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Onsite Tests of Controlling a Large Constant Speed Centrifugal Chiller for Grid Frequency Regulation

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ABSTRACT

High penetration of intermittent renewables may cause safety and stability problems to the electricity grid. Building HVAC systems could contribute to grid frequency regulation. Constant speed centrifugal chillers have rarely been studied for grid frequency regulation. A control strategy is proposed to control constant speed centrifugal chillers to follow grid regulation signals. It is proposed to regulate the chiller power consumption by dynamically limiting its power consumption and resetting its supply chilled water temperature. Onsite tests were conducted to find critical parameters. The total delay time in chiller power was about 20–25 seconds. And the maximum ramping speed of chiller power was 2.53 kW/s. When providing a regulation capacity of 100 kW (7.46% of the rated chiller power), the composite performance scores were 0.901 and 0.885 for Regulation A test and Regulation D test, respectively.

Keywords: building demand response; frequency regulation; ancillary service; grid-responsive building; chiller; HVAC

1. INTRODUCTION

Renewable energy is projected to reach 40% of the global grid power generation in the 2040s [1]. However, the high penetration of such intermittent renewables would put high stress on the stability and safety operation of the grid [2].

Many researchers have studied demand side frequency regulation which enhances grid stability. Commercial building HVAC fans are the most extensively studied for frequency regulation because their power could be easily adjusted by VSDs (Variable Speed Drivers). A study on supply air duct and fans estimated that at least 4 GW regulation reserve capacity could be provided by commercial buildings in US [3]. A feedforward control architecture has been proposed to control the fan speed in commercial buildings [4]. A dynamic VAV (Variable Air Volume) system model has been developed to simulate the provision of grid frequency regulation [5]. Residential ventilation fans were also proposed to provide ancillary services through aggregation in another study [6].

Chillers and compressors have also been studied for grid frequency regulation. Studies found that the capacity of ancillary service could be increased by utilizing chillers [7]. A control method was developed for using VSD chillers for frequency regulation [8]. The study on using constant speed chillers for frequency regulation is still rare. Constant speed chillers are widely used in practice. Also, few studies have conducted onsite tests on the time delay in using chiller for frequency regulation.

This study investigates the potential of controlling a large and constant speed centrifugal chiller to follow grid frequency regulation signal. A control strategy is proposed to regulate chiller inlet guide vane opening for direct power consumption control. Onsite tests were conducted to find out the characteristics of the studied constant speed chiller including time delay, power ramping speed, etc. The tests results were used to fine-tune the critical parameters in a dynamic simulation platform built based on the real system for validation.

2. THE PROPOSED CONTROL METHOD

The control strategy proposed in this study tries to regulate chiller power consumption according to the grid

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frequency regulation signals. In the meantime, the building thermal environment will only be affected slightly due to the thermal buffer effect of the whole HVAC system.

The studied constant speed chiller accepts two settings. One is the supply chilled water temperature set-point, the other is the upper limit of the chiller power consumption. Fig. 1 shows the schematic of the proposed control strategy. Two PID controllers are used in the control loop. One is used to control the supply chilled water temperature, the other is used to constrain the power consumption of the chiller below the upper limit set-point. The control signals from the two controllers are compared, and only the lower one is used to command the chiller.

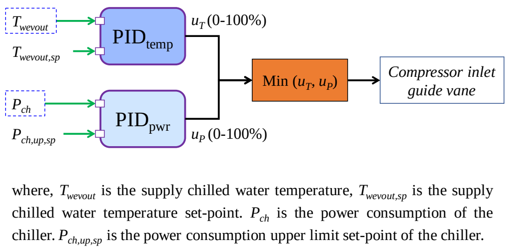

Fig. 1 Schematic of the proposed control strategy

The $T_{wevout,sp}$ and $P_{ch,up,sp}$ are two critical set-points in the whole control strategy. Fig. 2 demonstrates the determination process of the two set-pints. The left side of the figure shows the process for determining the $P_{ch,up,sp}$, and the right side of the figure shows the process for determining the $T_{wevout,sp}$. The reference power (P_{ref}) and regulation capacity (C_{reg}) are firstly determined based on the predicted building cooling load and chiller efficiency. The building load in the next hour is predicted by a previously developed multiple linear regression model [9]. The chiller power consumption in the future hour is then determined based on the load prediction and the chiller efficiency model.

The chiller power consumption upper limit set-point is determined to be the target power consumption. However, if the supply chilled water temperature is too high, the constrains on chillers power consumption have to be released, and the chiller power consumption upper limit set-point will be the chillers nominal power consumption.

An empirical equation (Eq. (1)) is used to determine the optimal supply chilled water set-point. The empirical optimal set-point is then compared with the actual measured supply chilled water temperature. If the measured value is higher than the optimal value (a threshold T_{th} is used), the internal value "Flag" is set to 1 and the uncorrected set-point ($T''_{wevout,sp}$) is the calculated empirical optimal set-point. Otherwise, the "Flag" is set to 0 and the uncorrected set-point is set to the allowed minimum supply chilled water temperature ($T_{wevout,sp,min}$).

$$T'_{wevout,sp} = a + b \cdot Q_{meas} \tag{1}$$

where, a and b are empirical coefficients. $T'_{wevout,sp}$ is the optimal chilled water temperature set-point, which ranges between 5 °C and 9 °C.

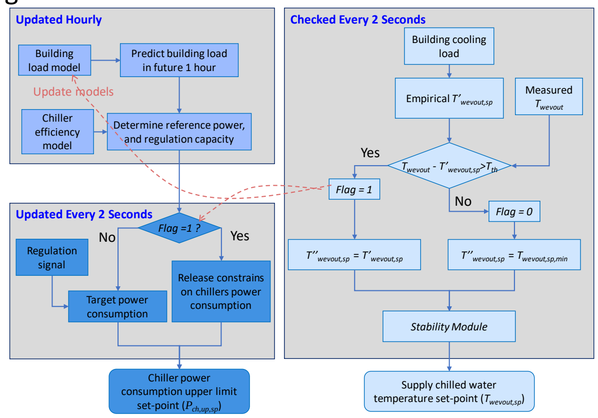

Fig. 2 Determination process of the two critical set-points

3. VALIDATION PLATFORM

This study is conducted based on a chiller in the chiller plant for a real high-rise commercial building. The chiller plant consists of six identical high voltage centrifugal chillers.

Fig. 3 demonstrates the framework of the simulation platform. It consists of a chiller model, a building model, a thermal buffer model, and a controller module. The detailed chiller model simulates the instantaneous chiller cooling capacity and power consumption based on inputs including the inlet water temperatures and flow rates of condenser and evaporator. The building model gets the cooling load from a data file which stores the historical cooling load of the studied real building and calculates the return chilled water temperature. A thermal buffer model is used to simulate the thermal storage effect of building mass and the chilled water.

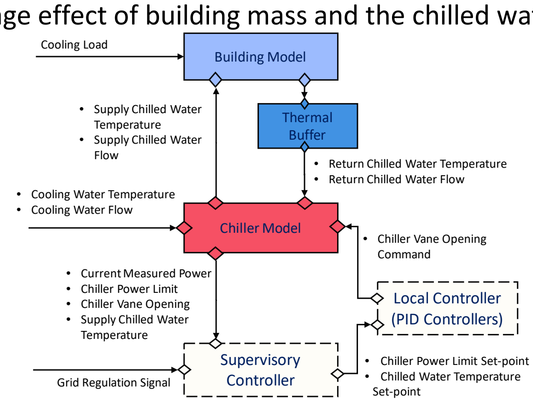

Fig. 3 Framework of the dynamic simulation platform

4. TEST RESULTS

4.1 Onsite tests of chiller critical parameters

The time delay of power consumption in response to regulation signal is of essential importance to the frequency regulation performance. It has to be found through onsite tests. The onsite test procedure is described as follows:

Step 1: Select a single chiller for the test. Set its supply chilled water temperature set-point to 5.5 °C. Set chiller power upper limit to 100%. Wait 15 minutes for the chiller to be stable; Step 2: Set the sampling period as short as possible (5 seconds in the test), and record essential data points; Step 3: Adjust the chiller power upper limit to 75%. Record data for 10 minutes; Step 4: Release the chiller power upper limit to 100% and end the test.

Fig. 4 shows the time series data of chiller power upper limit, chiller vane opening, and chiller power consumption. When the chiller power limit was changed from 100% to 75% at 19:34:15, and the vane opening began to drop significantly 20 seconds later at 19:34:35. That means the chiller controller and chiller vane opening together needs about 20 seconds to respond to the change in chiller power limit settings. Prior to the change in chiller power limit, the chiller power varied slightly between 1170 kW and 1190 kW. But when the vane opening dropped significantly from 55.59% to 28.96% after the change in chiller power limit, the chiller power dropped almost in line with the vane opening from 1180 kW to 1041 kW. It took about 55 seconds for the vane opening to change from 55.59% to 28.96%. The changing speed of chiller vane opening is therefore calculated as 0.4842 %/s according to the onsite test. And the ramping speed of chiller power was 2.53 kW/s.

It can also be noticed that there was a variation in chiller power after 19:35:30. Because of this, the chiller controller further reduced chiller vane opening at 19:37:15. And the chiller power reduced to 1013 kW 25 seconds later at 19:37:40.

The response time of chiller power to the changes in power limit settings consists of two parts. One part is the time for chiller controller and chiller vane opening to response to the power limit, the other part is the time for chiller power consumption to response to vane opening. Test results shown that the first part was about 20–25 seconds, while the second part was almost instant. Therefore, the overall delay time of chiller power was about 20–25 seconds. Also, the maximum changing speed of chiller vane opening was about 0.4842 %/s. The maximum ramping speed of chiller power was 2.53 kW/s.

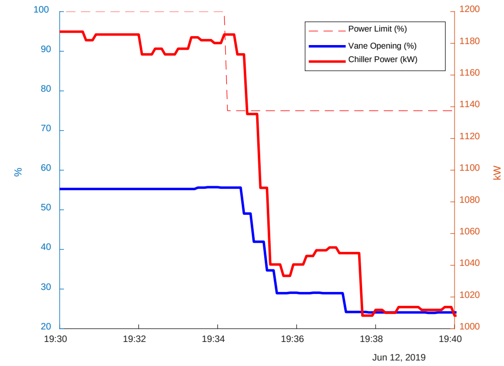

Fig. 4 Changing in chiller power upper limit, chiller vane opening, and chiller power consumption

4.2 Tests of the complete control strategy on the dynamic platform

Based on the critical parameters identified from onsite tests, the dynamic simulation platform built based on the real HVAC system is further fine-tuned.

The proposed strategy for grid frequency regulation was tested. Totally three chiller operation modes were tested for comparison and evaluation. The three modes are (a) RegA test: Providing frequency regulation to follow the Regulation A test signals; (b) RegD test: Providing frequency regulation to follow Regulation D test signals; (c) Regular test: Not providing frequency regulation. In all the three test modes, the same working condition were adopted. The reference power and regulation capacity in both RegA test and RegD test were 1250 kW and 100 kW (7.46% of the rated chiller power), respectively.

Table 1 Comparison on the three modes

Test mode	Performance sub-scores			Composite score
	Accuracy	Delay	Precision	
RegA	0.939	0.890	0.872	0.901
RegD	0.960	0.929	0.765	0.885
Regular	NA	NA	NA	NA

Table 1 shows a summary on the tests. The composite scores were 0.901 and 0.885 for RegA test and RegD test, respectively. The accuracy, delay and precision sub-scores for RegA test were 0.939, 0.890, and 0.872, respectively. In the RegD test, the accuracy, delay and precision sub-scores were 0.960, 0.929, and 0.765, respectively. As mentioned previously, the acceptable score for PJM frequency regulation market is 0.75. Therefore, it is possible to use the chiller to provide grid frequency regulation with the proposed control strategy.

Fig. 5–6 demonstrates a comparison on the target power and actual power of the chiller during the frequency regulation tests. It is clear that the actual power follows the target power closely in both figures. It is also noticeable that the difference between the target and actual power was large whenever there was a deep change in the target power. For instance, the starting period in both RegA and RegD tests and the time period between 24 and 28 minutes in RegD test. That was because the changing speed of chiller vane opening was limited, and the chiller power had reached its maximum changing speed.

The regulation signals are continuous in practical applications, and those large power difference at the beginning of the tests would therefore be ignored. From this point of view, the chiller power could follow the target power perfectly when RegA signal was in use. However, the power difference between actual and target power could be high when RegD signal was tested.

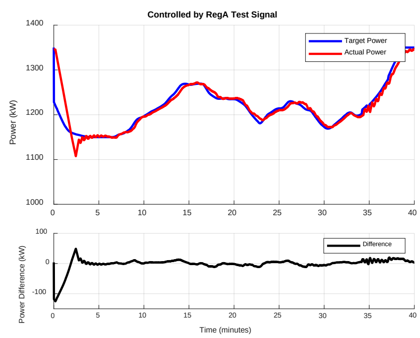

Fig. 5 Variation of chiller power in RegA Test

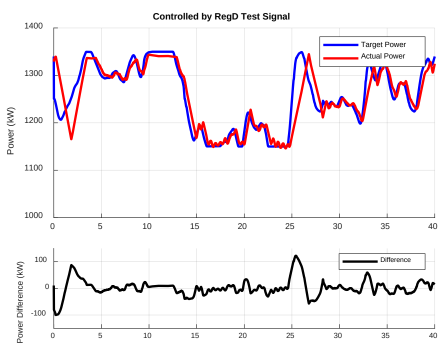

Fig. 6 Variation of chiller power in RegD Test

5. CONCLUSIONS

This study proposes a control strategy for using a large constant speed centrifugal chiller to follow grid frequency regulation signals. It aims to enable a constant speed chiller to follow the grid frequency regulation signals while providing the demanded cooling supply.

Onsite tests show the overall delay time of chiller power was about 20–25 seconds upon changing the settings of power upper limit. The maximum changing speed of chiller vane opening was around 0.4842 %/s. And the maximum ramping speed of chiller power was 2.53 kW/s.

A dynamic platform has been built based on the real chiller plant and fine-tuned based on the onsite tests results. The 40 minutes Regulation A and Regulation D test signals provided by PJM were used in the validation of the proposed control strategy. When providing 100 kW (7.46% of the rated chiller power) regulation capacity, the composite scores were 0.901 and 0.885 for Regulation A test and Regulation D test, respectively.

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