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Investigation on the Use of Pumps in HVAC Systems for Providing Ancillary Services in Smart Grids

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Abstract

The proportion of electric generation from renewable resource has been growing rapidly in recent years, especially in Microgrids in remote areas. However, the intermitted nature of the renewable energy resource has posed a great pressure on the reliability of power grids and asked a great amount of ancillary services, especially for frequency regulation (FR). Heating, ventilation, and air-conditioning (HVAC) systems are promising resources to solve this challenge because they can take full use of thermal storage capacity of buildings. In this paper, a pump in HVAC system in a hotel is employed to provide the frequency regulation by adjusting its frequency to follow the automatic generation control (AGC) signals, RegA and RegD signals from Pennsylvania–New Jersey–Maryland (PJM). Performance scores are adopted to assess the control performance. In addition, the thermal capacity of the cooling coil is considered to evaluate its side-effect when providing this service. The results indicate that the pump can provide nearly 30kW total capacity with a relatively high average performance score. Moreover, the impact to indoor air temperature is almost neglectable with the thermal capacity of the cooling coil and indoor air hedging against the fluctuation of pump frequency.

Keywords: Ancillary services; HVAC; Demand response; Smart Grid; Microgrid;

1. Introduction

The reliability of power grids is one of the most important issues for power grid management. To maintain the balance of supply and demand of power, ancillary services are applied to improve the flexibility of the grid. Normally, these

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Nomenclature

$a_1 a_2 a_3$	coefficients	β	a coefficient dependent on the control valve flow characteristics
c_1	coefficient	ρ	fluid density
D	internal diameter of a pipe	ε_0	flow resistance when the control valve is fully open
f	frequency	τ	time constant
H	pump head	*Subscripts*	
L	length of a pipe	av	average
M	water flow	b	baseline
P	pressure difference/loss	c	current
Pow	power consumption	r	frequency regulation
v	average fluid flow velocity in a pipe	set	set-point
y	valve opening		
α	friction factor selected from the Moody chart		

services are provided by supply side by generators which can response to Automatic generation control (AGC) signals. However, the proportion of electric generation from renewable resource has been growing rapidly in recent years, and many research has demonstrated that this trend can increase the ancillary services requirement [1, 2], and it will exceed the ability of the supply side (both the ramping rate and capacity) to provide ancillary services very soon [3]. This situation can be more serious in Microgrids in remote areas because renewable electricity may even dominate in the grid while the ramping rate of generators can limit the frequency regulation capacity significantly. Great investment, if solving the problem from supply side as usual, is inevitable either by building energy/power storages or by setting up more generators for reserve, and the annual working hours of generators will decrease dramatically due to the rapid increase of installed capacity [4]. In recent years, more and more interest is aroused in encouraging demand-side to participate this services. Technically, the advantages of HVAC systems in providing FR is two-fold. First, they account for a large proportion of both energy and electric. Currently, the building sector takes up 74% of electric energy in the United States [5] and about 16% of electric power is consumed by HVAC systems in buildings [6]. In Hong Kong, buildings consume over 90% of the total electricity, and HVAC systems contribute about 29.8% electricity in buildings [7]. Second, the internal mass in buildings is natural heat storage. FR is attributed to forecast errors which are unbiased and zero-mean, so the indoor temperature will just have some fluctuation when providing FR, which makes buildings are almost ideal candidates to provide this service.

There are some efforts have been made to demonstrate HVAC systems' ability to provide FR in recent years. In reference [8, 9], a fan was applied to provide FR by manipulating its frequency set-point. The result showed that 15% of fan power capacity can be used for FR with indoor temperature variation being within ±0.2 ℃; In research [6, 10], a chiller was adopted as a candidate to provide FR by resetting its output temperature continuously. Experiment validated has also been conducted with performance score defined by PJM. However, there is no research about utilizing pumps in HVAC systems to provide FR. As we know, HVAC is a complicated system in which all the components are thermally coupled. Technically, each component in HVAC has its own advantages for providing FR. For chillers, each of them may have the greatest power consumption among all the components in HVAC and thus can provide a great amount of FR. On the other hand, it may sacrifice a lot of energy performance due to its internal control logic and regimes. In addition, the large time constant indeed has restricted its response speed. Regarding fans, they can respond rapidly to follow the signal. However, they may have a direct influence on the indoor air temperature which may sacrifice the main function of HVAC systems. Moreover, not all kinds of fans can provide this kind of services due to the architecture of existing building automation systems. For example, fans in cooling coil systems are locally controlled and can be hardly adopted for FR. Unfortunately, the typical type of HVAC systems in hotels is cooling coil system and hotels are more favourable to provide FR because the systems are operating 24 hours a day which can provide stable and continuous service while systems in most commercial buildings and office buildings are just operating during the day.

Pumps have their own advantages in providing this service. First, it can also respond quickly enough. Second, it will not have a great influence on the terminal indoor air temperature because there is an air loop between pumps and room which can hedge against the fluctuation of water flow. This paper intends to conduct a demonstration of adopting pumps for FR and evaluate its side-effect to the indoor temperature fluctuation in a hotel with a cooling coil system.

2. Control architecture and model description

As shown in Fig.1, it is a typical HVAC system with a variable secondary pump and cooling coils for cooling services of multi-rooms. In the air loop, based on the measured indoor temperature and its corresponding set-point, a proportional-integral-derivative (PID) controller is employed to control the opening of the air dampers. Here, fans in cooling coils are working at a constant frequency. Similarly, in the water loop, based on the measurement of supply air temperature and its corresponding setpoint, a PID controller will change the cooling supply of cooling coil by adjusting the opening of the water valve. The secondary pump is also controlled by a PID controller to guarantee the set-point of pressure difference in the furthest AHU loop by managing its speed. The primary chilled water pump is constant and the cooling water side is not considered for simplification.

When providing FR, AGC signal is given by PJM, which is a sequence of pulses from -1 to 1 at a 2 seconds intervals and represents the power difference between the supply side and demand side in a power grid [11]. To compensate this deviation and maintain the frequency of the power grid, a regulation controller is proposed to manipulate the power consumption of the secondary pump by changing its frequency. As observed in the figure, f_b is the original pump speed command produced by pump PID controller, the regulation controller will add an extra command f_r on f_b based on the current frequency f_c, and AGC signals.

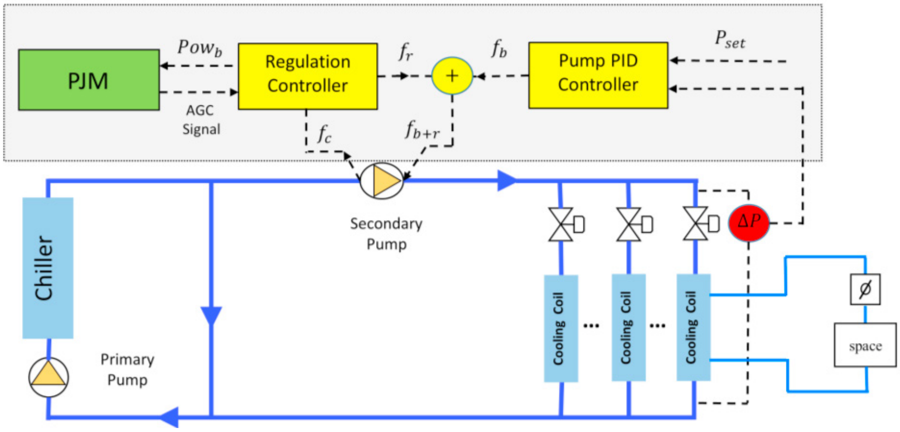

Fig. 1. Control architecture for the secondary pump in providing frequency regulation.

In this study, the simulation platform is built by the combination of TRNSYS and MATLAB. Multi-zone building model (type 56) in TRNSYS is employed as building thermal dynamic. Model type 666 and type 654 are used as chiller and primary pump model, respectively. To evaluate the impact of FR to the fluctuation of indoor air temperature, the thermal capacity of cooling coils is considered. The details of this model can be found in authors' previous publications [12].

The pressure losses across water pipes and cooling coils caused by the fluid friction are computed using the Darcy–Weisbach equation as expressed by Eq. (1). The flow resistance of the control valve is related to its opening, and the pressure loss across a control valve at a given opening (y) is computed by Eq. (2).

$$P = \alpha(\frac{L}{D})(\frac{\rho v^2}{2}) \tag{1}$$

$$P_{valve} = \frac{\varepsilon_0}{y^\beta}\frac{v^2}{2} \tag{2}$$

The variable speed pump is simulated using a series of polynomial approximations representing head versus flow and frequency, as expressed by Eq. (3). The water flow M is finally determinated by solving the Eq. (3) and Eq. (4) by iterating [13]. The power consumption of the pump is proportional to the cube of its speed [14]. As show in Eq. (5). c_1 is estimated as 2.5×10^{-3} which is obtained by regression.

$$H_{pump} = a_1 M^2 + a_2(\frac{f}{f_0})M + a_3(\frac{f}{f_0})^2 \tag{3}$$

$$H_{pump} = P_{pipe} + P_{cooling\ coil} + P_{valve} \tag{4}$$

$$P_{pump} = c_1 f(t)^3 \tag{5}$$

Because of the inertia of water, the ramping rate is also considered when its frequency is changed. In this study, its transfer function is assumed as of first order, as shown below. Time constant τ is chosen as 10 seconds.

$$\tau \frac{df(t)}{dt} + f(t) = f_{b+r}(t) \tag{6}$$

In this study, both $RegA$ and $RegD$ are selected which are the low filter and high filler of Area Control Error signal, respectively. After that, $f_r(t)$ can then be calculated by derivation based on Eq. (5), showed in Eq. (7). $f_{av}(t)$ is the nominal fan frequency due to the cooling load of building. In addition, regulation controller will also send back consumption baseline of this component, $Pow_b(t)$ which refers to the nominal power consumption of the component without providing FR. This value will vary through the day when the cooling load is changed.

$$f_r(t) = \frac{\Delta Pow_{pump}}{3c_1 f_{av}(t)^2} \tag{7}$$

$$f_{av}(t) = \sum_{i=t-3600}^{t} f(t) \tag{8}$$

$$Pow_b(t) = \sum_{i=t-3600}^{t} Pow_{pump}(t) \tag{9}$$

3. Test platform

In the simulation, 90 rooms ($40\text{m} \times 40\text{m} \times 3m$) are modelled in TRNSYS system in which each 30 rooms are considered have the same orientation. The settings, the patterns of occupancy, equipment, lighting, sensible and latent heat, and fresh air flow can be found in authors' previous work [15]. A typical day in summer is selected and one hour during the day is picked up for FR.

4. Results and discussion

4.1. Performance

The frequency regulation service begins at 13:00. Fig.2 represents the actual and baseline power consumption Pow_b of the pump. The difference between these two profiles is the capacity provided for frequency regulation service. The power consumption has a larger deviation from its baseline when the pump following RegA signal due to lager accumulated deviation of the signal which can be called as "energy content".

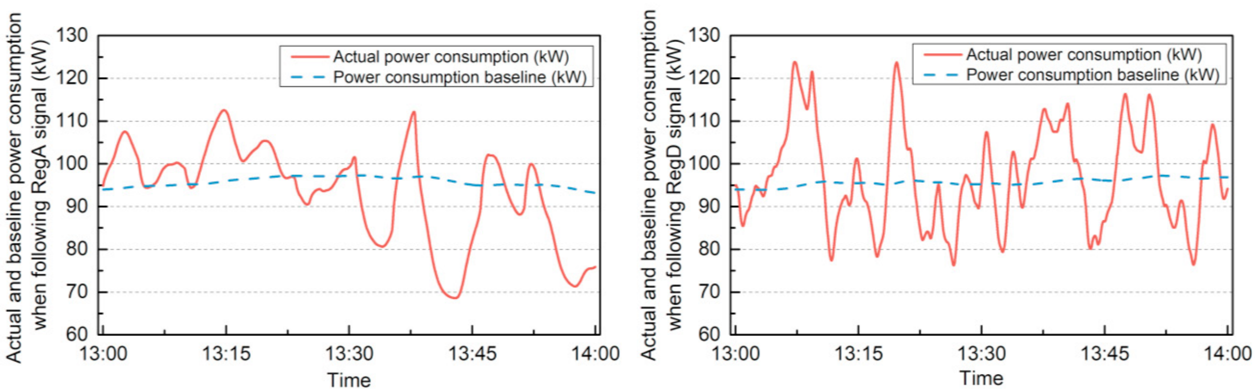

Fig. 2. Actual and baseline power consumption of the pump when following (a) RegA and (b) RegD signals.

In Fig.3, the blue dashed lines are the AGC signals multiplied by total regulation, TReg of 30kW to present an equivalent comparision with the real-time frequency regulation capacity indicated by red lines. In the red circles, there are some obvious dealies. To evaluate the performance of the frequency regulation service, three scores derived from PJM manual are adopted [11], including delay score S_d, correlation score S_c and precision score S_p, as shown in Eqs.(10-12). δ is defined as the time shift with which the response has the highest correlation coefficient with the

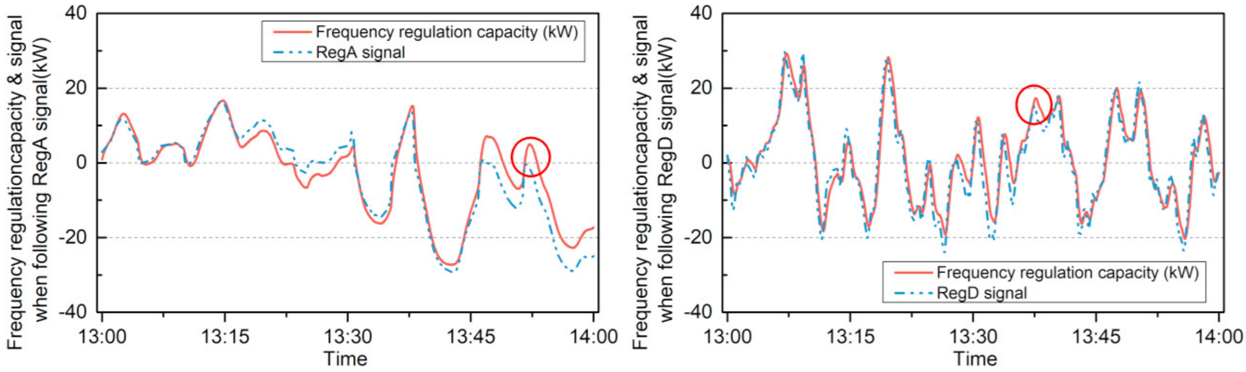

Fig. 3. Frequency regulation capacity and signal when following (a) RegA and (b) RegD signal.

signal, and this highest correlation coefficient value is the S_c. This candidate component is qualified only when the average of these three scores are higher than 0.75. Table 2 represents the average score the pump got in the testing hour. As can be observed from the result, the precision score when following RegD is a little lower than that when following RegA which may result from a high requirement of respond speed of RegD. However, both of them have a higher score than 0.75 which indicate that pumps can follow both of them with fulfilling the requirement of the PJM standard to participate for the frequency regulation service.

$$S_d = \left|\frac{\delta - 5\ Min}{5\ Min}\right| \tag{10}$$

$$S_c = r_{Signal,Response\ (\delta,\delta+5Min)} \tag{11}$$

$$S_p = 1 - \frac{1}{n}\sum\left|\frac{Response - Regulation\ Signal}{Hourly\ Average\ Regulation\ Signal}\right| \tag{12}$$

Table 1.Performance Score for the pump following RegA signal and RegD signal

Signal Type	TReg	Correlation Score	Delay Score	Precision Score	Total score
RegA	30kW	0.98	0.95	0.81	0.91
RegD	30kW	0.98	0.95	0.70	0.87

4.2. Side-effect

Except for the performance, another concern is its side-effect, the impact to the main function of HVAC to guarantee the indoor air temperature. When providing this service, the water flow will fluctuate with the variation of pump frequency. This will further influence the outlet temperature of the cooling coil and the indoor air temperature eventually.

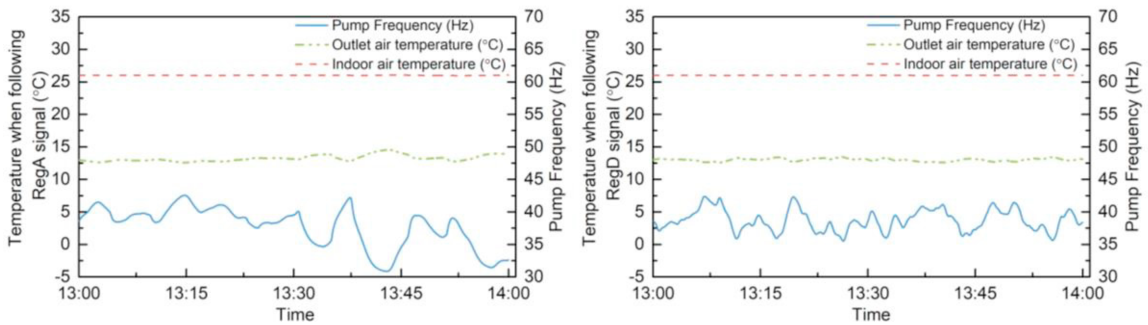

Fig. 4. The fluctuation of pump frequency, outlet air temperature, and indoor air temperature when following (a) RegA and (b) RegD signals.

Fig.4 presents the profiles of pump frequency, the outlet temperature of the cooling coil and the indoor air temperature when following RegA and RegD signals. The absolute and relative variations of these three parameters are shown in Table 2. The results show that the pump frequency fluctuation has more influence when following RegA due to its larger “energy content”. Moreover, the relative variations of pump frequency, outlet air temperature, and indoor air temperature show a downward trend whenever following RegA or RegD. It is because although the fluctuation of pump frequency is significant, the heat thermal capacity of the cooling coil will firstly hedge against the fluctuation and make the outlet temperature smoother. Eventually, the indoor air temperature is almost constant because of the thermal capacity of indoor air.

Table 2.Variation of parameters when providing frequency regulation

Signal Type	Parameter	Pump Frequency (Hz)	Outlet air temperature (℃)	Indoor air temperature (℃)
RegA	Absolute variation	±6.89	±1.32	±0.04
	Relative variation	±18.26%	±9.96%	±0.17%
RegD	Absolute variation	±3.66	±0.46	±0.01
	Relative variation	±9.45%	±3.55%	±0.04%

5. Conclusion

Frequency regulation capacity is increasing rapidly with the growing penetration of renewable electricity generation, especially in Microgrids. In this paper, a secondary variable pump is adopted for FR services to follow the RegA and RegD signals. A regulation controller is proposed to manage the power consumption of the pump by control its frequency. The ramping rate of the pump, as well as the thermal capacity of the cooling coil, has been considered.
The simulation results indicate that the proposed control strategy of secondary variable pump in HVAC system of the hotel can follow the RegA and RegD signals very well. Although the performance score for RegD is a little lower, both of these two scenarios can provide nearly 30 kW regulation capacity and meet the standard of PJM. Pump frequency variation for RegA has a larger influence to the indoor air temperature due to its larger “energy content”. However, pump frequency variation in both scenarios has been compensated significantly because of the thermal capacities of cooling coil and indoor air, with the indoor air temperature almost being constant.

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