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Hardware-in-the-Loop and Field Demonstration towards Voltage Regulation in Distribution System Considering Adjustable Inverter Air Conditioners

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***Abstract*—The voltage quality of distribution systems is facing challenges due to the increasing intermittency and uncertainty of renewable energy generation. In contrast to the traditional regulation method, the demand response through regulating demand-side resources' power consumption is gaining greater attention. Inverter air conditioners (IACs) have a high percentage in the demand-side resources and have huge regulation potential for distribution system voltage regulation services. However, considering the large scale and complexity of the distribution system, most previous studies on IACs' voltage regulation are verified only by simulation tools, e.g., Simulink and Pandapower. This study demonstrates a hardware-in-the-loop (HIL) platform for voltage regulation by realistic IACs with a real time digital simulator. The voltage sensitivity matrix evaluates the number of IACs participating in the voltage regulation. A modified IEEE 33-node distribution system with fluctuating photovoltaic generation is used to validate the proposed method. The experiment results show that the proposed method effectively maintains voltage stability in the distribution system.**

***Index Terms*—demand response, hardware-in-the-loop, inverter air conditioners, real time digital simulator, voltage sensitivity matrix, voltage regulation**

I. Introduction

Distributed renewable energy sources (RESs), such as photovoltaic (PV) solar systems, are being installed in the distribution systems gradually [1]. However, the intermittent and uncertain character of RESs will bring many voltage problems to the distribution system [2]. The power supply and power demand in a distribution system should be in a relatively balanced state [3]. As shown in Fig. 1, the over-voltage problem will occur if the power supply is larger than the power demand. The under-voltage problem will occur if the power supply is smaller than the power demand. Over-voltage problems or under-voltage problems can lead to equipment malfunctions, reduced equipment lifespan, and disruptions in power supply [4]. Therefore, effective voltage control mechanisms can ensure stable and reliable operation of the power system while integrating more RESs.

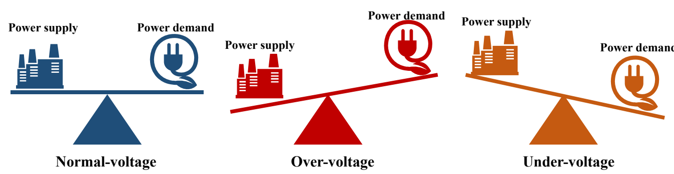

Fig. 1. The relationship between power supply-side and demand-side in the distribution system.

The common methods of voltage regulation include on-load voltage regulators (OLTCs), static var compensators (SVC), static synchronous compensators (STATCOM), control of distributed energy resources (DERs), and demand response (DR). The advantages and disadvantages of these methods are shown in Table I. In conclusion, traditional voltage regulation methods(e.g., OLTC, SVC, STATCOM, et al.) cannot deal with the rapid fluctuations brought by RESs. With the development of the Internet of Things, it is possible to monitor and control demand-side resources, which provides technical support for the conduct of DR [10]. DR stands out as a significant advantage in voltage regulation for distribution systems. Luo *et al.* [11] demonstrated through literature review and comparison that demand-side resource rapid response capability can efficiently regulate the adjustment of power loads to stabilize the voltage. DR is relatively cost-effective, which will further increase the flexibility and reliability of the distribution system.

Among the various demand-side resources, temperature-controlled loads play a pivotal role, in which air conditioners are a significant donor [12]. Therefore, many researchers have focused on the participation of air conditioners in DR to provide auxiliary regulation services to the distribution systems [13]. Air conditioners can be classified into fixed-

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TABLE I
THE COMMON METHODS FOR VOLTAGE REGULATION

	Operation	*Advantages*	*Disadvantage*
OLTC	OLTC adjusts the output voltage by changing transformer winding connections to modify the turn ratio. [5]	OLTC is suitable for moderate-scale voltage regulation with a relatively fast response. It can adequately adjust the voltage in high-renewable-energy systems.	Adjustment speed of OLTC is relatively slow and difficult to cope with rapid fluctuations from RESs. Mechanical switching may cause transient voltage fluctuations.
SVC	SVC controls reactive power output to influence system voltage. [6]	SVC provides fast response capability and can effectively regulate reactive power.	SVC is expensive, complex equipment and requires precise control.
STATCOM	STATCOM regulates current and power factor in real time and stabilizes the voltage. [7]	STATCOM provides stabilized reactive power, contributing to voltage regulation and system stability. It can provide auxiliary support for highly renewable energy systems.	STATCOM is expensive and needs to be synchronized with the distribution systems.
DERs	DERs like solar inverters and wind inverters can be adjusted output by the intelligent control system. [8]	DERs enable precise voltage regulation, suitable for localized control. DER effectively adapts to voltage fluctuations in highly renewable energy systems.	DERs are susceptible to weather, require reliable control strategies, and have limited regulation capacity.
DR	DR regulates demand-side load consumption to balance power supply and consumption. [9]	DR can rapidly regulate demand-side loads to cope with fluctuations from RESs in the distribution system and enhance voltage stability. Demand-side resources are small in capacity and large in scale. It can provide a significant amount of auxiliary regulation capacity to the distribution system.	How to efficiently cluster control demand-side loads remains a major challenge.

frequency air conditioners and inverter air conditioners (IACs) based on the compressor's operation mode and energy-efficient control technology. IACs are gradually replacing traditional fixed-frequency air conditioners with their high energy efficiency, temperature consistency, low noise levels, and accuracy of temperature control. Hua *et al.* [14] proposed an IACs scheduling strategy to participate in voltage regulation in distribution systems. This method allows the IAC to offer advantages in respect of energy efficiency, comfort, and accurate control. Therefore, IACs are ideally matched for distribution systems voltage regulation [15]. Although existing research has demonstrated the great potential of adjustable IACs for DR, most of them are still based on simulation and lack field demonstrations [16].

To bridge this experimental validation gap, this study conducted hardware-in-the-loop (HIL) experiments with a real time digital simulator (RTDS) device and the load control system. A realistic IAC is selected to provide auxiliary regulation services to the distribution systems. To verify the effectiveness of DR, we analyze the relationship between node voltage fluctuations and variations of IACs based on voltage sensitivity matrices. By controlling the operating mode of IACs, the load control system can adjust the active and reactive power output of the IAC. Through HIL experimental verification, we confirm the efficacy of this approach in maintaining voltage stability. These findings provide valuable insights and guidance for future intelligent development and sustainable integration of energy in distribution systems.

The remainder of this paper is organized as follows. Section II models the voltage regulation method. Section III describes the proposed HIL platform. Section IV describes the experiments and analyzes the outcomes of the experiments. Section V concludes this paper.

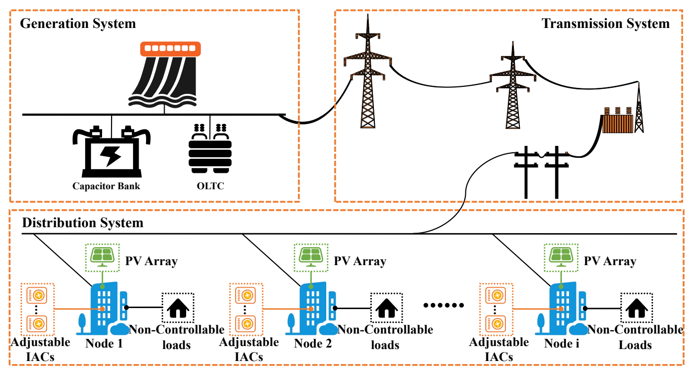


Fig. 2. The structure of modern power systems.

II. VOLTAGE CONTROL IN DISTRIBUTION SYSTEM WITH ANCILLARY SERVICES FROM IACS

Fig. 2 shows a modern power systems structure, including the generation system, the transmission system, and the distribution system. This research focuses on the voltage problem in the distribution system. There are distributed PV and demand-side resources in the distribution system. Demand-side resources consist of adjustable IACs and non-controllable loads.

A. Modelling of IACs

The change in output power of the IAC is realized by dynamically adjusting the compressor operating frequency. IAC controls the operation by adjusting the compressor's rotational frequency. When indoor temperature needs regulation, the frequency increases to engage the compressor, generating cooling or heating effects. As the room temperature nears the setting temperature, the frequency decreases or stops to save energy and achieve precise control. This modulation prevents frequent starts/stops, enhancing efficiency and longevity. The

IAC's operating state $S_{\text{IAC}}(t)$ and IAC's operating frequency $f_{\text{IAC}}(t)$ at time t as follows:

$$S_{\text{IAC}}(t)=\begin{cases} S_{\text{cool}}(t), & T_{\text{A}(t)}>T_{\text{set}}(t)+T_{\text{hy}}(t),\\ S_{\text{styb}}(t), & T_{\text{A}(t)}\le T_{\text{set}}(t)+T_{\text{hy}}(t),\end{cases}$$
$$f_{\text{IAC}}(t)=\begin{cases} f_{\text{cool}}(t), & S_{\text{cool}}(t),\\ f_{\text{styb}}(t), & S_{\text{styb}}(t),\end{cases} \tag{1}$$

where $S_{\text{styb}}(t)$ is IAC's standby state; $S_{\text{cool}}(t)$ is IAC's cooling state; $f_{\text{styb}}(t)$ is IAC's operating frequency in standby state; $f_{\text{cool}}(t)$ is IAC's operating frequency in cooling state; $T_{\text{set}}(t)$ is the setting temperature of the IAC in a room; $T_{\text{A}}(t)$ is the temperature of the room; $T_{\text{hy}}(t)$ is temperature set lag width. Temperature set lag width $T_{\text{hy}}(t)$ is the maximum deviation between the room temperature $T_{\text{A}}(t)$ and the setting temperature $T_{\text{set}}(t)$.

Based on previous studies [17], the active power consumption of the IAC can be expressed as follows:

$$P_{\text{IAC}}(t)=\mu\Delta f_{\text{IAC}}(t)(1-e^{-t/T_{\text{c}}})+P_{\text{IAC}}(t-1), \tag{2}$$

where P_{IAC} is the active power of the IAC; f_{IAC} is the operating frequency of the IAC; μ is the constant coefficient of the IAC; T_{c} is the time constant of the IAC's compressor. Reactive power regulation of the IAC is impacted by the power factors of the compressor. The reactive power consumption of the IAC can be expressed as follows:

$$Q_{\text{IAC}}(t)=\sqrt{(\tfrac{P_{\text{IAC}}(t)}{\cos\phi})^2-(P_{\text{IAC}}(t))^2}, \tag{3}$$

where Q_{IAC} is the reactive power of the IAC; ϕ is the phase deviation between the voltage and current of the IAC; $\cos\phi$ is the power factor of the IAC.

The status of IAC changes from standby state $S_{\text{styb}}(t)$ to cooling state $S_{\text{cool}}(t)$ when the room temperature is over the maximum temperature limit $(T_{\text{set}}(t)+T_{\text{hy}}(t))$. The status of IAC changes from cooling state $S_{\text{cool}}(t)$ to standby state $S_{\text{styb}}(t)$ when the room temperature is below the temperature limit $(T_{\text{set}}(t)+T_{\text{hy}}(t))$. The relationship between active power $P_{\text{IAC}}(t)$ and reactive power $Q_{\text{IAC}}(t)$ of IAC and the operating state of IAC at time t as follows:

$$P_{\text{IAC}}(t)=\begin{cases} P_{\text{cool}}(t), & S_{\text{cool}}(t),\\ P_{\text{styb}}(t), & S_{\text{styb}}(t),\end{cases}$$
$$Q_{\text{IAC}}(t)=\begin{cases} Q_{\text{cool}}(t), & S_{\text{cool}}(t),\\ Q_{\text{styb}}(t), & S_{\text{styb}}(t),\end{cases} \tag{4}$$

where $P_{\text{cool}}(t)$ is the active power of the IAC in cooling state; $P_{\text{styb}}(t)$ is the active power of the IAC in standby state; $Q_{\text{cool}}(t)$ is the reactive power of the IAC in cooling state; $Q_{\text{styb}}(t)$ is the reactive power of the IAC in standby state.

The active power $\mathbf{P}_{\text{IACs}}$ and reactive power $\mathbf{Q}_{\text{IACs}}$ of all the IACs in the campus at time t can be expressed as follows:

$$\begin{cases} \mathbf{P}_{\text{IACs}}(t)=[\sum\limits_{j\in\mathcal{J}}P_{\text{IAC}}^{1,j}(t),\sum\limits_{j\in\mathcal{J}}P_{\text{IAC}}^{2,j}(t),...,\sum\limits_{j\in\mathcal{J}}P_{\text{IAC}}^{i,j}(t)]^{\text{T}},\\ \mathbf{Q}_{\text{IACs}}(t)=[\sum\limits_{j\in\mathcal{J}}Q_{\text{IAC}}^{1,j}(t),\sum\limits_{j\in\mathcal{J}}Q_{\text{IAC}}^{2,j}(t),...,\sum\limits_{j\in\mathcal{J}}Q_{\text{IAC}}^{i,j}(t)]^{\text{T}},\end{cases} \tag{5}$$

where i is the node number of distribution system, $\forall i\in\mathcal{I}$; $\mathcal{I}$ is the sets of the node; j is the IAC number in each node, $\forall j\in\mathcal{J}$; $\mathcal{J}=[1,2,3,...,J-1,J]$ is the sets of IAC in each node; J is the total number of IAC in each node;

B. Modelling of Voltage Regulation in Distribution Systems

The voltage sensitivity matrix plays an important role in distribution system power flow analysis [18]. It can be used to calculate how voltages at different nodes change when external conditions or loads are altered, helping predict the distribution system's response. The voltage relationship between the different nodes of the distribution system is as follows:

$$\begin{aligned}\begin{bmatrix}\Delta\boldsymbol{\theta}\\ \Delta\mathbf{U}\end{bmatrix}&=\mathbf{J}^{-1}\begin{bmatrix}\Delta\mathbf{P}_{\text{dist}}\\ \Delta\mathbf{Q}_{\text{dist}}\end{bmatrix}\\ &=\begin{bmatrix}\mathbf{S}_{\text{P}\theta} & \mathbf{S}_{\text{Q}\theta}\\ \mathbf{S}_{\text{PU}} & \mathbf{S}_{\text{QU}}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{P}_{\text{dist}}\\ \Delta\mathbf{Q}_{\text{dist}}\end{bmatrix},\end{aligned} \tag{6}$$

where $\Delta\boldsymbol{\theta}$ is the change of phase angle at each node in the system; $\Delta\mathbf{U}$ is the change of phase angle at each node in the system; $\Delta\mathbf{P}_{\text{dist}}$ is the disturbance of active power at each node in the system; $\Delta\mathbf{Q}_{\text{dist}}$ is the disturbance of reactive power at each node in the system; $\mathbf{J}$ is the jacobian matrix; $\mathbf{S}_{\text{P}\theta}$ is the phase angle sensitivity of active power; $\mathbf{S}_{\text{Q}\theta}$ is the phase angle sensitivity of reactive power; $\mathbf{S}_{\text{PU}}$ is the voltage sensitivity of active power; $\mathbf{S}_{\text{QU}}$ is the voltage sensitivity of reactive power.

As shown in Fig. 2, the voltage in the distribution system is correlated with the RESs and loads. PVs are selected as RESs in this research. The power fluctuation of PV is the disturbance of the distribution system. The relationship is as follows:

$$\begin{cases} \mathbf{P}_{\text{dist}}(t)=\mathbf{P}_{\text{RESs}}(t)-\mathbf{P}_{\text{loads}}(t),\\ \mathbf{Q}_{\text{dist}}(t)=\mathbf{Q}_{\text{RESs}}(t)-\mathbf{Q}_{\text{loads}}(t),\end{cases} \tag{7}$$

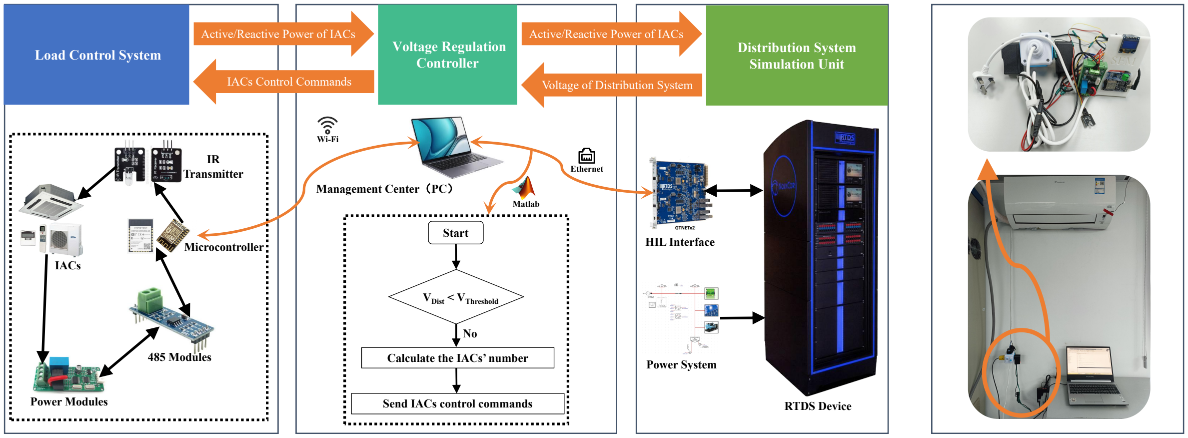
where $\mathbf{P}_{\text{RESs}}$ is the active power support by RESs; $\mathbf{Q}_{\text{RESs}}$ is the reactive power support by RESs; $\mathbf{P}_{\text{loads}}$ is the active power of all the demand-side resources in the system; $\mathbf{Q}_{\text{loads}}$ is the reactive power of all the demand-side resources in the system.

Assuming that the IACs of demand-side resources can participate in the voltage regulation for the above disturbance at time t. Here we separate the active load power $\Delta\mathbf{P}_{\text{loads}}$ and reactive load power $\Delta\mathbf{Q}_{\text{loads}}$ into two parts, as shown in Fig. 2. The first part is controllable part $\mathbf{P}_{\text{IACs}}$ and $\mathbf{Q}_{\text{IACs}}$. This part can be adjusted by adjusting the active power and reactive power of IACs. The second part is non-controllable loads. It is assumed that the disturbance is from the fluctuating output power of RESs due to the variable environment, and the available regulation service is from RESs and IACs. Therefore, the variational active power and reactive power of the distribution system can be calculated by:

$$\begin{cases} \Delta\mathbf{P}_{\text{RESs}}(t)=\Delta\mathbf{P}_{\text{IACs}}(t),\\ \Delta\mathbf{Q}_{\text{RESs}}(t)=\Delta\mathbf{Q}_{\text{IACs}}(t),\end{cases} \tag{8}$$

where

$$\begin{cases} \Delta\mathbf{P}_{\text{RESs}}=\mathbf{P}_{\text{RESs}}(t+1)-\mathbf{P}_{\text{RESs}}(t),\\ \Delta\mathbf{Q}_{\text{RESs}}=\mathbf{Q}_{\text{RESs}}(t+1)-\mathbf{Q}_{\text{RESs}}(t),\\ \Delta\mathbf{P}_{\text{IACs}}=\mathbf{P}_{\text{IACs}}(t+1)-\mathbf{P}_{\text{IACs}}(t),\\ \Delta\mathbf{Q}_{\text{IACs}}=\mathbf{Q}_{\text{IACs}}(t+1)-\mathbf{Q}_{\text{IACs}}(t).\end{cases} \tag{9}$$



(a) Platform structure. (b) Field demonstration.

Fig. 3. The hardware-in-the-loop platform structure and field demonstration.

Algorithm 1: Voltage regulation with ancillary services from IACs

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Input: System voltage $\mathbf{V}$.

Output: Active power of IACs $\mathbf{P}_{\text{IACs}}$, reactive power of IACs $\mathbf{Q}_{\text{IACs}}$.

if *Voltage does not exceed the setting threshold of* $0.0001 p.u.$ **then**

  Return $\mathbf{P}_{\text{IACs}}$ and $\mathbf{Q}_{\text{IACs}}$.

else

  while *No voltage fluctuation* **do**

    Calculate the $\mathbf{P}_{dist}$ and $\mathbf{Q}_{dist}$;

    Update the $\mathbf{P}_{\text{IACs}}$ and $\mathbf{Q}_{\text{IACs}}$;

    Return $\mathbf{P}_{\text{IACs}}$ and $\mathbf{Q}_{\text{IACs}}$.

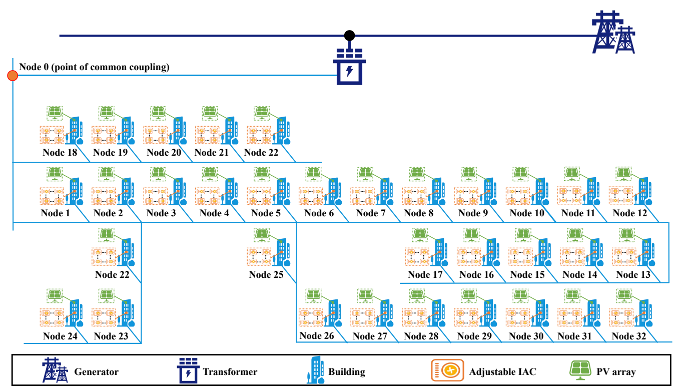


Fig. 4. A modified IEEE 33-node distribution system.

This study focuses on the voltage problem. Therefore, we make a variant for the above equation (6) for the voltage variation as follows:

$$\Delta\mathbf{U} = \begin{bmatrix} \mathbf{S}_{\text{PU}} & \mathbf{S}_{\text{QU}} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{P}_{\text{IACs}} \\ \Delta\mathbf{Q}_{\text{IACs}} \end{bmatrix}, \tag{10}$$

which can be re-written as:

$$[\mathbf{V}(t+1)] = [\mathbf{V}(t)] + \begin{bmatrix} \mathbf{S}_{\text{PU}} & \mathbf{S}_{\text{QU}} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{P}_{\text{IACs}} \\ \Delta\mathbf{Q}_{\text{IACs}} \end{bmatrix}, \tag{11}$$

where $\mathbf{V}$ is the voltage matrix of the distribution system; $\mathbf{V}(t+1)$ and $\mathbf{V}(t)$ are the voltage at time $t+1$ and t, respectively.

III. Hardware-in-the-Loop Platform Development

A hardware-in-the-loop platform is developed to verify the proposed method's effectiveness. The platform includes the distribution system simulation unit, the load control system, and the voltage regulation controller. Fig. 3(a) is the platform structure and Fig. 3(b) is the field demonstration.

A. Distribution System Simulation Unit

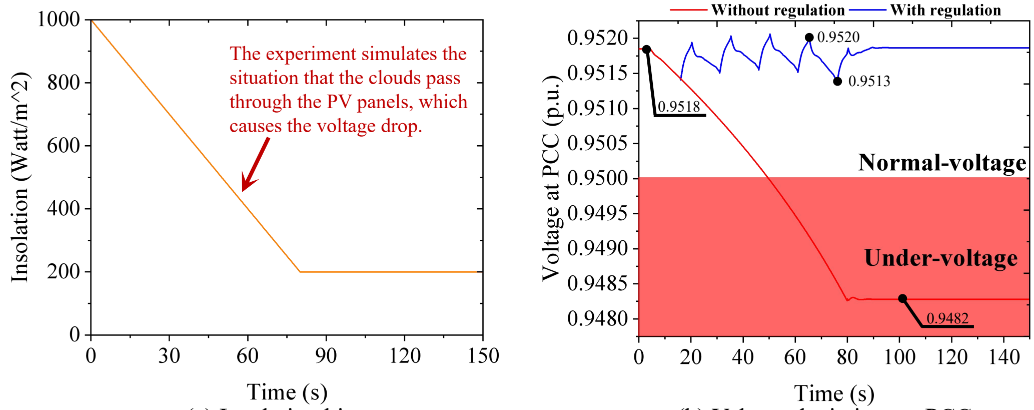
The distribution system simulation unit consists of RTDS. RTDS is a strong power system simulator that realistically reflects the operating status of the power system [19]. The RTDS provides a HIL interface to communicate with the computer. The HIL interface sends the real load data to the grid and obtains the real time operating status of the distribution system.

B. Load Control System

In order to better verify the effectiveness of the proposed method, a realistic IAC is installed to achieve hardware-in-the-Loop with RTDS. The load control system, as shown in Fig. 3, can adjust the operating status of the IAC and monitor the IAC's operating data in real time. Since the compressor of the IAC cannot be adjusted directly, the regulation method on this realistic IAC is limited to switching on/off or adjusting the set temperature and fan speed. We multiplexed the operating data of this IAC, which can be considered as various IACs in this experiment.

C. Voltage Regulation Controller

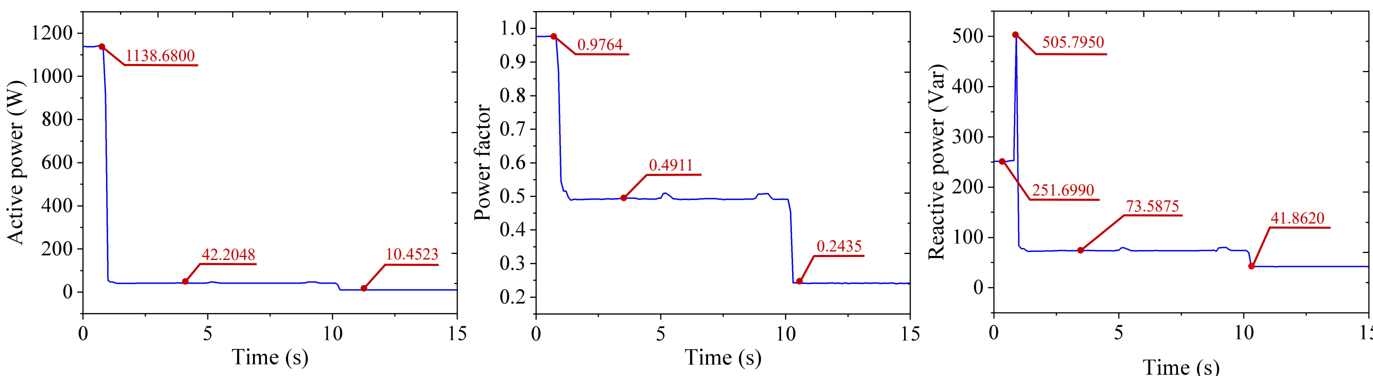
The voltage regulation controller makes a judgment based on the distribution system's voltage from the distribution system simulation unit. When the distribution system's voltage drops beyond the setting threshold, the voltage regulation controller will send the command to the load control system. The



(a) Insolation bias.

(b) Voltage deviations at PCC.

Fig. 5. The experiment results of clouds passing through the PV panels causing the distribution system's voltage drop.



(a) Active power variation.

(b) Power factor variation.

(c) Reactive power variation.

Fig. 6. Variation of IAC's power parameters.

load control system will dispatch the IAC to provide auxiliary regulation to the distribution system. The voltage regulation controller is developed based on Matlab. The pseudocode is shown in Algorithm 1.

IV. Case Study and Experiment

A. Experiment Setup

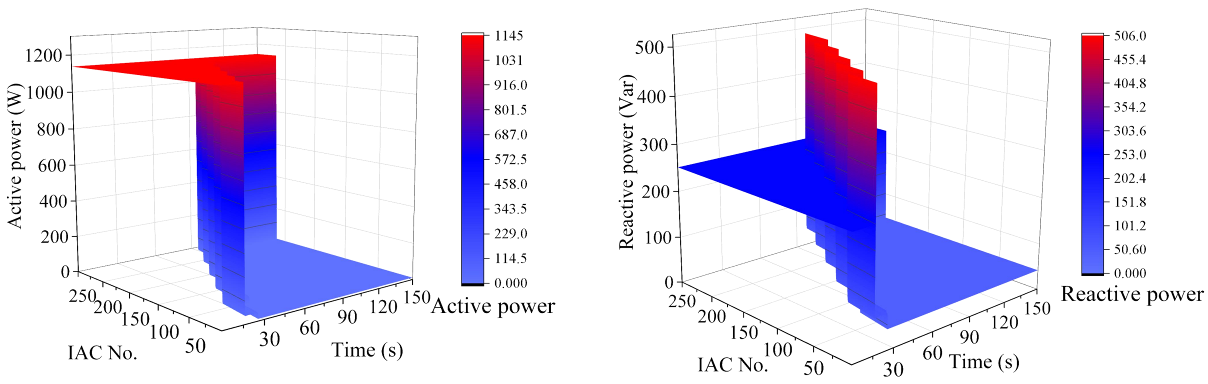
The voltage regulation experiment is carried out based on a modified IEEE 33-node distribution system, as shown in Fig. 4. The IEEE 33-node distribution system is a small-scale system for testing power distribution systems and is widely used in power distribution system research [20]. Node 0 is the point of common coupling (PCC), and the other nodes are all "PQ" nodes in the distribution system. Each "PQ" node in the system has 300 controllable IACs to provide voltage regulation for the distribution system. The power production capacity of the distribution system is set to 165 MW, of which 20 MW of power production capacity comes from PV power generation. Set the voltage range of the distribution system for normal operation is $[0.95, 1.05]$ p.u..

B. Result Analysis of Voltage Regulation

Fig. 5(a) shows the experiment results of clouds passing through the PV panels causing the distribution system's voltage drop. The insolation of the PV panel is dropped from 1000W/m^2 to 200W/m^2 in the 80s, as shown in Fig. 5(a). As shown in Fig. 5(b), the distribution system voltage is dropped from 0.9518 p.u. to 0.9482 p.u. if the system is without voltage regulation. In this situation, the distribution system voltage drops below the minimum limit of $0.95p.u.$ will cause the system fault. The proposed method can keep the voltage fluctuation within $[0.9513, 0.9520]$ p.u. to ensure that the system is in a safe condition. The maximum deviation in the case with voltage regulation is 0.0005 p.u. while the maximum deviation in the case without voltage regulation is 0.0036 p.u.. The proposed method ensures that the voltage operates within the safe zone and reduces the maximum voltage fluctuation by 86.12% compared to the case without voltage regulation.

C. Analysis of IACs Variation

The load control system in the hardware-in-the-loop platform can send the control commands and collect the variation of the IAC during the regulation process. The IAC is adjusted from the operating temperature of 20 °C and fan speed 3 to the operating temperature of 30 °C and fan speed 1, respectively. When the IAC receives the control command, the active power of the IAC changes from 1138.68 W to 42.20 W and finally stabilizes at 10.45 W, as shown in Fig. 6(a). The power factor of the IAC changes from 0.98 to 0.50, finally stabilizing at 0.24, as shown in Fig. 6(b). Due to the unsynchronized decreasing rate of active power and power factor in IAC, the reactive power will first rise and then drop (i.e., the pulse), as



(a) Active power deviations of each IACs.

(b) Reactive power deviations of each IACs.

Fig. 7. Power deviations of each IAC.

shown in Fig. 6(c). Fig. 7 shows the variation of active and reactive power of the 300 IACs during the whole experiment.

V. Conclusion

With more and more distributed RESs connected to the distribution system, the structure of the current power system is transformed. RESs will bring voltage stability and quality problems to the distribution system due to the intermittent and uncertain characteristics. This article analyzes the relationship between demand-side resources and node voltages through the voltage sensitivity matrix. Then a method is proposed to provide auxiliary regulation capability to the distribution system by changing the operating state of the IAC's operation. The proposed method is validated by designing HIL experiments combining RTDS with realistic IAC. The experimental results show that the voltage operates within the safe zone and reduces the maximum voltage fluctuation by 86.12% compared to the case without voltage regulation. This article provides valuable insights and guidance for future intelligent development and sustainable integration of energy in distribution systems.

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