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Hardware-in-the-loop Towards Frequency Regulation Service by HVACs with Real-time Digital Simulator

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***Abstract*—The carbon peaking and carbon neutrality goals bring a rapid expansion of renewable energies, such as photovoltaic power and wind power. However, the output power of renewable energies is intermittent which may bring frequency deviation problems. The regulation ability of traditional generators may be insufficient to handle the frequency deviations since the great scale of renewable energies is replacing traditional power generators. With the development of communication technologies, demand response acquires more attention. Heating, ventilation, and air-conditioning (HVAC) systems are suitable for demand response because they occupy a large portion of energy consumption and have huge regulation potential. Moreover, HVAC systems' power consumption is flexible and adjustable by using the thermal storage feature of the buildings. When turning off the air conditioner or adjusting the set temperature, customers' comfortable indoor temperatures can be maintained. However, considering the complexity and large scale of the power system, most previous studies on HVACs' frequency regulation are verified only by simulation tools, e.g., MATLAB and Simulink. This study investigates the hardware-in-the-loop (HIL) towards frequency regulation service by HVACs with RTDS. The HIL platform is implemented in the case of frequency regulation in a high photovoltaic power penetrated campus grid. The scenario is designed with a building thermal model based on the quantized architecture characteristic parameter which is considered the part of HVAC operation model.**

***Index Terms*—demand response, HVAC system, RTDS, hardware-in-the-loop, frequency regulation**

I. INTRODUCTION

The increasing penetration of renewable energies, such as photovoltaic (PV) and wind power, has significantly changed the traditional power system structure. Since the output power from renewable energies is intermittent and uncontrollable, it brings more unbalances and fluctuation problems between power consumption and power supply [1]. If the power consumption is higher than the power supply, the power system frequency may be lower than the rated value, which may bring very serious consequences such as generator collapse with 0.2Hz of frequency deviation [2]. As a prior solution, power generators should adjust their output power associated with the demand side changes. However, traditional power generators no longer have enough resources to do the adjustment, especially with the replacement of traditional generators by renewable energies. With the development of information and communication technologies, using demand-side resources to do power regulation is a better solution, which is called demand response (DR) [3].

DR participants in the power system regulation by adjusting the dispatch of the demand side loads. A customer and a decision maker may sign up a contract that allows the decision maker to adjust or switch the customer's load for balancing the power system. Heating, ventilation, and air-conditioning (HAVC) system is a satisfactory resource for DR, because HVAC loads take a significant portion of the total power consumption nowadays, whose significance is continually growing. In the Finnish residential sector, HVAC systems take up around 70% of the total energy consumption [4]. Based on the evaluation [5], the total cooling capacity in China will reach 5410 GWc, which is a quarter of the worldwide cooling capacity. The great amount of load provides an adequate resource to balance the power supply shortage or excessive.

HVAC load can be flexibly adjusted by adjusting the set temperature or simply turning it on or off. The compressor of an HVAC provides a large adjustable range to handle different regulation requirements [6]. Since HVAC systems can take advantage of the thermal storage feature of buildings, which offered HVAC inherent thermal inertia. Unlike some other loads, such as wash machines, television, and fluorescent lights, HVAC load adjustment brings less impact on the customer's comfort [7]. The impact of switching temperature or turning off ventilation can be remission by the building envelope. Therefore, it can keep the indoor temperature in a comfortable range during the DR [8].

Due to the complexity and large scale of the power system, most previous studies on HVACs' frequency regulation are

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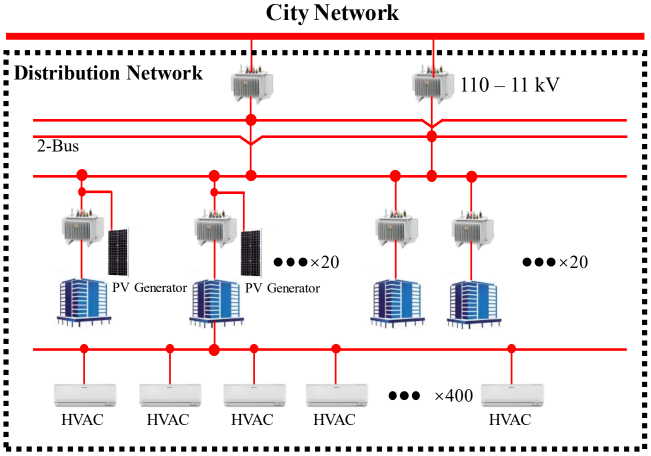


Fig. 1. The distribution network structure of the campus.

verified only by simulation tools, e.g., MATLAB and Simulink [9]. These simulation results may have some deviations or errors when these methods are applied in realistic systems. To address this issue, we investigate the hardware-in-the-loop (HIL) towards frequency regulation service by HVACs. HIL is a strong method to adopt a system that is difficult to build and can curate models [10]. First, the thermal building model and HVAC model are developed. On this basis, a real-time HVAC DR control method is proposed to deal with frequency deviations that are triggered by fluctuating PV power supply. The supervising and decision-making system can adjust the HVAC's operating power to provide frequency regulation services while keeping the comfortable indoor temperature. Our test is operated under a Real-Time Digital Simulator (RTDS) environment. RTDS is a strong power system simulator that has been highly approved, and its simulation result can be regarded as realistic tests [11]. It is highly accurate that the step size of the simulation can reach 2 microseconds [12]. RTDS also allows HIL testing, which means the outside hardware data can be read and written in the system in real time [13]. With the strong ability of RTDS, this paper originally used real HVAC to do the HIL frequency regulation in high PV penetration distribution campus grid on the RTDS platform. In this manner, a real HVAC load under a smart appliance management system is also tested in this study to verify the proposed models and methods.

II. MODELING OF THE FREQUENCY REGULATION TEST SYSTEM BY HVACS

A. Modeling of the Power System

The power system is considered as a 2-bus campus grid that contains 40 buildings and 20 of them are installed PV generators as fig.1 shown. The red line in the figure stands for the bus in the power grid. And the two red lines in the figure are the main bus of the mentioned campus grid, which used a 2-bus power system for system stability. The total power load of all buildings is around 19.1MW and 12.3 MW of them are considered adjustable HVAC loads, a. PV generators can supply 10.6 MW of power. This means that PV generators account for more than 55% of the power supply in the distribution network. Since 16% percent of PV is high enough that can be considered as a high penetration rate, a much larger penetration ratio can be more persuasive [14]. If the power supply of PVs was cut off or suspended in a short time for any reason, there will be a strong unbalance between the power demand and power supply. This will lead to significant frequency fluctuations. The HVAC systems in the buildings are the target load that will be adjusted to do the frequency regulation service. It is assumed that the system frequency can be monitored by a smart meter for the adjustment of HVACs, which will be explained in detail in Section III.

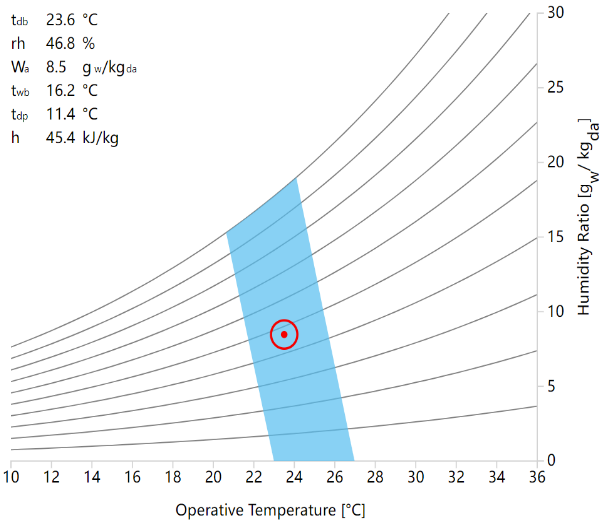


Fig. 2. Comfortable temperature range [20].

B. Modeling of HVAC and Building

A good thermal HVAC model is important to simulate a more realistic operation of HVAC and its effect on temperature [15]. The thermal model is associated with the building features and describes the thermal flow between indoor and outdoor environments with the impact of HVAC. This paper uses a simplified building thermal model [16], which is described as follows:

$$A_{surface} = 2 \cdot A_{room} + 4 \cdot H_{room} \cdot \sqrt{A_{room}}, \tag{1}$$

$$U = \gamma \cdot A_{room} \cdot H_{room}, \tag{2}$$

$$R_{Building} = \frac{10^{-3} m^3}{U \cdot A_{surface}}, \tag{3}$$

$$C_{heat} = C_{Air} \cdot D_{Air} \cdot A_{room} \cdot H_{room}, \tag{4}$$

where $A_{surface}$ is the total thermal dissipation superficial area; A_{room} is the flat area of the room; H_{room} is the height of the

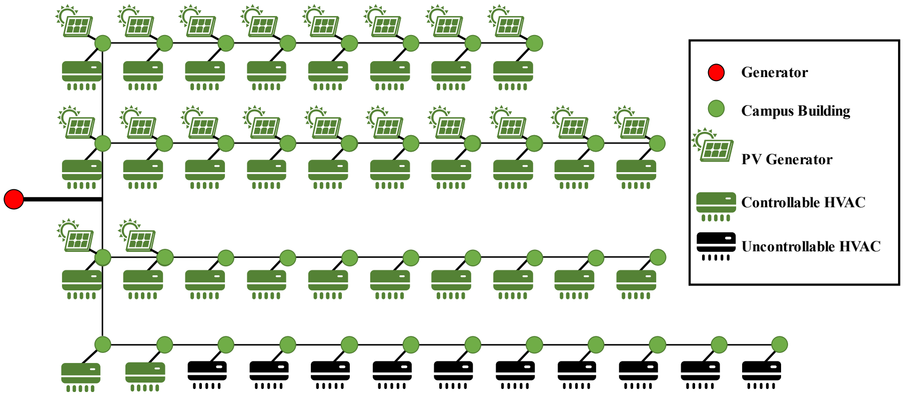


Fig. 3. The grid typology of the campus.

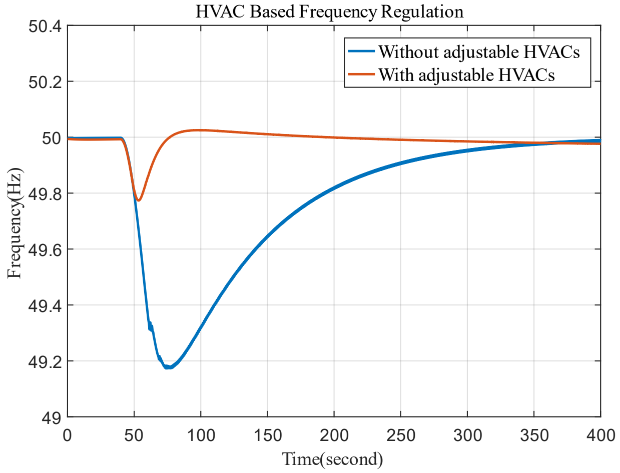


Fig. 4. The frequency regulation results with simulated adjustable HVACs.

room; U is the overall heat transfer coefficient, which is approximately evaluated according to the room superficial area; γ is a variable parameter of overall heat transfer coefficient that consist of building's structure; $R_{Building}$ is the building thermal resistance; C_{heat} is the heat capacity of the room; C_{Air} is the specific heat capacity; D_{Air} is the density of air.

The model of the HVAC system is simplified into its cooling supply associated with the operating power consumption, which is expressed as:

$$S_{cool} = P_i \cdot COP, \tag{5}$$

where S_{cool} is the cool supply by the HVAC; P_i is the HVAC power consumption; $COP$is the Chiller coefficient of performance. Based on the cooling supply and the thermal model of the building, the indoor temperature at the next time step can be evaluated by the following equation:

$$T_{i+1} = T_i + \frac{\left(\frac{T_{\mathrm{o}} - T_{\mathrm{i}}}{R_{Building}} - S_{cool}\right)\cdot t}{C_{heat}}, \tag{6}$$

where T_{i+1} is the expected temperature on the next time step; T_{o} is the ambient temperature; T_{i} is the current indoor temperature; is the time of each regulation step.

The proposed model parameterizes the thermal exchange between the indoor and outdoor environments through the building envelope by Eqs.(1)–(4) and defines the indoor temperature change under the effect of the HVAC operation in Eqs.(5)-(6). Since the cooling supply of HVAC is mainly decided by its power consumption, the parameterized thermal flow is necessary to describe the behavior of HVAC in demand response.

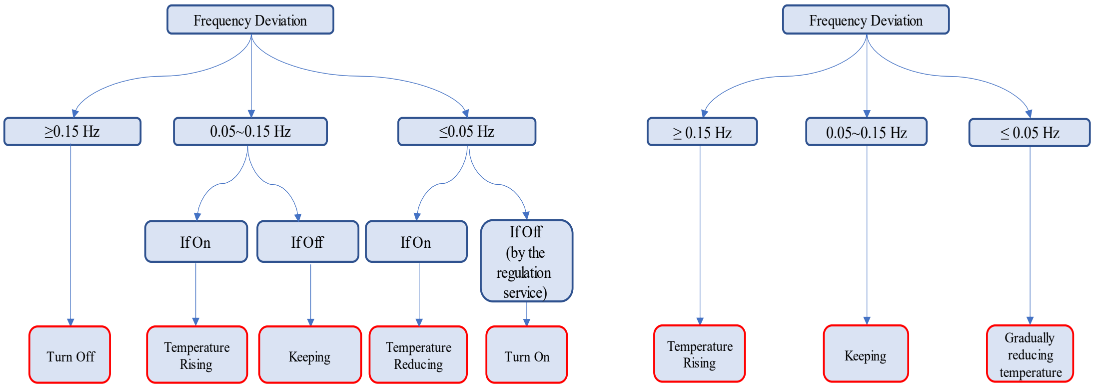
C. Thermal Comfort Evaluation

Thermal comfort is an important precondition for HVAC demand response. Maintaining the indoor comfortable temperature shall strongly affect customers' willingness to accept the DR contract [17]. The health and psychological issue brought by indoor temperature is necessary to be considered [18]. ASHRAE is a widely used standard to evaluate the thermal comfort temperature, it is specifically a series coefficient associated with nature situations, customers' behavior, customers' dressing, and indoor structure [19]. ASHRAE 55-2020 Standard is applied to evaluate the comfort temperature range in this study. A campus building scene is described and applied as the typical case. With reference to the ASHRAE 55-2020 Standard, a comfortable indoor temperature range was evaluated, as shown in Fig. 2 [20]. The red point in the figure is the midpoint of the comfort temperature and is set as the typical initial temperature, whose Dry-bulb temperature is 23.6 ℃.

III. FREQUENCY REGULATION METHOD

Indoor temperature, cooling power, and system frequency are continually monitored for adjusting HVACs. The load adjustment decision is according to the frequency deviations and temperature deviations, which are defined as follows:

$$\begin{cases} T_D = T_{set} - T_i \\ f_D = f_{rated} - f_i \end{cases}, \tag{7}$$



(a)

(b)

Fig. 5. Regulation method with (a) Switching-based regulation; (b)Temperature adjusting-based regulation.

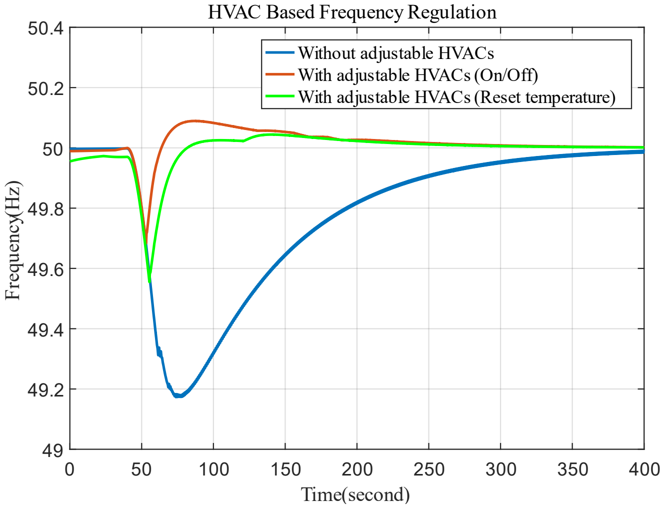


Fig. 6. The frequency regulation results with realistic HIL adjustable HVACs.

where T_D is temperature deviation; T_{set} is the set temperature; f_D is the frequency deviation; f_{rated} is the standard grid frequency; f_i is the current frequency.

A larger frequency deviation leads to more cutoff on loads. When the frequency deviation is larger than $f_D^{thr,upper}$, the situation is treated as an emergency case. The controller will ignore the temperature and only focus on the impact of frequency. However, when the frequency deviation is less than $f_D^{thr,lower}$, the controller will operate only based on the temperature deviations to recover the cooling supply. When the frequency deviation is between $f_D^{thr,lower}$ and $f_D^{thr,upper}$, the risk of frequency will be noticed but will not cut off load in the grid radically. The control strategy is described in the following equation:

$$P_{i+1} = P_i + \kappa_{F1} \cdot f_D + \lambda_{F1} \cdot f_D \times t, f_D \geq f_D^{thr,upper}, \quad (8)$$

$$\begin{aligned} P_{i+1} = P_i + \kappa_{F2} \cdot f_D + \lambda_{F2} \cdot f_D \cdot t + \kappa_{T1} \cdot T_D + \\ \lambda_{T1} \cdot T_D \cdot t, f_D^{thr,lower} < f_D < f_D^{thr,upper}, \end{aligned} \quad (9)$$

$$P_{i+1} = P_i + \kappa_{T2} \cdot T_D + \lambda_{T2} \cdot T_D \cdot t, f_D \leq f_D^{thr,lower}, \quad (10)$$

where P_{i+1} is the power supply to HVAC on the next time step after the adjustment; $f_D^{thr,upper}$ is the upper threshold of the frequency; $f_D^{thr,lower}$ is the lower threshold of the frequency; P_i is the current operating power supply of the HVAC system; κ_{F1}, λ_{F1},κ_{F2}, λ_{F2}, κ_{T1},λ_{T1}, κ_{T2}, λ_{T2} are the proportional-integral (PI) controller's coefficients.

As the load regulation model and strategy for one HVAC are built, the whole building regulation process can be described as follows:

$$P_{Building} = \sum_{n=1}^{N_{AC}} (P_{i+1})_n, \quad (11)$$

where $P_{Building}$ is the total load set in the next time step. The value will be sent into RTDS as HIL data to react with the grid. A pseudocode is shown in Algorithm 1 as follow to describe the regulation algorithm.

Algorithm 1 Regulation pseudocode algorithm

```
Initialize: Setting $T_s$,
while TRUE do
    Read system frequency from the RTDS
    if Frequency deviation $\geq f_D^{thr,upper}$ then
        Regulation mode 1, based on Eq. (8)
    else if $f_D^{thr,lower}$ ¡ Frequency Division ¡ $f_D^{thr,upper}$ then
        Regulation mode 2, based on Eq. (9)
    else if Frequency Division $\leq f_D^{thr,lower}$ then
        Regulation mode 3, based on Eq. (10)
    end if
    Write HVAC power into RTDS.
    Grid operation in RTDS
end while
```

IV. NUMERICAL STUDIES

A. Test system

Since the real distribution network is not available to be adjusted, RTDS is used in this paper to verify the proposed methods. A campus grid typology is shown in Fig. 3. The green points in Fig. 3 represent campus buildings with adjustable HVAC loads. There are a total of 40 buildings, where 30 buildings with adjustable HVAC loads and 20 buildings with PVs. By using the HIL function of the RTDS, the dynamic load data are rewritten by external controllers. The simulated HVACs and realistic HVACs are tested, respectively. The parameters of HVACs, buildings and controllers are set as follows: $\gamma = 0.14W/m^2{\cdot}^\circ C$; $f_{rate} = 50Hz$; $f_D^{thr,lower} = 0.05\text{Hz}$; $f_D^{thr,upper} = 0.15\text{Hz}$; $\kappa_{F1} = 0.045$; $\lambda_{F1} = 0.03$; $\kappa_{F2} = 0.0075$; $\lambda_{F2} = 0.0045$; $\kappa_{T1} = 0.0001$; $\lambda_{T1} = 0.00051$; $\kappa_{T2} = 0.00001$; $\lambda_{T2} = 0.00001$; $D_{Air} = 1.205kg/m^3$; $C_{Air} = 1.005J/g$; $T_o = 30^\circ C$.

B. Simulation Results of Adjustable HVACs with RTDS

Simulated HVACs are ideal dynamic loads as in most previous studies. That means the operating power of HVACs can be adjusted as an accurate value within the designed rate power. The frequency regulation results are established in Fig. 4. It can be seen that the HVACs have satisfactory performance. The original maximum frequency deviation is more than 0.8 Hz in the scenario without adjustable HVACs, and it is decreased to about 0.2 Hz. After the system frequency deviation returns within 0.05 Hz, the system recovers to operate in a stable state.

Compared with the scenario without adjustable HVACs, the frequency has a slightly decreasing trend after the system recovers the stable state. Because the HVACs are restarted to increase the operating power for recovering the cooling supply. Besides, though the simulated HVACs have good performance in frequency regulation, their operation procedure may be too idealistic for realistic loads to accomplish. Therefore, a realistic test of HVAC is applied in the next subsection.

C. Experimental Results of Adjustable HVACs with RTDS

A realistic air conditioner is installed to achieve HIL with RTDS. By setting different parameters to implement multi-time tests, we obtain a big amount of the HVAC system's operating data, which can be considered as various types of users and HVACs. We find that, unlike the simulated HVACs, the regulation on realistic HVACs is not so ideally flexible. Since the compressor of the installed HVAC cannot be adjusted directly, the regulation method on this realistic HVAC is limited to switching on/off or adjusting the set temperature. In this paper, the regulation strategy is shown in Fig. 5. The controller can monitor the real-time operating power of the HVAC. According to the frequency deviation and its associated risk level, the system defines three type control method for both switching-based regulation and temperature-adjusting-based regulation. Controllers send command to HVAC as regulation signals to control HVACs' behavior such as adjusting the switch or adjusting the set temperature.

The system frequency deviation curves are shown in Fig. 6, where three scenarios are compared, including those without adjustable HVACs, with adjustable HVACs to be regulated by the on/off control method, and with adjustable HVACs to be regulated by resetting temperature. It can be seen that the maximum frequency deviations are about 0.30 Hz and 0.43 Hz in the two scenarios with adjustable HVACs, respectively. It means that the realistic HVAC performs a bit worse compared with the simulated HVAC, where the maximum frequency deviation is decreased to about 0.2 Hz. This is because some delay time exists during the smart meter monitoring and data transferring processes in the HIL. Moreover, the frequency is recovered to be larger (i.e., around 0.1 Hz) than the rated value with the on/off control method, because the radical adjustment may cause the over-regulation problem. By contrast, the resetting temperature method is more conservative, which can reduce the impact of the over-regulation problem. Nevertheless, the over-regulation value is tolerable (only around 0.1 Hz) and the HVAC's regulation still plays a positive role in maintaining the system stability by decreasing the maximum frequency deviation.

V. CONCLUSION

High portion of intermittent renewable energy sources and the reduction of traditional power generators bring new fluctuation problems. To address this issue, demand response is considered as a good solution. The HVAC system is widely used due to its huge regulation potential. This paper builds a campus distribution network model in RTDS to verify the regulation performance of HVACs. Both simulated HVAC and realistic HVAC are applied as real-time data sources to connect with RTDS using HIL. All the test results show good performances with fast response speed. However, the realistic HVAC regulation still faces some problems, such as i) the delay time exists during the smart meter monitoring and data transferring processes in the HIL, ii) the expected reduction value of HVAC's operating power cannot be realized exactly because some HVACs can only be regulated by on/off method, iii) the system frequency drops quickly and may lead to the overestimation of the system risk.

In future work, more parameters of the distribution network should be monitored for diversified control, such as frequency changing rate, bus voltage, and operating power changes. The detection point may also be extended from one bus to multiple buses to provide more information. Some new methods can also be explored, such as the reinforcement learning algorithm may be used to do the regulation capacity evaluation and control.

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