfortable area. In the case of DR flexibility values of 1 and 0.5, the indoor temperature variance is significant while the PMV value also exceeds the comfortable area. For the DR flexibility value is 1, the PMV value goes out of the comfortable area after 50 min of power regulation. For the DR flexibility value is 0.5, the PMV value goes out of the comfortable area after 70 min of power regulation. In this case, the fuzzy control strategy in the VRFS controller can stop the increase of the PMV value within 30 min. The PMV value can return to the comfortable area after 35 min.

From the above analysis, it can be observed that the DR flexibility values can provide regulation configuration for DR in practical engineering. In this experiment, the DR for the customer with the DR flexibility value of 1 in less than 50 min. For the customer with the DR flexibility value of 0.5, the DR is within 70 min. The DR flexibility value can balance the power demand of the power system and the customer comfort. The customer can select the appropriate DR flexibility value according to the different scenarios. The power system operators can also send appropriate power regulation commands based on the DR flexibility value. This method is helpful in guiding consumers to participate in the DR.

## 5. Conclusion

This paper proposes a power-controllable VRFS with DR flexibility value for power regulation. A DR flexibility value is designed as a subjective indicator to satisfy the heterogeneous customer comfort requirement. The objective indicator(i.e., PMV value) and the subjective indicator(i.e., DR flexibility value) are considered to satisfy the customer comfort. A fuzzy control strategy for the VRFS cluster is used for the regulation requirements of the power system and the comfort requirements of the customer. The experiment for the power-controllable VRFS is carried out to evaluate the validity of the proposed power-controllable VRFS and fuzzy control strategy, and the results are as follows:

- The power-controllable VRFS can provide power regulation service to the power system with a maximum power regulation deviation of 3.67%. The up and down-regulation process of the power can be completed in 1 min.
- The DR can be carried out for the customer with the DR flexibility value of 1 in less than 50 min in this study. The DR can also be carried out for the customer with the DR flexibility value of 0.5 in less than 70 min in this study. The DR flexibility value has significant engineering value in guiding the customer to participate in DR more conveniently.

In summary, the power-controllable VRFS proposed in this paper can directly change the operating power of VRFS to better participate in DR. The power-controllable VRFS only needs to focus on power regulation when participating in DR and does not need to establish relationships between temperature or compressor state with power like in previous studies. The DR flexibility value, as a subjective indicator, can guide the customer to adjust their power consumption behavior according to the power system operating requirements voluntarily.

## CRediT authorship contribution statement

**Peng Ren:** Writing – original draft, Project administration. **Lunshu Chen:** Writing – original draft, Software, Methodology, Investigation. **Hongxun Hui:** Writing – review & editing, Supervision.

## Declaration of competing interest

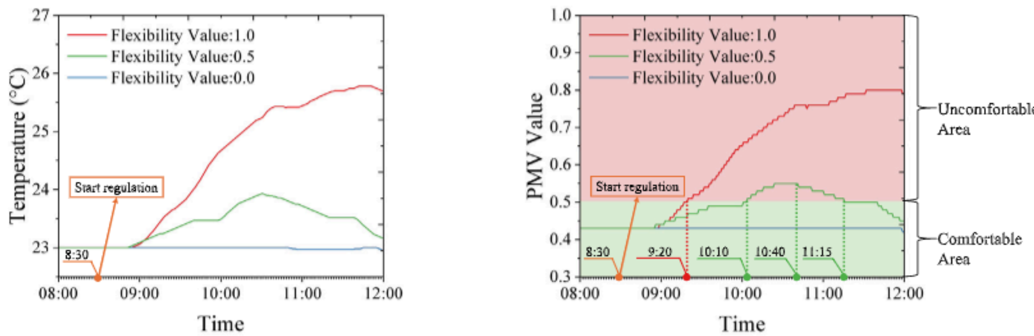
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

This work is funded in part by the National Natural Science Foundation of China (Grant No. 52407075), in part by the Science and Technology Development Fund, Macao SAR (File no. 001/2024/SKL, and File no. 0117/2022/A3), and in part by the Multi-Year Research Grant – General Research Grant 2024 of University of Macau (File no. MYRG-GRG2024-00112-IOTSC).

## Data availability

No data was used for the research described in the article.




(a) Temperature variation. (b) PMV value variation.

**Fig. 7.** The indoor temperature and PMV value variation under different demand response flexibility values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## References

[1] Bharatee A, Ray PK, Ghosh A. Hardware design for implementation of energy management in a solar-interfaced dc microgrid. IEEE Trans Consum Electron 2023;69(3):343–52.
[2] Zhang Z, Wang C, Wu Q, Dong X. Optimal dispatch for cross-regional integrated energy system with renewable energy uncertainties: A unified spatial–temporal cooperative framework. Energy 2024;292:130433.
[3] Wang J, Zhong H, Ma Z, Xia Q, Kang C. Review and prospect of integrated demand response in the multi-energy system. Appl Energy 2017;202:772–82.
[4] Talaat M, Elkholy M, Farahat M. Operating reserve investigation for the integration of wave, solar and wind energies. Energy 2020;197:117207.
[5] Hong J, Hui H, Zhang H, Dai N, Song Y. Distributed control of large-scale inverter air conditioners for providing operating reserve based on consensus with nonlinear protocol. IEEE Internet Things J 2022;9(17):15847–57.
[6] Song M, Deng R, Yan X, Sun W, Gao C, Yan M, et al. Two-stage decision-dependent demand response driven by tcls for distribution system resilience enhancement. Appl Energy 2024;361:122894.
[7] Yang S, Lao KW, Hui H, Su J, Wang S. Secure frequency regulation in power system: A comprehensive defense strategy against fdi, dos, and latency cyber-attacks. Appl Energy 2025;380:124772.
[8] Yang S, Lao KW, Hui H, Chen Y. Secure distributed control for demand response in power systems against deception cyber-attacks with arbitrary patterns. IEEE Trans Power Syst 2024;39(6):7277–90.
[9] Ismail M, Hassan H. Influence of coupling air conditioner with hybrid pcms on building interior conditions and consumed power: Experimental investigation. Energy Build 2024;310:114112.
[10] Zhang Z, Hui H, Song Y. Response capacity allocation of air conditioners for peak–valley regulation considering interaction with surrounding microclimate. IEEE Trans Smart Grid 2024. early access, http://dx.doi.org/10.1109/TSG.2024.3482361.
[11] Luo Y, Hao H, Yang D, Yin Z, Zhou B. Optimal operation strategy of combined heat and power system considering demand response and household thermal inertia. IEEE Trans Consum Electron 2023;69(3):366–76.
[12] Hui H, Ding Y, Liu W, Lin Y, Song Y. Operating reserve evaluation of aggregated air conditioners. Appl Energy 2017;196:218–28.
[13] Dai S, Mansouri SA, Huang S, Alharthi YZ, Wu Y, Bagherzadeh L. A multi-stage techno-economic model for harnessing flexibility from iot-enabled appliances and smart charging systems: Developing a competitive local flexibility market using stackelberg game theory. Appl Energy 2024;373:123868.
[14] Mansouri SA, Ahmarinejad A, Javadi MS, Nezhad AE, Shafie-Khah M, J.P. Catalão. Demand response role for enhancing the flexibility of local energy systems. In: Distributed energy resources in local integrated energy systems. 2021, p. 279–313.
[15] Mansouri SA, Paredes Á, González JM, Aguado JA. A three-layer game theoretic-based strategy for optimal scheduling of microgrids by leveraging a dynamic demand response program designer to unlock the potential of smart buildings and electric vehicle fleets. Appl Energy 2023;347:121440.
[16] Wang K, Wang C, Yao W, Zhang Z, Liu C, Dong X, et al. Embedding p2p transaction into demand response exchange: A cooperative demand response management framework for ies. Appl Energy 2024;367:123319.
[17] Nie X, Mansouri SA, Jordehi AR, Tostado-Véliz M. A two-stage optimal mechanism for managing energy and ancillary services markets in renewable-based transmission and distribution networks by participating electric vehicle and demand response aggregators. Int J Electr Power Energy Syst 2024;158:109917.
[18] Xia W, Ren Z, Li H, Pan Z. A data-driven probabilistic evaluation method of hydrogen fuel cell vehicles hosting capacity for integrated hydrogen-electricity network. Appl Energy 2024;376:123895.
[19] Hua Y, Xie Q, Hui H, Ding Y, Wang W, Qin H, et al. Collaborative voltage regulation by increasing/decreasing the operating power of aggregated air conditioners considering participation priority. Electr Power Syst Res 2021;199:107420.
[20] Chen T, Cui Q, Gao C, Hu Q, Lai K, Yang J, et al. Optimal demand response strategy of commercial building-based virtual power plant using reinforcement learning. IET Gener Transm Distrib 2021;15(16):2309–18.
[21] Qi T, Ye C, Hui H, Zhao Y. Fast frequency regulation utilizing non-aggregate thermostatically controlled loads based on edge intelligent terminals. IEEE Trans Smart Grid 2023.
[22] Cui W, Ding Y, Hui H, Lin Z, Du P, Song Y, et al. Evaluation and sequential dispatch of operating reserve provided by air conditioners considering lead–lag rebound effect. IEEE Trans Power Syst 2018;33(6):6935–50.
[23] Hui H, Ding Y, Chen T, Rahman S, Song Y. Dynamic and stability analysis of the power system with the control loop of inverter air conditioners. IEEE Trans Ind Electron 2021;68(3):2725–36.
[24] Hong J, Hui H, Zhang H, Dai N, Song Y. Event-triggered consensus control of large-scale inverter air conditioners for demand response. IEEE Trans Power Syst 2022;37(6):4954–7.
[25] Dong L, Wu Q, Hong J, Wang Z, Fan S, He G. An adaptive decentralized regulation strategy for the cluster with massive inverter air conditionings. Appl Energy 2023;330:120304.
[26] Zhou T, Chen H, Zhang N, Han Y, Zhou S, Li Z, et al. An analogue on/off state-switching control method suitable for inverter-based air conditioner load cluster participating in demand response. Appl Energy 2024;363:123096.
[27] Yu ZC, Bao YQ, Yang X. Day-ahead scheduling of air-conditioners based on equivalent energy storage model under temperature-set-point control. Appl Energy 2024;368:123481.
[28] Hua Y, Xie Q, Hui H, Ding Y, Cui J, Shao L. Use of inverter-based air conditioners to provide voltage regulation services in unbalanced distribution networks. IEEE Trans Power Deliv 2022;38(3):1569–79.
[29] Wang J, Wei Z, Zhu Y, Zheng C, Li B, Zhai X. Demand response via optimal pre-cooling combined with temperature reset strategy for air conditioning system: A case study of office building. Energy 2023;282:128751.
[30] China central air conditioning market summary report, (first half of 2023) (in chinese). 2023.
[31] Hao H, Corbin CD, Kalsi K, Pratt RG. Transactive control of commercial buildings for demand response. IEEE Trans Power Syst 2016;32(1):774–83.
[32] Zhou X, Mansouri SA, Jordehi AR, Tostado-Véliz M, Jurado F. A three-stage mechanism for flexibility-oriented energy management of renewable-based community microgrids with high penetration of smart homes and electric vehicles. Sustainable Cities Soc 2023;99:104946.
[33] Buyak N, Deshko V, Bilous I, Pavlenko A, Sapunov A, Biriukov D. Dynamic interdependence of comfortable thermal conditions and energy efficiency increase in a nursery school building for heating and cooling period. Energy 2023;283:129076.
[34] Chen X, Li K, Mi Z, Wang F. An air conditioning control method based on non-measurement thermal comfort standard correction for demand response. IEEE Trans Ind Appl 2024;60(3):4736–48.
[35] Das SR, Mishra AK, Sahoo AK, Hota AP, Viriyasitavat W, Alghamdi NS, et al. Fuzzy controller designed based multilevel inverter for power quality enhancement. IEEE Trans Consum Electron 2024.
[36] Li Y, De La Ree J, Gong Y. The smart thermostat of hvac systems based on pmv-ppd model for energy efficiency and demand response. In: 2018 2nd IEEE conference on energy internet and energy system integration. IEEE; 2018, p. 1–6.
[37] Zhang X, Pipattanasomporn M, Chen T, Rahman S. An iot-based thermal model learning framework for smart buildings. IEEE Internet Things J 2019;7(1):518–27.
[38] Yang Z, Ren Z, Li H, Sun Z, Feng J, Xia W. A multi-stage stochastic dispatching method for electricity-hydrogen integrated energy systems driven by model and data. Appl Energy 2024;371:123668.

[39] Chen X, Hu Q, Shi Q, Quan X, Wu Z, Li F. Residential hvac aggregation based on risk-averse multi-armed bandit learning for secondary frequency regulation. J Mod Power Syst Clean Energy 2020;8(6):1160–7.
[40] Song M, Gao C, Yan H, Yang J. Thermal battery modeling of inverter air conditioning for demand response. IEEE Trans Smart Grid 2017;9(6):5522–34.
[41] Qin M, Yang Y, Zhao X, Xu Q, Yuan L. Low-carbon economic multi-objective dispatch of integrated energy system considering the price fluctuation of natural gas and carbon emission accounting. Prot Control Modern Power Syst 2023;8(4):1–18.