A Controller Algorithm (ILC) for the Variable Differential Pressure Control of Freezing Water in a Central Air Conditioning System

Qingchang Ren and Hongmei Jiang

Abstract In actual operation, due to the change of many factors, the central air conditioning system runs at non-designed working conditions in most of the time. Usually, it works under partial load, cannot meet the maximum load, causes great waste of energy. This paper proposes an Iterative Learning Controller algorithm (ILC) for the air conditioning water system, deal with the variable frequency control for the secondary pump. Optimization settings of water pressure differential value are given according to customer demand and based on the water valve features, thus make water valve in the chilled system having the largest opening as far as possible to provide the required minimum water differential pressure. By this way not only good control effects can be obtained, but also the energy consumption of pump delivery can be reduced.

Keywords Air conditioning system · Iterative learning controller algorithm (ILC) · Variable differential pressure · Energy saving

1 Introduction

In recent years, with the rapid development of the economy in China, the application of the air conditioning system in the buildings is increasing. Air conditioning energy consumption becomes more and more. This made the demand for energy increased. The energy supply appears serious. Reducing the energy consumption of an air

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Q. Fang et al. (eds.), *Advancements in Smart City and Intelligent Building*, Advances in Intelligent Systems and Computing 890,
https://doi.org/10.1007/978-981-13-6733-5_24

conditioning system is necessary, therefore, the research on energy consumption of air conditioning water system is urgent.

In the actual operation, due to the change of many factors, most of the air conditioning systems are not in the designed running condition. They are generally working under the partial load, cannot meet the requirement of the maximum load, and cause a big waste in energy. The reasons are the indoor personnel flow change, the change of outdoor temperature and the indoor heat source and so on. Many factors will make the load of the air conditioning room deviate from the designed condition of the load. Therefore, the design of the air conditioning system should be adjusted along with the load condition, real-time tracking of the load change. The tracking way does not just adjust the air output, that is, the so-called variable air volume (VAV) air conditioning system. The chilled water also can be realized as the variable flow by the control strategy. This paper proposes an iterative learning controller (ILC) on secondary pump frequency control, according to the customer's demand for the differential pressure value of optimization settings. This makes the position of chilled water valve close to fully open state, and provide the required minimum water differential pressure for the system. This method can realize the energy saving of the water pump [1, 2].

2 Variable Water Volume Air Conditioning Systems

Variable water volume (VWV) system refers to the system in which supply and return water temperature difference remains unchanged. If the air conditioning loads change, the water flow can be changed to adapt to the change of the terminal load of the air conditioning system. When the terminal load is reduced, water flow in the water system reduced. The cold quantity is reduced to feed the actual load, therefore, can meet the requirements for the reduction of load. Because the decrease in water flow can reduce the transportation energy consumption of the water system, thus it has significant effects on energy saving.

The main steps of the variable flow technique are based on the actual load changes to adjust the speed of the frozen water pump, in order to realize the chilled water flow control. Usually, the differential pressure is chosen for reflecting the system load changes that means to adjust the speed of the water pump according to the change of the differential pressure. If the selection of the differential pressure value is too large, it will not be able to fully excavate the pump energy-saving potential under the partial load. If the selection of differential pressure value is too small, it may not be able to meet each user's requirements under some conditions. Therefore, how to make balance on the load demand and the pump energy-saving effects is the key problem of the application of variable flow technology. Obviously, the optimal settings of the differential pressure value are very important.

3 Variable Differential Pressure Control

The principle of variable differential pressure control is as follows: when the temperature in the room decreases, the temperature controller turns down the chilled water valve. So it reduces the amount of cold so as to fit the change of the room temperature. The changes of valve opening can be detected by the detector in the valve control system, and then compare measured temperature with the setting value. By means of the frequency conversion controller, the pump speed is adjusted to reduce the indoor cold quantity to make the room temperature rise. When the room temperature controller detects the rise of the room temperature, it will turn the valve up. Thus, it not only meets the air conditioning user's need of load variation, remains the biggest valve opening, lowers the valve resistance loss, and saves the energy consumption of pump delivery.

The schematic diagram of the variable differential pressure control system is shown in Fig. 1. The idea of the variable differential pressure control system is implemented by a certain control algorithm, changing the differential pressure setting value. Under the premise of regulating and stable performance, the guarantee system tries to make the selection of regulating valve in fully open position, so as to minimize the valve throttling losses, and the biggest energy-saving effects can be obtained. Because the change of valve opening reflects the size of the load change to a certain extent, it can be used as adjusting parameters [3, 4].

Considering the differential pressure setting value and valve opening, the setting value can be considered as a variable. In an actual control system, if the adjustment of the valve is in high frequency, the adjustment of the differential pressure value should not set too frequently. That is to guarantee the stability of the water pump

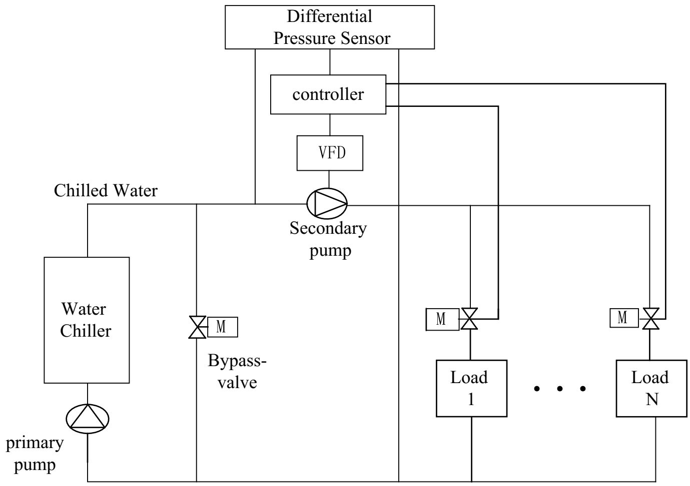

Fig. 1 Schematic diagram of water differential pressure-chilled air-conditioning system

control. As shown in Fig. 1, in the control mode, the specific practices are as follows: (1) Any time all the valve opening is less than 70%, and this state maintains for 30 min, the differential pressure setting value will be decreased by 10%. (2) At least one of the terminal valve position between 70 and 90%, the differential pressure setting value remains the same. (3) At any time the valve opening degree is more than 90%, and this state maintains for 30 min, the differential pressure setting value will be increased by 10%.

Because the selection of the valve in the different branches is different, so the definition of valve fully opening is different. Some of the valve reaching more than 75% is considered as the fully opening valve. So the variable pressure difference control needs not only to detect the valve opening of each branch, but judges the logic value of the valve opening also, takes control algorithm to control the change of pressure difference value according to the requirements of reliability.

4 Variable Differential Pressure Control Based on Iterative Learning Algorithm

In order to compensate process model error caused by the time change, prevent strong shock and avoid system instability, it is required the setting values gradually add to the differential pressure control system. The differential pressure control process is according to the given target trajectory in advance from a steady state to another steady-state operation.

For the differential pressure optimal control process, the controller's setting point produced from the differential pressure setting algorithm is the step sequence of different amplitude. Therefore, the differential pressure amplitude of ideal trajectory will change with the controller set value. At the same time, the ideal trajectory of differential pressure will have good dynamic quality, such as little or no overshoot, quick response in speed, short transition in time and other good characteristics [5, 6]. Therefore, an iterative learning control algorithm (ILC) for variable differential pressure control can be used, and its schematic diagram is shown in Fig. 2, in which $p_1, p_2, \ldots, p_k, p_{k+1}$ refers to the differential pressure value sequence, $y_{dk}(t)$ is the ideal trajectory, $y_k(t)$ is the real output value, and $x_k(t)$ is the input of the last iteration.

4.1 Selection of Ideal Trajectory of Differential Pressure

Pressure difference optimization algorithm is to produce differential pressure value sequence $p_1, p_2, \ldots, p_k, p_{k+1}$, in order to prevent the strong shock and even instability in the system, it is requested every time finding the value to gradually match the pressure difference control system.

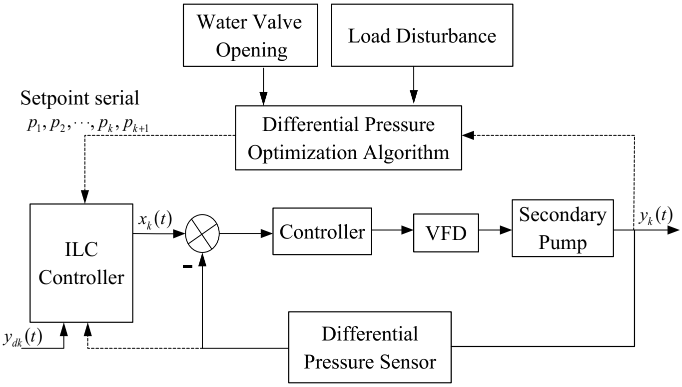

Fig. 2 Schematic diagram of the control system with iteration algorithm

For the differential pressure optimal control process, the ideal trajectory of differential pressure should have good dynamic quality. Thus, the selection of the ideal trajectory of the differential pressure method can be as follows: if the differential pressure corresponds to the set point p_1, select $y_{d1}(t)$; then $y_{dk}(t)$ corresponds to the set point p_k, $y_{dk}(t) = p_k(1 - \frac{1}{(1+t)^n})$, $(n \geq 3)$. For $y_{dk}(t) = p_k(1 - \frac{1}{(1+t)^n})$, the value of n is greater, the response speed is faster.

4.2 *The Iterative Learning Control Unit*

The differential pressure setting algorithm produces the sequence of controller setting values $p_1, p_2, \ldots, p_k, p_{k+1}$. The iterative learning control unit produces current input $x_{k+1}(t)$ of the control system based on the controller setting value p_{k+1}, the real output value of differential pressure controller, the differential pressure ideal track $y_{dk}(t)$ and the input of the last iteration $x_k(t)$. To improve the efficiency of iterative learning control, weighted closed-loop PID type of iterative learning control algorithm can be used:

$$x_{k+1}(t) = \alpha_{k+1}x_k(t) + \Gamma_p e_{k+1}(t) + \Gamma_i \int_0^t e_{k+1}(\mu)d\mu + \Gamma_d \dot{e}_{k+1}(t) \tag{1}$$

$$\alpha_{k+1} = \frac{p_{k+1}}{p_k} \tag{2}$$

$$e_k(t) = y_{dk}(t) - y_k(t) \tag{3}$$

where

k the number of iterations;
α_{k+1} the weighted coefficient;

$e_k(t)$ the error of differential pressure ideal track and actual differential pressures output;
Γ_p learning gains for the proportion;
Γ_i learning gains for the integration; and
Γ_d learning gains for the differential

When the control input $x_{k+1}(t)$ is imposed on the differential pressure control system which purpose is to make the steady-state value of $x_{k+1}(t)$ is equal to the controller setting value p_{k+1} when the transient process is ended.

4.3 Simulation Experiments

In order to verify the correctness of the algorithm, the algorithm simulation needs to be done before the experimental research. The simulation background is a VAV air conditioning system installed in the laboratory of Xi'an University of Architecture & Technology. Identify the model describing the relationship of secondary pump frequency $u(t)$ and the differential pressure $p(t)$ with M sequence. The model is

$$p(t) = 0.78p(t-1) - 0.2273p(t-2) + 0.5115u(t-1) - 0.2093u(t-2)$$

Fitting the differential pressure $p(t)$ and flow rate $Q(t)$ relationship, it can be seen as

$$Q(t) = -0.0001p(t)^2 + 0.0335p(t) + 1.9369$$

The experiment is on a summer day from 8:00 to 20:00. The load changed because the outdoor temperature and indoor load of the air conditioning area changed. The initial chilled water flow and the water pump frequency can be calculated based on the outdoor weather and indoor conditions.

According to the changes of every terminal load, detecting the changes of every frozen water valve opening, using the differential pressure setting algorithm, we can get the differential pressure setting serial as {17, 17, 19, 19, 21, 23, 26, 29, 32, 36, 40, 45, 50, 55, 55, 50, 45, 40, 40, 45, 40, 36, 32, 29, 26}. The effect of differential pressure adopted iterative learning control is shown in Fig. 3.

If the iterative learning control is not adopted, the control effect comparing with the iterative learning control case is shown in Fig. 4.

Figure 4 shows that under the variable pressure difference control system with a differential value of 45 kPa, using the iterative learning control, the maximum deviation is 7.181 kPa, in case of non-using iterative learning control the maximum deviation is 9.168 kPa. The adjusted time is 428 s and 563 s corresponding to using and non-using iterative learning control algorithm respectively. Using iterative learning

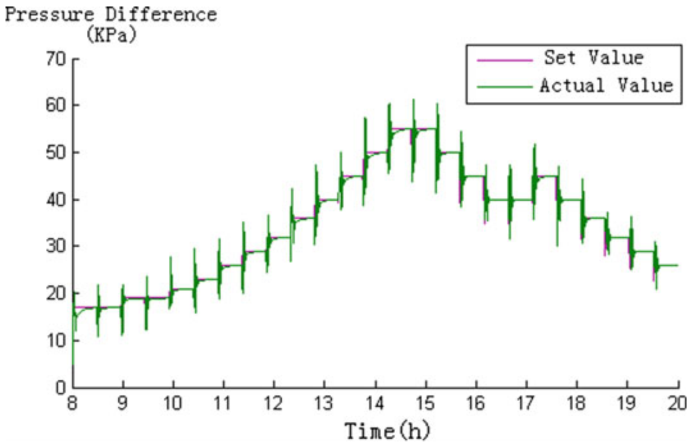

Fig. 3 Iterative learning control effect

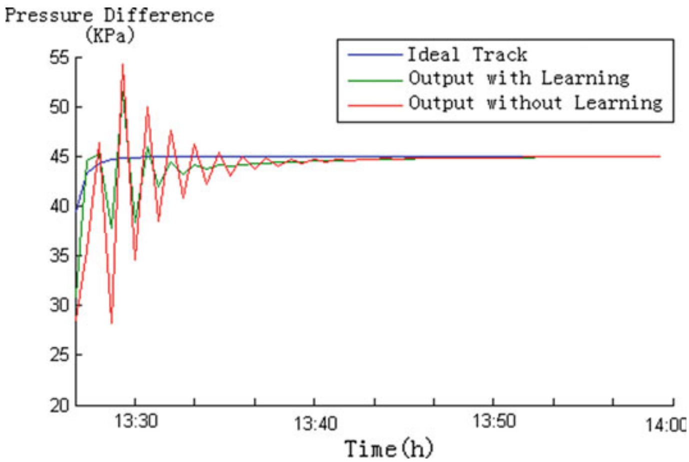

Fig. 4 Iterative learning control comparison chart

control, the steady-state error is 0.0142 kPa and 0.0173 kPa corresponding to using and non-using iterative learning control algorithm, respectively. And observing other indicators, the rise time is accelerated, transition time become shortened. In a word, the dynamic performance of the system is improved significantly.

5 Analysis of Energy Consumption

The differential pressure is associated with the frequency of secondary pump and energy consumption. For secondary pump experiment, the change of secondary pump frequency causes water supply and return pressure difference, and the frequency is obtained by the power measurement of secondary pump power. By the pressure difference and power experimental data, the relationship between differential pressure $p(t)$ and power $W(t)$ can be achieved as

$$W(t) = 0.0015P(t)^3 - 0.1293P(t)^2 + 15.0833P(t) + 322.4632$$

From experimental testing, the secondary pump power curve is shown in Fig. 5.

According to the actual change of pressure difference, the secondary pump power can be measured, which values are changed as {279.441, 274.441, 286.329, 279.441, 274.441, 309.615, 326.793, 343.861, 360.939, 383.937, 407.458, 438.033, 470.439, 511.237, 505.237, 479.439, 438.033, 407.458, 412.458, 438.033, 407.458, 383.804, 360.919, 348.650, 326.732}, its curve is shown in Fig. 5. It can be seen that using the variable and the constant differential pressure control, the energy consumption of secondary pumps is 9486.112 (W.h) and 13200 (W.h), respectively, under conditions of that, the differential pressure should meet the requirements of the maximum load and the measured load power 1100 (W.h). Thus, the energy-saving rate is 28.135%.

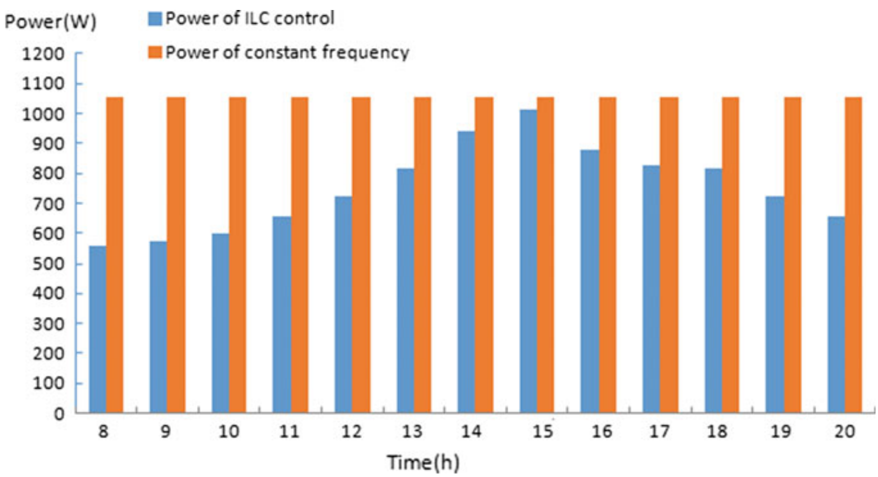

Fig. 5 Secondary pump power change curve

6 Conclusions

The variable water volume in the air conditioning system can be stably adjusted according to the change of the air conditioning system load with the variable differential pressure control algorithm based on the Iterative Learning controller algorithm (ILC). It automatically sets the differential pressure value, meets the demand of the air conditioning load from the users. It always makes the valve opening at the largest, it can lower the heat resistance loss, save the energy consumption of pump delivery. Compared with the conventional constant differential pressure control, this method can effectively reduce the energy consumption of the secondary pump.

Acknowledgements The work was supported by the Science and Technology Project of the Ministry of Housing and Urban-Rural Development, China (No. 2016 - K1 - 013) and the Key Laboratory of Gansu Advanced Control for Industrial Processes, China (Grant No. XJK201813).

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