Equivalent Modeling of Inverter Air Conditioners for Providing Frequency Regulation Service

Hongxun Hui, *Student Member, IEEE*, Yi Ding, *Member, IEEE*, and Menglian Zheng

***Abstract*—The frequency regulation service (FRS) is playing an increasingly important role in maintaining the power balance between generation and consumption. Moreover, the recent progress in information and communication technologies has enabled residential customers to participate in FRS through direct control over appliances, such as inverter air conditioners (ACs), whose market share is growing rapidly and has made up a large fraction of electricity consumption. Inverter ACs can change compressor's speed continuously to adjust operating power and provide FRS for the system operation. In this paper, the thermal model of a room and the electrical model of an inverter AC for providing FRS are developed. The model of the inverter AC is equivalent to a generator. In this manner, the aggregation of inverter ACs can be controlled just as traditional generators. Besides, a stochastic allocation method of the regulation sequence among inverter ACs is proposed to reduce the effect of FRS on customers. A hybrid control strategy by taking into account the dead band control and the hysteresis control is also developed to reduce the frequency fluctuations of power systems. The effectiveness of the proposed models and control strategies is illustrated in the numerical studies.**

***Index Terms*—Frequency regulation service (FRS), hysteresis control, inverter air conditioner (AC), stochastic allocation method.**

Nomenclature

AC	Air conditioner.
AT	Activation time [s].
DT	Duration time [s].
DSR	Demand-side resource.
FRS	Frequency regulation service.
PI	Proportional integral.
PFR	Primary frequency regulation.
SFR	Secondary frequency regulation.
Q_{gain}	Total heat gains of the room [kW].
Q_{AC}	Refrigerating capacity of the AC [kW].
Q_{dis}	Heat power from people, lights, appliances, and other disturbances [kW].
P_{AC}	Operating power of the inverter AC [kW].
f_{AC}	Operating frequency of the inverter AC [Hz].
T_O, T_A, T_{set}	Ambient temperature, indoor temperature, and set temperature of the inverter AC [°C].
T_{dev}	The deviation between the indoor temperature and the set temperature [°C].
T_c	Time constant of inverter AC's compressor [s].
ΔP_G	Regulation capacity of the generator [kW].
ΔP_{AC}	Regulation capacity of the inverter AC [kW].
Δf	The frequency deviation of the system [Hz].
β_i	The allocation coefficient of the regulation capacity among inverter ACs.
R	The speed droop parameter of PFR.
K	The integral gain of SFR.
H	The inertia of the generator.
K_D	The load-damping factor of the system.
F_{HP}	The power fraction of the high pressure turbine section.
T_g, T_r, T_t	Time constants of the speed governor, the reheat process, and the turbine [s].
$\Delta f_W^{\text{AC}i}$	Dead band of the frequency deviation [Hz].
$\kappa_P, \kappa_Q, \mu_P, \mu_Q$	Constant coefficients of the inverter AC.

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(Corresponding author: Yi Ding.)

H. Hui and Y. Ding are with the College of Electrical Engineering, Zhejiang University, Hangzhou, 310058, China (e-mail: huihongxun@zju.edu.cn; yiding@zju.edu.cn).

M. Zheng is with the College of Energy Engineering, Zhejiang University, Hangzhou, 310058, China (e-mail: menglian_zheng@zju.edu.cn).
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I. Introduction

The high penetration of intermittent renewables and the increasing severe contingencies of generation, transmission, and distribution infrastructures have led to more fluctuations faced by current power systems [1]. For example, the bipolar locking of the ultrahigh voltage direct current transmission line in the East China Grid resulted in the system frequency decline by 0.41 Hz abruptly on September 9th, 2015 [2], and the large-scale blackout in Taiwan impacted 5.92 million customers on August 15th, 2017 [3]. Therefore, the FRS is becoming increasingly important by maintaining power balance between generation and consumption. Conventionally, FRS is provided by generators, such as thermal power generators [4]. However, traditional generators may be phased out in the future due to the constraint of the greenhouse gas emissions on a global scale, making the traditional generators insufficient to deal with the increasing requirements of FRS [5].

The information and communication technology has improved a lot over the past decades, and in the meantime smart home appliances become more popular, which make it easier for loads to be controlled directly to assist the system in maintaining balance [6], [7]. Loads can reduce/increase operating power to provide FRS when the system frequency drops/rises [8]. Moreover, the operating power of DSRs can be regulated rapidly, while the generator regulates its power generation through a series of processes, such as the speed governor process and the reheat steam turbine process, leading to a larger inertia compared with DSRs [9]. Meanwhile, customers can get benefits for their contributions to maintaining the system stability [10], [11]. Therefore, a number of studies are turning from supply side to demand side [12], [13]. For example, Benysek *et al.* [14] develop an application-ready control algorithm based on the stochastic and decentralized strategy to realize the load frequency control. A hybrid hierarchical control scheme of DSRs is developed to support FRS in [15] and [16].

Among common home appliances, such as lights, televisions, ACs, refrigerators, and water heaters, the ACs top the list of power consumption [17], [18]. A short time regulation of the operating power of the AC has little effect on the room temperature due to the heat preservation property [5]. Therefore, ACs are suitable and have huge potential to serve as DSR. Apart from regular fixed speed ACs, the market share of inverter ACs is expanding rapidly [19]. For example, the sale volume of inverter ACs in China has exceeded the regular fixed speed ACs [20]. The main difference of the regular and inverter ACs is the compressor, which is also the main power consumption component of the AC [21]. The regular AC's compressor operates in only two modes, i.e., ON or OFF mode. Therefore, the operating power of regular ACs can be approximated as switching between the rated power and zero. In contrast, the compressor's speed of the inverter AC can be adjusted continuously by changing the operating frequency, making it more flexible to adjust AC's operating power and follow FRS instructions [21].

Authors in [22] and [23] develop an inverter AC model based on the simulation method and experimental data, respectively. However, these two studies only focus on the physical model and do not consider the interaction between the ACs and power systems. Authors in [24] and [25] present an accurate mathematical model of ACs to provide FRS for power systems, while the model is based on regular ACs with fixed speeds. Besides, a control method considering customer's set temperature is proposed in [26] to dispatch regular ACs for providing balancing services for power systems, while this method is developed particularly for the AC and the system operator has to dispatch the generators and the ACs in two different ways.

In existing power systems, the FRS is mainly provided by traditional generators, such as thermal power generators [4], [9]. Many sophisticated control methods for these traditional generators have been developed [27]. For example, generators are equipped with speed governors to provide PFR with the proportional control method. Some generators are installed with synchronizers to participate in SFR with the integral control method [28]. However, the operation characteristics of the inverter AC are different from traditional generators. A major difference rests in that the inverter AC is not installed with speed governors or synchronizers. Some control methods for the inverter AC have been proposed such as changing the operating states (ON/OFF control method) [6] or adjusting the set temperatures to achieve adjustable operating power [5]. Although the above control methods for the generator and inverter AC have been developed in previous studies, the dispatching models of the generator and inverter AC are remarkably distinct. It is not yet clear how to dispatch generators and inverter ACs to provide FRS simultaneously by using the same set of the control system.

To address this issue, this paper develops a novel thermal and electrical model of the inverter AC, which is equivalent to a generator, so that the inverter AC can be controlled as a generator to provide FRS. In this manner, the existing control system for generators can send scheduling instructions to inverter ACs (similar as those sent to generators), making it more accessible for inverter ACs to participate in FRS. The main contributions of this paper are as follows.

1) A novel thermal and electrical model of the inverter AC for providing FRS is developed. Based on this model, the inverter AC can be controlled to change the operating power for providing FRS.
2) The model of the inverter AC is derived and equivalent to a traditional generator, including the control parameters and evaluation criteria. In this manner, the inverter AC can be scheduled and compatible with the existing control system.
3) A stochastic allocation method of the regulation sequence among inverter ACs is proposed to reduce the effect of FRS on customers. Besides, a hybrid control strategy by taking into account the dead band control and the hysteresis control is developed to reduce the frequency fluctuations of power systems.

The remaining of this paper is organized as follows. Section II develops the thermal and electrical model of the inverter AC considering providing FRS. The equivalent modeling of the inverter AC is developed in Section III. Section IV introduces the control strategies of aggregated inverter ACs. Numerical studies are presented in Section V. Finally, Section VI concludes this paper.

II. Thermal and Electrical Model of the Inverter AC Considering Providing FRS

A. Thermal Model of a Room

To study the operating characteristics of inverter ACs, it is necessary to develop the thermal model of a room. Some valid models have been built to describe the relationship between the room temperature and the thermal deviation [5], [22], which can be expressed as follows [26]:

$$c_A \rho_A V \cdot \Delta T_A = \int (\Delta Q_{\text{gain}} - \Delta Q_{\text{AC}}) \mathrm{d}t \tag{1}$$

$$\Delta Q_{\text{gain}} = (U_{O-A} A_S + c_A \rho_A V \xi)(\Delta T_O - \Delta T_A) + \Delta Q_{\text{dis}} \tag{2}$$

where Δ denotes the deviation of the parameters; c_A is the heat capacity of the air; ρ_A is the density of the air; V and A_S are the volume and the surface area of the room, respectively; T_A is the indoor temperature; Q_{gain} is the total heat gains of the room; Q_{AC} is the refrigerating capacity of the inverter AC; U_{O-A} and ξ are the heat transfer coefficient and air exchange times between the room and the ambience, respectively; T_O is the ambient temperature; and Q_{dis} is the heat power from people, lights, appliances, and other disturbances.

The thermal model can also be expressed in the frequency domain by the Laplace transform

$$c_A \rho_A V \cdot T_A(s)s = Q_{\text{gain}}(s) - Q_{\text{AC}}(s) \tag{3}$$

$$Q_{\text{gain}}(s) = (U_{O-A} A_S + c_A \rho_A V \xi) \times [T_O(s) - T_A(s)] + Q_{\text{dis}}(s) \tag{4}$$

where s is the Laplace operator.

B. Electrical Model of an Inverter AC Considering Providing FRS for Power Systems

The major differences between inverter ACs and regular fixed speed ACs are the frequency converter and the compressor. The regular AC's compressor only works in a fixed speed, while the inverter AC's compressor can change the speed continuously by adjusting the operating frequency. The operating power and refrigerating capacity are also regulated with the operating frequency, which can be expressed as

$$\Delta P_{\text{AC}} = \kappa_P \Delta f_{\text{AC}} (1 - e^{-t/T_c}) \tag{5}$$

$$\Delta Q_{\text{AC}} = \kappa_Q \Delta f_{\text{AC}} (1 - e^{-t/T_c}) \tag{6}$$

where P_{AC} and Q_{AC} are the operating power and refrigerating capacity of the inverter AC, respectively; f_{AC} is the operating frequency of the inverter AC; κ_P and κ_Q are the constant coefficients of the inverter AC; and T_c is the time constant of the compressor. The electrical model can also be expressed in the frequency domain [22]

$$P_{\text{AC}}(s) = \frac{\kappa_P}{T_c s + 1} f_{\text{AC}}(s) + \mu_P \tag{7}$$

$$Q_{\text{AC}}(s) = \frac{\kappa_Q}{T_c s + 1} f_{\text{AC}}(s) + \mu_Q \tag{8}$$

where μ_P and μ_Q are the constant coefficients of the inverter AC. Therefore, the relationship between the operating power and the refrigerating capacity can be described as

$$Q_{\text{AC}}(s) = \frac{\kappa_Q}{\kappa_P} P_{\text{AC}}(s) + \frac{\kappa_P \mu_Q - \kappa_Q \mu_P}{\kappa_P}. \tag{9}$$

The operating frequency of the inverter AC is mainly based on the gap between the set temperature and the current room temperature, which can be expressed as

$$\Delta f_{\text{AC}}(s) = C(s) \cdot \Delta T_{\text{dev}}(s) \tag{10}$$

$$\Delta T_{\text{dev}}(s) = \Delta T_A(s) - \Delta T_{\text{set}}(s) \tag{11}$$

where $C(s)$ is the temperature controller of the inverter AC and T_{dev} is the deviation between the indoor temperature T_A and the set temperature T_{set}.

PI controller is a conventional classical control method adopted by inverter ACs, which can meet the control requirement simply and effectively. The PI controller can be described as [29]

$$C(s) = \theta + \eta / s \tag{12}$$

where θ and η are the constant coefficients of the controller.

In the time domain, the operating frequency of the inverter AC can be expressed as

$$\Delta f_{\text{AC}} = \theta \cdot \Delta T_{\text{dev}} + \eta \cdot \int \Delta T_{\text{dev}} \text{d}t. \tag{13}$$

If the inverter AC provides FRS for power systems, the AC's operating frequency will also be influenced by the system frequency, which can be described as

$$\Delta f_{\text{AC}}(s) = C(s) \cdot \Delta T_{\text{dev}}(s) + D(s) \cdot \Delta f(s) \tag{14}$$

where Δf is the frequency deviation of the power system and $D(s)$ is the controller of the inverter AC for participating in FRS.

In the time domain, the operating frequency can be expressed as

$$\Delta f_{\text{AC}} = \theta \cdot \Delta T_{\text{dev}} + \eta \cdot \int \Delta T_{\text{dev}} \text{d}t + \delta \cdot \Delta f + \gamma \cdot \int \Delta f \text{d}t. \tag{15}$$

From (5) and (15), the operating power of the inverter AC can be expressed as

$$\Delta P_{\text{AC}} = \kappa_P (1 - e^{-t/T_c})(\theta \cdot \Delta T_{\text{dev}} + \eta \cdot \int \Delta T_{\text{dev}} \text{d}t + \delta \cdot \Delta f + \gamma \cdot \int \Delta f \text{d}t). \tag{16}$$

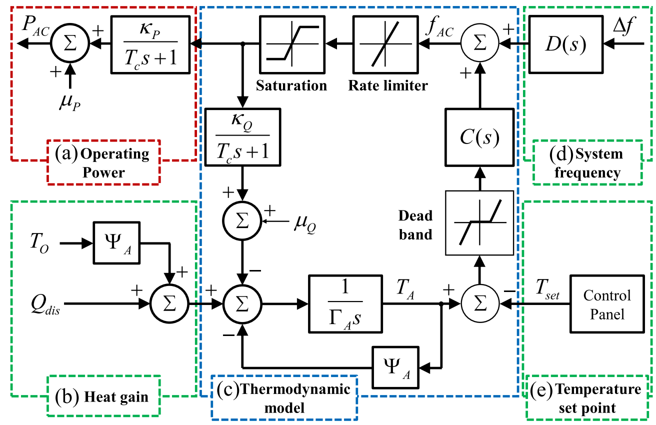

Fig. 1. Thermal and electrical model of the inverter AC.

C. Analysis of the Thermal and Electrical Model

The above thermal and electrical model can be derived as shown in Fig. 1, where Γ_A and Ψ_A equal to $(c_A \rho_A V)$ and $(U_{O-A} A_S + c_A \rho_A V \xi)$, respectively. The model is divided into five portions. Portion (c) is the main body of this model and all the other four portions connect with it. The dead band of the temperature gap is set to prevent the operating frequency from adjusting too frequently under tiny perturbations. The rate limiter is set to limit the adjusting speed of the compressor to

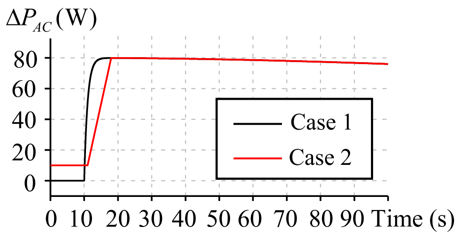

Fig. 2. Analysis of the inverter AC's response speed in the time domain.

ensure its safety. Besides, the deviation range of the operating frequency is limited in the saturation function.

Portions (b), (d), and (e) in this model can affect the operating power of the inverter AC. Portion (b) is the heat source of the model, which includes the transferred heat through the room envelope, the exchanged heat through the gaps of the doors or windows and the radiated heat from people or appliances. Portion (e) is the expected comfortable temperature of the customer, which can be adjusted through the remote control panel. Portion (d) is the additional signal for the inverter AC to participate in FRS. When the system frequency decreases, the inverter AC's operating frequency will also decrease to cut down the operating power and assist the recovery of the system frequency. Deviations in the above three portions will finally affect the operating power in Portion (a).

Fig. 2 shows the analysis of the inverter AC's response speed in the time domain. It is assumed that the system frequency deviates from the rated value abruptly and the Δf is regarded as a step signal. The desired response speed is shown in Case 1. However in fact, the adjusting speed of the compressor is limited by the rate limiter to ensure its safety, which is considered in Case 2. It can be seen that ΔP_{AC} increases rapidly and reaches the maximum value within 10 s.

As for the response time for PFR, the Union for the Co-ordination of Transmission of Electricity in Europe [30], [31] requires that the generator should reach the required value within 30 s. Moreover, SFR should start to respond within 30 s and reach the required value within 15 min. Therefore, the FRS provided by the inverter AC can meet the requirements of the response time.

III. Equivalent Modeling of Inverter ACs for Providing FRS

A. Equivalent Modeling of Inverter ACs

This paper takes reheat steam generators as an example to analyze the characteristics of FRS [9]. The power–frequency regulation model of the reheat steam generator can be expressed as

$$\Delta P_G(s) = -\frac{(1/R + K/s)(F_{\mathrm{HP}} T_r s + 1)}{(T_g s + 1)\,(T_t s + 1)\,(T_r s + 1)} \Delta f(s) \quad (17)$$

where R is speed droop parameter of PFR; K is the integral gain of SFR; F_{HP} is the power fraction of the high pressure turbine section; and T_g, T_r, and T_t are the speed governor time constant, reheat time constant, and turbine time constant, respectively.

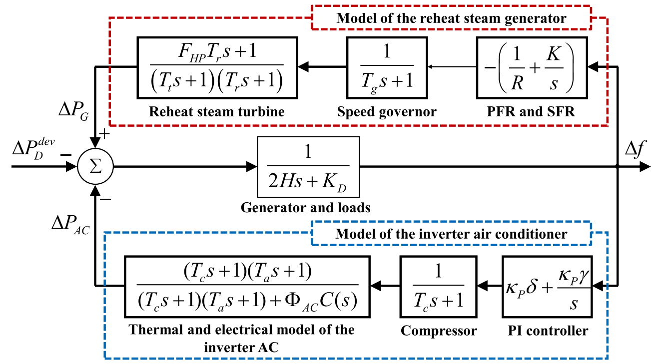

Fig. 3. Frequency regulation model of the system.

From (1) to (16), the operating power deviation of the inverter AC can be derived as

$$\Delta P_{\mathrm{AC}}(s) = \frac{\kappa_P\,(\Gamma_A s + \Psi_A)\,(D(s)\Delta f(s) + C(s)\Delta T_{\mathrm{set}}(s))}{(T_c s + 1)(\Gamma_A s + \Psi_A) + \kappa_Q C(s)} + \frac{\kappa_P C(s)\,(\Psi_A \Delta T_O(s) + \Delta Q_{\mathrm{dis}}(s))}{(T_c s + 1)(\Gamma_A s + \Psi_A) + \kappa_Q C(s)} \quad (18)$$

where the operating power deviation ΔP_{AC} is affected by four factors: the system frequency deviation Δf, the set temperature deviation ΔT_{set}, the ambient temperature deviation ΔT_O, and the radiated heat deviation ΔQ_{dis}. Generally, the DT of the FRS process is short (within 30 s) [30], [31]. Therefore, the ambient temperature and the radiated heat can be assumed as invariable. When the inverter AC system enters a stable operating state, the set temperature is fixed, unless the customer adjusts the set value exactly at the time interval when the inverter AC is providing FRS. To sum up, considering the short FRS time, the three deviations ΔT_{set}, ΔT_O, and ΔQ_{dis} can be omitted with regard to a stable operating inverter AC. Therefore, the ΔP_{AC} can be simplified to

$$\Delta P_{\mathrm{AC}}(s) = \frac{\kappa_P D(s)(T_a s + 1)}{(T_c s + 1)(T_a s + 1) + \Phi_{\mathrm{AC}} C(s)} \Delta f(s) \quad (19)$$

where T_a and Φ_{AC} equal to (Γ_A/Ψ_A) and (κ_Q/Ψ_A), respectively.

If the frequency regulation strategy of the inverter AC is the same with generators, the function $D(s)$ can be described as

$$D(s) = \delta + \gamma/s \quad (20)$$

where δ and γ are the constant coefficients of the controller.

As shown in Fig. 3, the power generation of generators and the power consumption of inverter ACs both are related to the system frequency. When the system frequency decreases, the generator will increase power generation, while the inverter AC will decrease operating power. Both adjustments contribute to the stability of the system frequency.

Fig. 4 shows the Bode diagram of the power system before and after considering the FRS provided by inverter ACs. The phase margin and gain margin are two important parameters of the stability criteria in the Bode diagram. In Case 1, the FRS is provided only by generators, where the phase margin and the gain margin are 51° and 27.9 dB, respectively. In Case 2, the

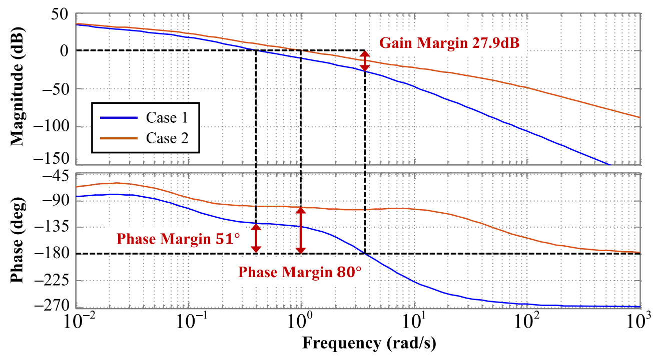

Fig. 4. Bode diagram for the frequency-domain analysis of the power system considering the FRS provided by inverter ACs.

FRS is provided by both generators and inverter ACs, where the phase margin widens to 80° and the gain margin is expanded toward infinity (here, the operating power of inverter ACs has no limitation). It indicates that the system's stability and frequency regulation ability get improved after the inverter ACs participating in FRS.

B. Equivalent Control Parameters

1) Equivalence of the PFR and SFR: Every generator can participate in PFR because all of them are equipped with speed governors [4]. The PFR is able to respond within 30 s [30] and mainly deals with random loads. The speed droop parameter of PFR is defined as R [9]. Correspondingly, the proportional controller $(\kappa_P \delta)$ in the inverter AC model is the equivalent regulation parameter to provide PFR.

However, the system frequency cannot recover the rated value only by PFR. Therefore, some generators are installed synchronizers to provide SFR. The integral coefficient of SFR is defined as K [4]. Correspondingly, the inverter AC can also provide SFR by the equivalent integral parameter $\kappa_P \gamma$.

2) Equivalence of the First-Order Inertia Element: The first-order inertia element exists in the two models, which are the speed governor in the generator model and the compressor in the inverter AC model, respectively. Due to the little inertia of the compressor, the time constant T_c is less than the time constant of the speed governor T_g. Therefore, the inverter AC can regulate the operating power more rapidly than traditional generators.

3) Equivalence of the Power Performing Component: The power performing component of the generator is the reheat steam turbine. Correspondingly, the inverter AC regulates the operating power by the thermal and electrical model, which can change the operating power temporarily without exceeding the customer's comfort temperature interval. The equivalent parameters are shown in Table I.

C. Equivalent Evaluation Parameters

1) Regulation Capacity: As shown in Fig. 5(a), the generator will increase the power generation when the system frequency decreases. The maximum regulation capacity can be expressed as $\Delta P_G^{\max}$. Similarly, the inverter AC will provide

TABLE I
EQUIVALENT PARAMETERS OF GENERATORS AND INVERTER ACS

Parameter	Generator	Inverter AC
Proportionality coefficient of PFR	$1/R$	$\kappa_P \delta$
Integral coefficient of SFR	K	$\kappa_P \gamma$
Time constant of the first-order inertia element	T_g	T_c
Power performing component	T_r, T_t , F_{HP}	T_c, T_a, Φ_{AC}
Regulation capacity	ΔP_{GP}	ΔP_{AC}
Activation time	AT_G	AT_{AC}
Delay time	DEL_G	DEL_{AC}

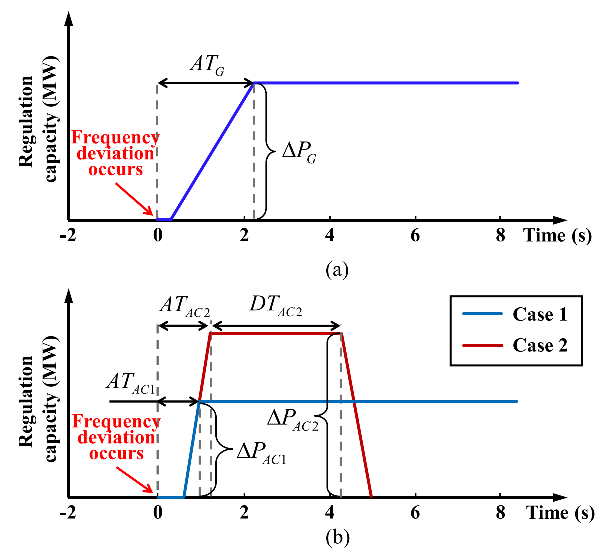

Fig. 5. Evaluation parameters for providing FRS. (a) Generator. (b) Inverter AC.

regulation capacity by decreasing the operating power when the frequency deviation occurs. From (1) to (9), the maximum regulation capacity of the inverter AC can be expressed as

$$\Delta P_{\mathrm{AC}}^{\max} = \kappa_P f_{\mathrm{AC}}^{\min} - \frac{\kappa_Q}{\kappa_P} \left[\Psi_A (T_O - T_A) + Q_{\mathrm{dis}} - \mu_Q\right]. \quad (21)$$

2) AT: The AT is the time interval from the occurrence moment of the frequency deviation to the moment when the regulation capacity reaches the maximum value. The AT is expressed as AT_G in the generator model and AT_{AC} in the inverter AC model.

As shown in Fig. 5(b), the activation time AT_{AC} and the regulation capacity ΔP_{AC} of the inverter AC are different in the two cases. Due to the limitation of the compressor's adjusting speed, a larger regulation capacity needs a longer AT.

3) DT: The additional power generation of the generator can last more than 15 min until reserve generators are dispatched to make up the shortage of power [30], [31]. Therefore, the FRS provided by generators can be assumed to continue for an infinite time.

Different from generators, the FRS provided by inverter ACs may not continue for a long time. If the operating power is adjusted widely, the room temperature will change rapidly and

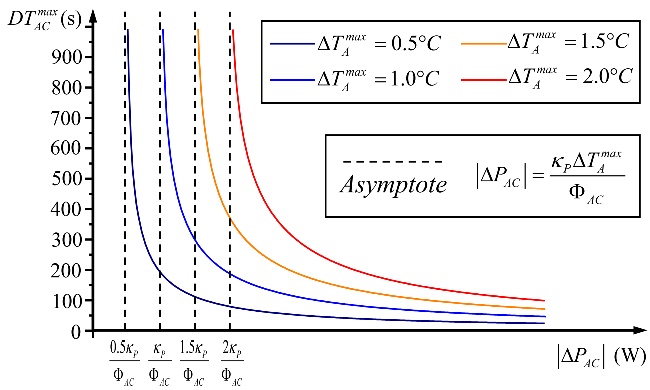

Fig. 6. Longest DT of the inverter AC.

reach the limitation of the comfortable temperature. Then, the inverter AC has to increase operating power to ensure the customer's comfort. Therefore, the duration time $DT_{\mathrm{AC}}^{\max}$ is defined to evaluate the relationship between the available regulation time and the regulation capacity ΔP_{AC}, which can be derived as

$$DT_{\mathrm{AC}}^{\max} = \begin{cases} +\infty & ,0 \le |\Delta P_{\mathrm{AC}}| \le \kappa_P \Delta T_A^{\max}/\Phi_{AC} \\ -T_a \cdot \ln\left(1 + \frac{\kappa_P \Delta T_A^{\max}}{\Phi_{\mathrm{AC}} \Delta P_{\mathrm{AC}}}\right) & ,\kappa_P \Delta T_A^{\max}/\Phi_{\mathrm{AC}} < |\Delta P_{\mathrm{AC}}| \le |\Delta P_{\mathrm{AC}}^{\max}| \end{cases} . \tag{22}$$

As shown in Fig. 6, the $DT_{\mathrm{AC}}^{\max}$ will be shorter with the increase of ΔP_{AC}. By contrast, the $DT_{\mathrm{AC}}^{\max}$ will be longer with the increase of the maximum allowable deviation of the room temperature $\Delta T_A^{\max}$.

IV. Control of Aggregated Inverter ACs for Providing FRS

A. Regulation Capacity Allocation Among Generators and Inverter ACs

The regulation capacity of one inverter AC is paltry for the system. Therefore, the inverter ACs are aggregated and equivalent as a traditional generator. The maximum regulation capacity of the aggregation can be calculated as

$$\Delta P_{\mathrm{AC}}^{\max} = \sum_{i=1}^{N} \Delta P_{\mathrm{AC}i}^{\max}. \tag{23}$$

Generally, the required regulation capacity of FRS (P_{RE}) is proportional to the loads in the system [4]. Each participant for FRS in the system will be allocated a certain proportion of the P_{RE}, which can be expressed as

$$P_{\mathrm{RE}} = \alpha_G P_{\mathrm{RE}} + \alpha_{\mathrm{AC}} P_{\mathrm{RE}} = \sum_{j=1}^{M} \alpha_{Gj} P_{\mathrm{RE}} + \sum_{i=1}^{N} \alpha_{\mathrm{AC}i} P_{\mathrm{RE}}$$
$$= \sum_{j=1}^{M} \Delta P_{Gj}^{\max} + \sum_{i=1}^{N} \Delta P_{ACi}^{\max} \tag{24}$$

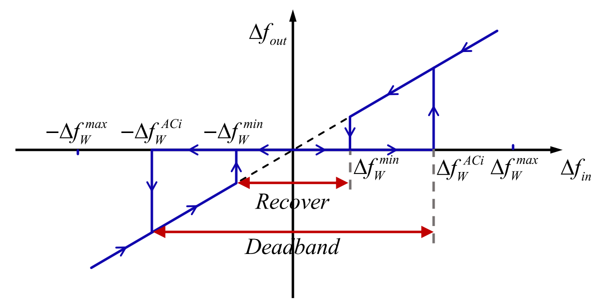

Fig. 7. Hybrid control strategy of the inverter AC for providing FRS.

where α_G and α_{AC} are the shares of P_{RE} provided by generators and inverter ACs, respectively. M and N are the number of generators and inverter ACs, respectively.

Generators can provide FRS by increasing power generation and last until the reserve generators are dispatched to make up the power shortage. However, inverter ACs will return to the original operating power when the system frequency recovers to the rated value. Therefore, the inverter ACs can mainly provide PFR, while SFR is still mainly provided by the generators. In order to avoid the capacity shortage of SFR, the maximum share of inverter ACs in the total regulation capacity should be limited to a safety threshold, which can be expressed as

$$\alpha_{AC} \le \chi\%. \tag{25}$$

B. Control Strategy of Inverter ACs

With increasing power system's frequency deviation, more inverter ACs should participate in FRS to provide more regulation capacity. The threshold value $\Delta f_W^{\mathrm{AC}i}$ is defined as the frequency deviation where the ith inverter AC starts to provide FRS. Each inverter AC's $\Delta f_W^{\mathrm{AC}i}$ is uniformly distributed in the range from $\Delta f_W^{\min}$ to $\Delta f_W^{\max}$, which produces the sequence of inverter ACs to provide FRS. It is obvious that no inverter AC provides FRS if the system frequency deviation is tiny and less than $\Delta f_W^{\min}$, while all the inverter ACs will provide FRS if the system frequency deviation is larger than $\Delta f_W^{\max}$.

As for an individual inverter AC, if the $\Delta f_W^{\mathrm{AC}i}$ is small, it will be in the front of the regulation sequence. In order to avoid a certain inverter AC always being at the forefront, each inverter AC's $\Delta f_W^{\mathrm{AC}i}$ is reset and generated randomly in each round of dispatch (every 15 min).

As shown in Fig. 7, the hybrid control strategy for inverter ACs takes into account the dead band control and the hysteresis control. The ith inverter AC selected by the abovementioned allocation method will start participating in FRS when the Δf exceeds $\pm\Delta f_W^{\mathrm{AC}i}$, while the inverter AC will withdraw from FRS when the Δf is returned to the range $\pm\Delta f_W^{\min}$.

C. Communication and Control Process of Inverter ACs

The communication of the system is shown in Fig. 8, where the signal sequence is labeled from 1 to 5. First, before the next round of dispatch, the system operator sends the regulation capacity shares, i.e., α_G and α_{AC}, to the generators and aggregated inverter ACs, respectively. Second, the aggregator

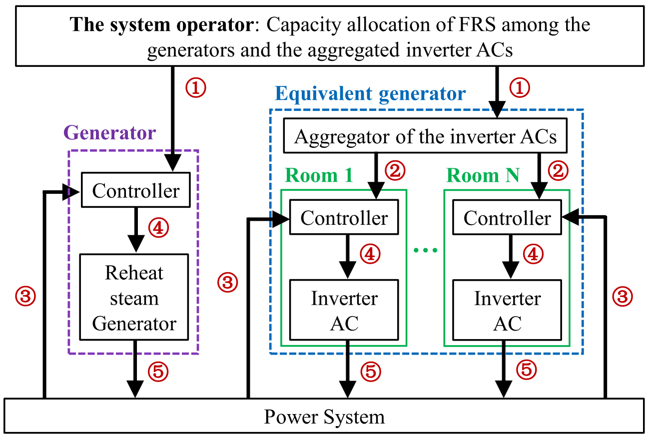

Fig. 8. Communication of the system.

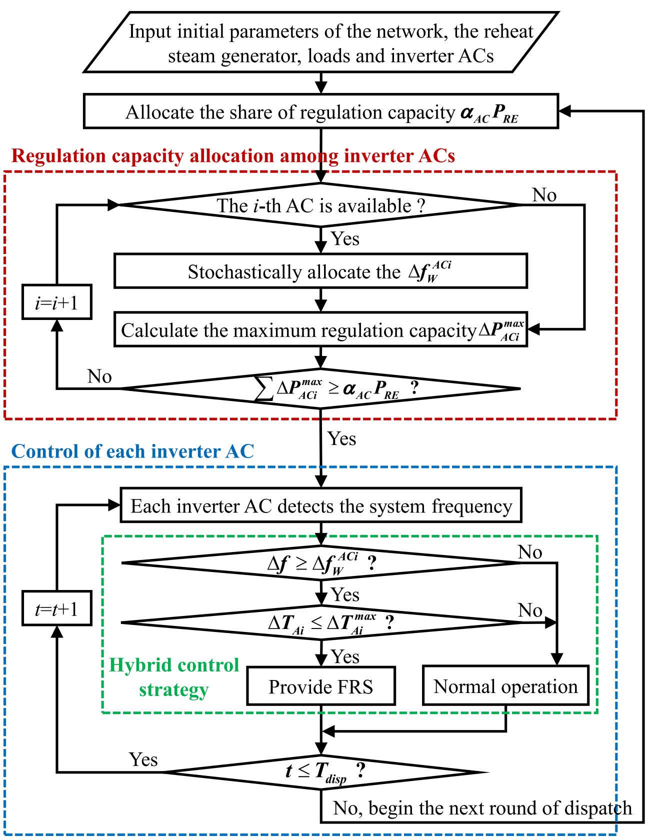

Fig. 9. Flowchart of the control process of inverter ACs.

will communicate with each inverter AC to determine whether it is available for the FRS. The threshold value of $\Delta f_W^{\mathrm{AC}i}$ will also be stochastically set in the controller between $\Delta f_W^{\min}$ and $\Delta f_W^{\max}$ for each available AC. Third, after the new round of dispatch starts, the controllers of the generators and inverter ACs will monitor the system frequency locally in real time. Fourth, if there is a frequency deviation, the controllers will send signals to the generators and inverter ACs to provide FRS. Finally, the power system's frequency will be regulated by the generators and inverter ACs.

As illustrated in Fig. 9, the control process of the inverter ACs can be divided into three steps.

1) The first step is the initialization of the system, where initial parameters of the network, the reheat steam generator, loads and inverter ACs are set. The share of the required regulation capacity is also allocated among generators and the aggregated inverter ACs.
2) The second step is the regulation capacity allocation among inverter ACs. The aggregator will communicate with each inverter AC to set the threshold value $\Delta f_W^{\mathrm{AC}i}$ for the available ACs. Besides, the aggregator will evaluate the maximum regulation capacity $\Delta P_{ACi}^{\max}$ and keep communicating with more inverter ACs until the total regulation capacity reaches the required value.
3) The third step is the control of each inverter AC. The system frequency is detected locally. If the system frequency deviation exceeds the threshold $\Delta f_W^{\mathrm{AC}i}$ and the room temperature is within the maximum allowable deviation $\Delta T_{Ai}^{\max}$, the inverter AC will adjust its operating power to provide FRS. Otherwise, the inverter AC will keep operating at the normal state. After the third step ends, the program will repeat Steps 1–3 for the next round of dispatch.

V. Case Studies

A. Test System

The test model adopts the power system in Fig. 3, which includes the reheat steam generator, conventional loads, and inverter ACs. The parameters of the temperature and the thermal model are based on the test data and the national standards in Hangzhou, China, on August 1st, 2015 [5]. The ambient temperature is 33 °C at 12:00 AM. The number of inverter ACs and corresponding rooms is 30 000. The living areas of these rooms are assumed to follow the normal distribution, where the mean value is $100\ \mathrm{m}^2$ and the standard deviation is $40\ \mathrm{m}^2$. The height of all the rooms is 2.5 m. The set temperatures of inverter ACs are distributed randomly between 22 and 26 °C to simulate different requirements of room temperature for various customers. The maximum allowable deviation of the room temperature $\Delta T_A^{\max}$ is 1 °C. Moreover, the frequency range of each inverter AC is 1–150 Hz. Time constant and the rate limiter of the compressor are 0.02 s and 10 Hz/s, respectively. The proportional gain θ and the integral gain η of the temperature controller are 0.52 Hz/°C and 0.032 Hz/(°C·s), respectively. The other controller, which connects the system frequency and the inverter AC's frequency, is set by the proportional parameter 200 and the integral parameter 0.02(1/s), respectively. Moreover, other constant parameters of the thermal model and electrical model are shown in Table II.

The generation capacity of the reheat steam generator is 800 MW [9]. The generator inertia H is 10. The load-damping factor K_D is 1. The speed governor time constant T_g, reheat time constant T_r, and turbine time constant T_t are 0.2, 7, and 0.3 s, respectively. The power fraction of the high pressure turbine section F_{HP} is 0.3. The speed droop parameter R and the integral gain K are 0.05 and 0.50, respectively [9].

TABLE II
CONSTANT PARAMETERS OF THE THERMAL MODEL AND ELECTRICAL MODEL

Symbols	Descriptions	Values	Units
c_A	Heat capacity of the air	1.005	$\mathrm{kJ/(kg \cdot {}^{\circ}C)}$
ρ_A	Density of the air	1.205	$\mathrm{kg/m^3}$
ξ	Air exchange times	0.50	$1/h$
U_{O-A}	Heat transfer coefficient	3.60	$\mathrm{W/(m^2 \cdot {}^{\circ}C)}$
Q_{dis}	Heat power of disturbances	0.43	kW
κ_P	Constant coefficient of the inverter AC's power	0.04	kW/Hz
κ_Q		0.12	kW/Hz
μ_P	Constant coefficient of the AC's refrigerating capacity	0.02	kW
μ_Q		-0.05	kW
Δf_W^{min}	The minimum dead band of the frequency deviation	0.01	Hz
Δf_W^{max}	The maximum dead band of the frequency deviation	0.03	Hz

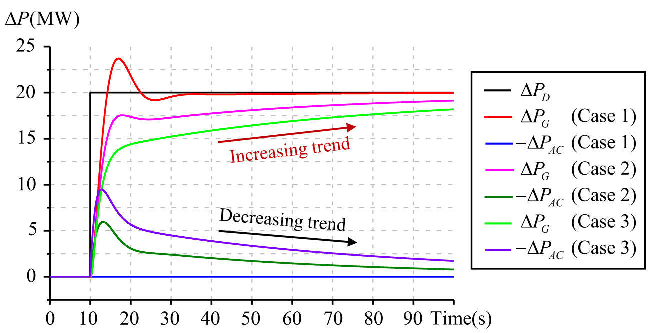

Fig. 10. Regulation power of the generator and inverter ACs in the underfrequency scenario.

It is assumed that the system operates in the normal state and maintains the rated frequency at 50 Hz. The initial load is around 560 MW and the required capacity for FRS is 80 MW. The maximum allowable share of FRS provided by inverter ACs is 50%, which is 40 MW. Three cases are simulated: all the required capacity of FRS (80 MW) is provided by the generator in Case 1, while 20 and 40 MW of the required capacity of FRS are provided by inverter ACs in Cases 2 and 3, respectively. The frequency deviation is assumed to occur at 12:00 AM, when 20-MW loads are abruptly added to the system in the underfrequency scenario and cut down in the overfrequency scenario, respectively.

B. Simulation Results

The simulation results of the power deviations are shown in Figs. 10 and 11, respectively. With the increasing share of inverter ACs in the FRS, the regulation power provided by inverter ACs becomes larger, while the corresponding regulation power provided by the generator becomes smaller. It illustrates that part of the regulation power can be supplied from inverter ACs in place of the generator, and thus, it shows that inverter ACs can be equivalent to the generator to provide FRS.

However, the regulation power provided by inverter ACs cannot last for a long time as the generator. As shown in Fig. 10, the regulation power of inverter ACs has a decreasing trend

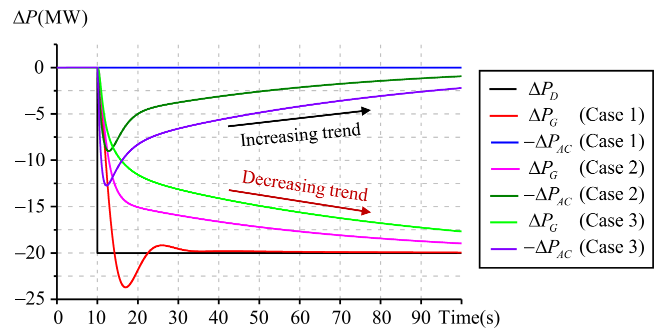

Fig. 11. Regulation power of the generator and inverter ACs in the overfrequency scenario.

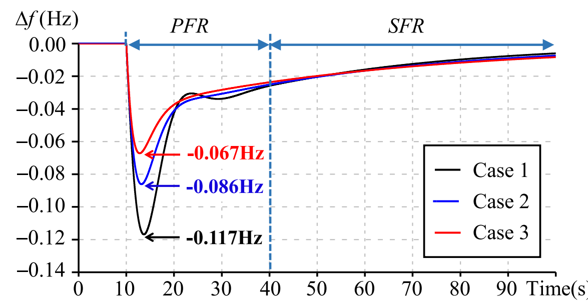

Fig. 12. Frequency deviation process in the underfrequency scenario.

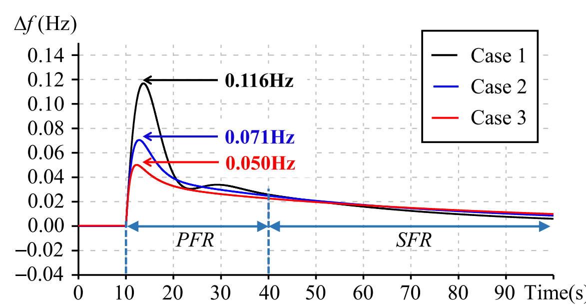

Fig. 13. Frequency deviation process in the overfrequency scenario.

after reaching the required maximum capacity, which indicates that the operating power of inverter ACs rises again and ACs return to the normal operation state along with the recovery of the system frequency. Around 90 s later, inverter ACs' regulation power will be close to zero. By contrast, the regulation power provided by the generator has an increasing trend and will finally compensate for the regulation capacity provided by inverter ACs.

The fluctuation processes of the frequency deviation are shown in Figs. 12 and 13, respectively. In the underfrequency scenario, the maximum frequency deviation decreases from 0.117 Hz in Case 1 to 0.067 Hz in Case 3, when half of the frequency regulation capacity is provided by inverter ACs. In order to explain this observation, some evaluation parameters are shown in Tables III and IV.

It can be seen from Tables III and IV that the total regulation powers $(|\Delta P_G^{\max}|+|\Delta P_{\mathrm{AC}}^{\max}|)$ in the three cases are almost the same. The AT of inverter ACs (AT_{AC}) is shorter than that of the generator (AT_G), where the AT_{AC} and AT_G are 3.19 and 7.95 s

TABLE III
SIMULATION RESULTS IN THE UNDERFREQUENCY SCENARIO

Cases	ΔP_G^{max} (MW)	AT_G (s)	ΔP_{AC}^{max} (MW)	AT_{AC} (s)	Δf_{max} (Hz)	RT (s)
Case 1	23.704	6.98	0	N/A	−0.117	24.87
Case 2	17.545	7.95	−5.956	3.19	−0.086	21.19
Case 3	13.116	8.32	−9.491	2.81	−0.067	16.90

TABLE IV
SIMULATION RESULTS IN THE OVERFREQUENCY SCENARIO

Cases	ΔP_G^{max} (MW)	AT_G (s)	ΔP_{AC}^{max} (MW)	AT_{AC} (s)	Δf_{max} (Hz)	RT (s)
Case 1	−23.703	6.97	0	N/A	0.116	24.80
Case 2	−15.045	7.68	9.006	2.80	0.071	19.35
Case 3	−11.955	8.75	12.745	2.27	0.050	12.94

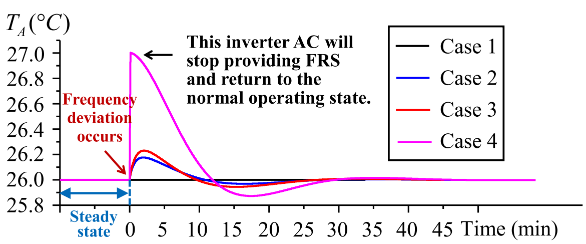

Fig. 14. Fluctuations of the room temperature in the underfrequency scenario.

in Case 2, respectively. It shows that inverter ACs can provide FRS more rapidly than the generator. The generator regulates its power generation through a series of processes, such as the speed governor process and the reheat steam turbine process, leading to a larger inertia compared with inverter ACs. Faced with the sudden power disturbance in power systems, the fast regulation speed is important and contributes to decreasing the frequency deviation.

The recovery time (RT) is defined as the time interval from the occurrence moment of the frequency deviation to the moment when the deviation is less than 0.06% of the rated frequency [32], which is mainly related to the regulation speed of the generator's power generation and the regulation speed of inverter ACs' power consumption. The RTs in the three cases are shorter than 30 s, which can meet the requirements of the RT in the practical power systems [30], [31].

Fig. 14 shows the fluctuations of the room temperature. As for the inverter ACs whose set temperatures are 26 °C, the maximum fluctuation of the corresponding room temperature is less than 0.25 °C, as shown in Fig. 14 (Cases 1, 2, and 3). Around 30 min later, the room temperature returns to the original set point, i.e., 26 °C. In the case that a certain room's temperature reaches the upper temperature limit during the process of providing FRS, the corresponding inverter AC will stop providing FRS and return to the normal operating state, as shown in Fig. 14 (Case 4). However, there would be few inverter ACs whose room temperatures reach the limit during the process of providing FRS, because the regulation period of FRS is short, and thus, the operation of inverter ACs is only interrupted in a short time.

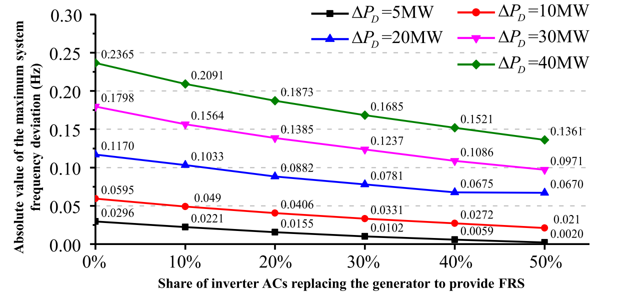

Fig. 15. Absolute value of the maximum system frequency deviation in the underfrequency scenario.

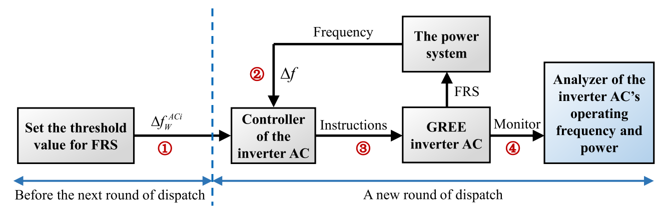

Fig. 16. Configuration of the experimental system.

Therefore, the service quality of the individual participants can be maintained.

More cases are simulated to verify the effectiveness of inverter ACs providing FRS. The initial parameters remain the same as the above three cases. The variable is the share of FRS provided by inverter ACs in the total required capacity (80 MW). Moreover, different deviations of loads (5, 10, 20, 30, and 40 MW) are considered, respectively.

The simulation results of the maximum frequency deviation are shown in Fig. 15. With the increasing of the sudden added loads, the frequency deviation becomes larger. Besides, inverter ACs can reduce the system frequency deviation by providing FRS. For example, the maximum frequency deviation decreases from 0.2365 to 0.1361 Hz under the same power deviation 40 MW.

C. Experimental Results

The experiment was developed on an inverter AC (GREE KFR-72LW/(72555)FNhAd-A3). The power supply voltage and rated frequency are 220 V and 50 Hz, respectively. The ambient temperature is 5 °C. The inverter AC operates in the heating mode and the set temperature is 26 °C.

As shown in Fig. 16, the threshold value $\Delta f_W^{\mathrm{AC}i}$ of the inverter AC to provide FRS is set on the controller before the next round of dispatch. When the new round of dispatch begins, the controller will keep monitoring the power system's frequency. If the system's frequency deviation Δf is larger than the threshold value $\Delta f_W^{\mathrm{AC}i}$, the controller will send instructions to the inverter AC to adjust the operating frequency of the compressor. The operating frequency and power of the inverter AC can be monitored by the analyzer, whose sampling time interval is 0.5 s.

Fig. 17 shows the relationship between the operating power and frequency of the inverter AC. It can be seen that the inverter

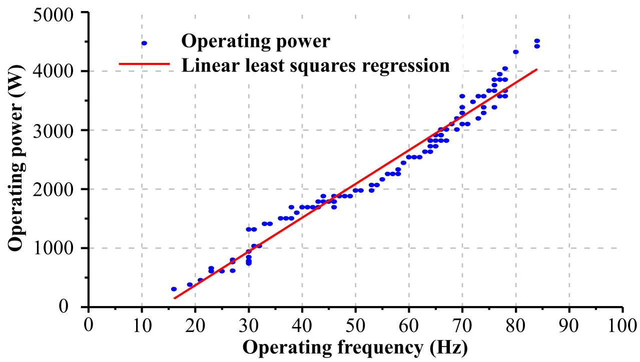

Fig. 17. Linear least squares regression of the inverter AC's operating power and frequency.

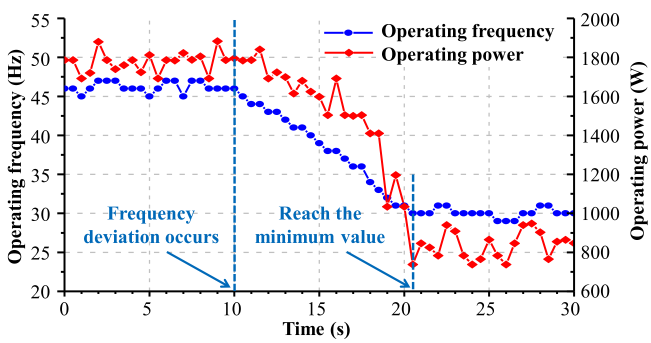

Fig. 18. Response process of the inverter AC for providing FRS.

AC's power is well fit with the operating frequency by the linear least squares approximation, where the slope is 57 W/Hz. Therefore, the inverter AC's operating power will rise/drop with the increase/decrease of its compressor's frequency. This observation verifies that the operating power of the inverter AC can be changed by adjusting the operating frequency of the compressor.

The threshold value $\Delta f_W^{\mathrm{AC}i}$ of the inverter AC is set to 0.01 Hz. The system's frequency deviation Δf is 0.05 Hz. The controller will send instructions to the inverter AC to adjust operating frequency of the compressor. As shown in Fig. 18, the compressor's operating frequency decreases from around 46 to 30 Hz, and the inverter AC's operating power also drops from around 1800 to 750 W. As shown in this experiment, the activation time AT_{AC} of the inverter AC as defined in this paper is 11 s, which can meet the requirements of the response time for FRS.

VI. Conclusion

This paper presented the aggregation of inverter ACs as a traditional generator to provide FRS for the system. A thermal model of a room and an electrical model of an inverter AC considering the participation of FRS were developed. Based on this model, the inverter AC is equivalent to a reheat steam generator, including equivalent transfer functions, control parameters, and evaluation criteria. In this manner, inverter ACs can be compatible with the existing control system and controlled just as traditional generators to provide FRS. A stochastic allocation method of the regulation sequence among inverter ACs was proposed to reduce the effect of FRS on customers. A hybrid control strategy, comprising the dead band control and hysteresis control, was also designed to reduce the frequency fluctuations of power systems. The simulation and practical results verified that the aggregation of inverter ACs can be equivalent to a generator to participate in FRS, while ensuring the requirement of customers' comfort. Besides, inverter ACs can be regulated more quickly, which makes up the generator's shortcoming on the regulation speed. The system stability gets enhanced when a certain share of FRS is provided by inverter ACs.

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Hongxun Hui (S'17) received the Bachelor's degree in electrical engineering from Zhejiang University, Hangzhou, China, in 2015, where he is currently working toward the Ph.D. degree in electrical engineering.

His research interests include smart grid, modeling and optimization of demand-side resources, and the power market.

Yi Ding (M'12) received the Bachelor's degree from Shanghai Jiaotong University, Shanghai, China, in 2000, and the Ph.D. degree from Nanyang Technological University, Singapore, Singapore, in 2007, both in electrical engineering.

He is a Professor with the College of Electrical Engineering, Zhejiang University, Hangzhou, China. His current research interests include power systems reliability/performance analysis incorporating renewable energy resources, smart grid performance analysis, and engineering systems reliability modeling and optimization.

Menglian Zheng received the Bachelor's degree in energy and environmental systems engineering from Zhejiang University, Hangzhou, China, in 2011, and the Doctoral degree in earth and environmental engineering from Columbia University, New York, NY, USA, in 2015.

She is an Associate Professor with the College of Energy Engineering, Zhejiang University. Her research interests include demand response, flow batteries, and smart grids.