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Iterative-Feedback-Tuning Control Strategy for Air-conditioning Refrigeration Station Systems

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Abstract. Progress of process control technology has motivated extensive research on various aspects of control for air-conditioning refrigeration systems. In refrigeration station systems, the steady-state operation of the chiller should take into account the roles of temperature, fluid flow, and heat transfer. These are restricted by the following parameters, i.e., (i) demand of refrigeration load, (ii) inlet temperature of condenser, (iii) structure features of the chillers, and (iv) impact of outdoor meteorological parameters. At present, the PID algorithm is widely used to control the operation of water pump in the refrigeration station system. However, PID algorithm may cause oscillation in the case of load changes. Instead, iterative feedback tuning (IFT) method is a model-free method driven by I/O data of the systems. It can adjust the control parameters of the chilled-water pump without destroyed the stable operation of pumps. This thesis is devoted to the development of a fundamental modeling and optimization methodology for the chiller optimal operation of air-conditioning refrigeration-station systems, meanwhile TRNSYS is used for establishing the system model. Based on IFT method, an optimal control system, for the control of constant-temperature-difference between chilled supply and return water, was developed. The iterative feedback controller calculates the optimal control signal of pumps with secant algorithm, and transmits the optimized parameters to the controlled equipment. Therefore, the temperature difference of chilled-water supply and return can maintain at the setpoint of 5 ºC and minimize the tracking error to the least. Simulation results show that, compared with PID algorithm, IFT method achieves better performance.

Keywords: constant-temperature-difference control, iterative feedback tuning method, refrigeration stations, TRNSYS

1 Introduction

One of the major objectives of installing advanced chillers in refrigeration stations is to improve the energy efficiency of systems. In addition, it can be achieved by using optimization algorithm and performing real-time adjustments of operation equipment in the refrigeration process [1]. The primary pump variable flow system is adopted in this paper. The system can use optimized energy-saving control strategy to maintain the temperature difference between chilled-water supply and return at setpoint, thus saving the energy consumption of the system.

However, the consensus is that most refrigeration station systems in practice have not performed to their potential with respect to optimizing functions. One of the reasons for poor performance is the fact that systems are operated at traditional control methodologies such as PID (Proportional-Integral-Derivative) algorithm. PID method, which remains the most dominating role today, has been used in controlling chilled-water pump of refrigeration stations for decades because of its simple structure and easy implement potential. PID controllers are popular in industrial process control in the last years [2]. Whereas air-conditioning refrigeration stations have complex structure and many facilities. As a result, these systems have large hysteresis and control performance is greatly affected by load, which makes parameter tuning more difficult when using PID algorithm [3]. On the other hand, currently intelligent control methods used in industry are heavily dependent on the mathematical model. But for this complex type of air-conditioning refrigeration station systems, it is difficult to obtain accurate mathematical model. To address this need, a more optimized control method of a refrigeration-station system which is suitable for control analysis is required.

Considering the traditional control method in variable flow rate air-conditioning system, on the one hand, it has high requirements for the accuracy of the mathematical model of the controlled system; on the other hand, it restricts its popularization and application in variable flow rate air-conditioning system because of the complex structure, poor control accuracy and anti-interference ability. IFT is a model-free method for the system I/O data-driven, and it was presented by Swedish scholar H. Hjalmarsson in 1994 [4-6]. The iterative feedback controller can control devices only by collecting I/O data and needs not any information of the internal model in the controlled system. Furthermore, the control strategy is not dependent on specific model, and it is easy for adjusting control parameters.

Specifically, IFT method can achieve stable control of constant-temperature-difference between chilled supply and return water, thus realize the optimal operation of air-conditioning refrigeration-station systems. As air-conditioning refrigeration-station systems have complicated structure, and are not easy to be studied in real project directly. This thesis uses the existing modules of TRNSYS (Transient System Simulation Program), which is a set of transient system simulation program software, to quickly establish the model of the chiller, pumps, cooling tower, pipes and other devices. A general system is designed in TRNSYS based on the system work-flow. The use of the control-oriented model has been given the study of IFT method for constant-temperature-difference control, namely using IFT method to control the parameter of the chilled-water pump frequency, thus affecting pump speed as to changing flow of chilled-water. As a result, it achieves constant control of the temperature difference between chilled supply and return water.

2 Iterative Feedback Tuning Method

2.1 Algorithm Principle

Iterative Feedback Tuning (IFT) is a model free technique for tuning the parameters of a fixed structure controller. The basic procedure of this method is as follows. Given controller structure previously, a LQG type optimization performance metrics is proposed for the controlled system. In addition, completing iterative experiment in the closed-loop system, the controller gradient parameters for performance function are calculated with the obtained data in advance. The Gauss-Newton iterative algorithm then is used for searching the controller parameters to minimization index function, and ultimately converging controlled parameter vector to a local minimum.

The outstanding contributions of IFT method is that it gives a non-model approach targeting calculating controller parameters unbiased gradient (ie, the unbiased differential signal of system output) for index function. In particular, however, these differential signals are obtained through estimating the acquisitioned dynamic model of controlled object and perturbation previously.

2.2 Iterative Feedback Tuning Control Formulation

The basic iterative feedback tuning method obtains the control variable for minimizing performance function, thereby tunes the controller parameters.

Consider the following system,

$$y(t) = Gu(t) + v(t) \tag{1}$$

The controller uses,

$$u(t) = C_r(\rho)r(t) - C_y(\rho)y(t) \tag{2}$$

Wherein, $\{v(t)\}$ is a process disturbance signal, $\{y(t)\}$ represents a response signal for the system output, $\{r(t)\}$ refers to the external reference signal, ρ is the controller parameter vector. Setting the desired track $y_d = T_d r(t)$, the error between expected response and actual output is,

$$\tilde{y}(\rho) = y(\rho) - y_d \quad (3)$$

The original version of IFT was derived for a general controller with two degrees of freedom for an unknown, linear and time-invariant system as in Fig. 1.

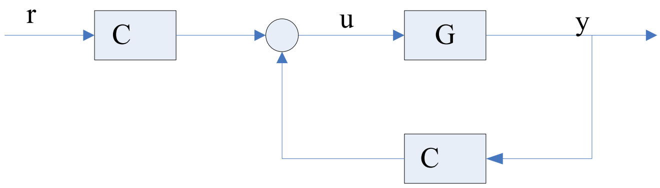

Fig. 1. Schematic diagram of IFT controller

Noted that, the controller C_r, C_y applied to the system G, where r, u, y and v are the reference signal, the control signal, the output signal and a disturbance.

The criterion to be minimized is

$$J(\rho) = \frac{1}{2N} E\left[\sum_{t=1}^{N} (L_y \tilde{y}_t(\rho))^2 + \lambda \sum_{t=1}^{N} (L_u u_t(\rho))^2 \right] \quad (4)$$

Where N is the number of data points, ρ is the controller parameter vector, L_y and L_u are frequency weighting filters, λ is a penalty factor. Note that all signals, except the reference signal r, are dependent of the controller parameters ρ. Note that all signals, except the reference signal r_t, are dependent of the controller parameters ρ and that the optimal controller parameter vector $\rho*$ is the one that minimizes the cost function (4).

$$\rho* = arg\, \min_{\rho} J(\rho) \quad (5)$$

When finding (5) using IFT, a feature is that an estimate of the gradient $\nabla J(\rho)$ of the cost function (4) is given by using signals from an experiment on the closed loop system, without knowing the true system.

2.3 The Application of IFT

The IFT method is compared with the other three typical methods: Z-N method, IMC method and ISE method, and the parameters of PID controller are determined [7]. A relay feedback PID parameter tuning method is proposed in paper [8], which combines the relay auto tuning method with the IFT method. The IFT is applied to the tuning of the time delay controller with positive feedback, which has achieved good results [9].

So far, the effectiveness of the IFT algorithm has been verified in simulation, experiments and petroleum, chemical and other process control industries [5, 10-16]. As IFT algorithm has been successfully applied in: DC servo system with delay [10], a robotic arm, inverted pendulum [11], the helicopter model and friction spring-control object system [12] and water-tank temperature control system ; for the robot joints controller adjustment [13], thermal cycling module control [14], cold-rolled controller tuning [15]. IFT algorithm has also been used in chemical industrial process control, such as temperature control, flow control and IC manufacturing photosensitive corrosion control [16]. Compared with the existing control methods using IFT control system performance has been greatly improved. IFT algorithm with its great strengths and that is not required and the system model favored by more and more scholars to obtain I / O information through the closed loop operation, are more and more areas plays its advantages. Iterative Feedback Tuning (IFT) is also used for tuning PID controllers for the case when it is of interest to reach a new set point level as quickly as possible. It turns out the method of using the IFT is superior to other methods in these two performance indicators of set-time and overshoot [17]. Yun-peng Ju proposed an iterative feedback tuning algorithm (IFT) based on PID controller structure, which uses the closed-loop system input and output data and the linear quadratic Gaussian criterion. It has PID controller parameter setting value obtained, and the hysteresis of the system improved [18]. The dynamic control performance of VAV system is optimized by using iterative learning control strategy, which makes the system energy saving about 18.2% [19]. Using fuzzy gain PD-type iterative learning control algorithm, Shao-xun ZHANG carried out simulation experiments and research on the VAV system. Simulation results show that this method achieves good static pressure control effect [20]. Based on iterative learning control and predictive control, Ji-pu GENG studied the temperature and humidity control of VAV air conditioning. The simulation results show that the iterative learning control can effectively improve the control precision and response speed of the humidity control loop [21].

3 Control System Design

3.1 Primary Pump Systems with Variable Flow Rate in Refrigeration Stations

The model of a primary pump system with variable flow rate is designed by applying the following principles: (i) chilled-water flow and temperature difference between supply and return water should be adjusted with the user-side load, and (ii) evaporator-side flow should be satisfied with load-side flow by using variable flow chillers and frequency-variable pumps. Thereby, it is recognized that a basic principle of such systems should be to control pump speed, so as to provide flow which system required [22].

Refrigeration stations are nonlinear systems with time-varying delay and large inertia. These systems have multi-inputs, such as chilled-water temperature, cooling-water temperature, chilled-water flow, and variable-frequency-pump frequency. It also has multiple-outputs, which include flow rate, temperature, and cooling capacity [23]. The operation process involves adjusting the optimal control problem of variety loops in time and determining optimal values of the control variables. The operating parameters between each loop should change with demand-side load. However, for this kind of complex systems, it is difficult to find precise dynamic-mathematical model, which makes the control problem more difficult.

In terms of its working and control method, the complex refrigeration-station system can be broadly classified into two categories, namely (i) the chilled-water circulation system and (ii) the cooling-water circulation system. And the parameters such as temperature, pressure and flow are often as the contact bridges of the two independent subsystems. The major components of the system are (i) the chillers, (ii) chilled-water pumps, (iii) cooling-water pumps and (iv) cooling towers, and they are controlled by separate circuits.

This thesis studies IFT method for constant-temperature-difference control of chilled water systems. The control objective is to maintain the temperature difference, between chilled supply and return water, at the set-point 5℃ under load changing. Fig. 2 shows a typical model of a chilled water system with variable flow rate considered in this study.

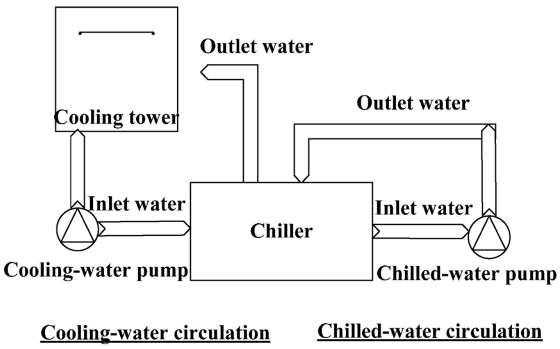

Fig. 2. Schematic diagram of a primary pump system

3.2 Primary Pump Systems with Variable Flow Rate in Refrigeration Stations

A water-cooled vapor compression refrigeration system is composed of an evaporator, a condenser, a variable speed reciprocating compressor and a thermostatic expansion valve. Some of the basic principles involved can be summarized as follows.

In the refrigeration system, the expansion valve is a cascaded device consisting of a main valve driven by a pilot valve. The compressor is powered by an electric motor, and steam is compressed into high-pressure high-temperature steam in it. This refrigerant returns to the evaporator inlet, and releases heat to the cooling medium (water or air) in the condenser.

Paper [24] studied and analyzed the advantages and disadvantages of classical PID algorithm for constant-temperature-difference control, and noted that PID algorithm is essentially three-part compromising of proportional, differential and integral control action. The tuning processes between the three parts affect each other, so it is difficult to receive desired results. PID algorithm cannot solve the contradiction between stability and accuracy. By increasing control action, it can make the deviation reduced and the accuracy improved. However, the stability will also be reduced. Conversely, when limiting the control effect, it can guarantee the stability of system, but yet reduce the accuracy of the control action.

The pumps and valves are used to control water flow rates. Load on the system can be varied by altering the temperatures of the water entering the evaporator and condenser, i.e., varying the operating conditions of these peripheral heat exchangers. Therefore, only the temperature difference between chilled supply and return water that have significant control effects is considered as the controlled variable in this study.

Chiller could satisfy variable-flow (constant-temperature-difference) control at partial load with allowed cooling water flow and could save more energy than constant-flow control (variable temperature difference). The objective of this thesis is achieving constant-temperature-difference control using IFT method, and the schematic diagram is shown in Fig. 3.

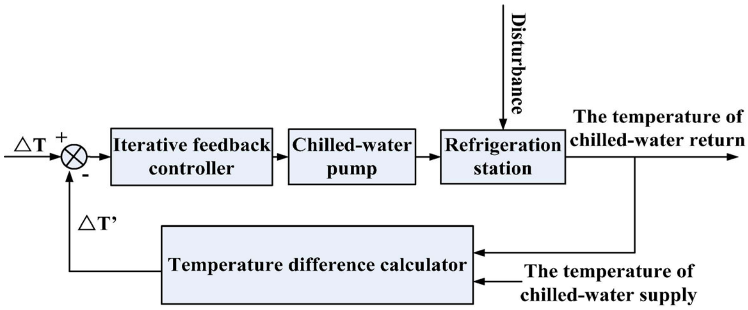

Fig. 3. Feedback loop for constant-temperature-difference control

When load of refrigeration stations changed, variables such as deviation of the measured value with set-point, frequency and flow of chilled-water pumps will also change with it. Eventually this process makes the indoor temperature back to the set-point.

Given the entering temperature conditions of the chiller, temperature difference between chilled supply and return water can be set at 5℃. Compared the measured value with set-point of temperature difference, iterative feedback controller adjusts the inverter output frequency according to the deviation, thus driving the pump operating variable speed rate to regulate flow. As a result, temperature difference between chilled supply and return water is stabilized at 5℃.

4 System Modeling

Design of efficient controllers for air-conditioning refrigeration-station systems largely depends on the availability of good dynamic models of the system. Consider of the fact that the coupling and interaction of each variable is serious in air-conditioning refrigeration station systems, it is necessary to establish an accurate model of the system. The models developed would be useful for comparison, validation and more importantly for finding global optimal dynamic operating strategies. This thesis uses IFT method for the design of multivariable controller in simulation of energy management and control systems.

4.1 Cold-source Equipment in TRNSYS

A centralized air-conditioning refrigeration station system is simulated in TRNSYS software, and the mathematical model of main cold-source equipment module are introduced are introduced as follows.

Chiller (Type666). In each simulation step, Type666 analyzes cooling-water temperature, and then determines the initial value of the chilled-water temperature, and returns COP value (coefficient of performance).

Frequency chilled-water pump (Type 110). Type110 is a changeable rotational speed water pump with any output of 0 to ratings. Type110 flow rate as an input. A comparison can be constructed between the current input control signal and set-point when Type110 automatically detects its flow rate parameters, then the output flow rate is set.

Constant-frequency cooling-water pump (Type 114). Type114 is in on when control signals greater than or equal 0.5, meanwhile the cooling-water flow rate is matched versus nominal flow rate immediately. Otherwise, Type114 is in the off state, other values are 0 in addition to the pump with the input water temperature remains the same.

Cooling tower(Type51). A heat change will occurred to the superheated steam and outdoor air due to the temperature difference between them. After that, the cooling-water temperature is down. Type 51 can achieve a parameters setting of cooling tower capacity and sump volume.

4.2 System Modeling

Each system is consisted of several subsystems (i.e., modules), and each module can implement a specific function attributed to TRNSYS features of modular. Therefore, a system can be simulated and analyzed when just calling these particular function modules and giving suitable input conditions. In addition to the component models discussed above, effort is also being devoted to system models. A set of system model includes a complete set of system components. In terms of the refrigeration principle of air-conditioning refrigeration-station systems, a set of dynamic model was developed. Fig. 4 shows a schematic diagram of the model of the air-conditioning refrigeration-station system considered in this study and it is established by TRNSYS. In this thesis, the major components module of the system are called from TRNSYS: (i) a chiller (Type666); (ii) a variable-frequency chilled water pump (Type110), (iii) a fixed-frequency cooling water pump (Type114); (iv) a cooling tower (Type51); (v) weather data (Type15).

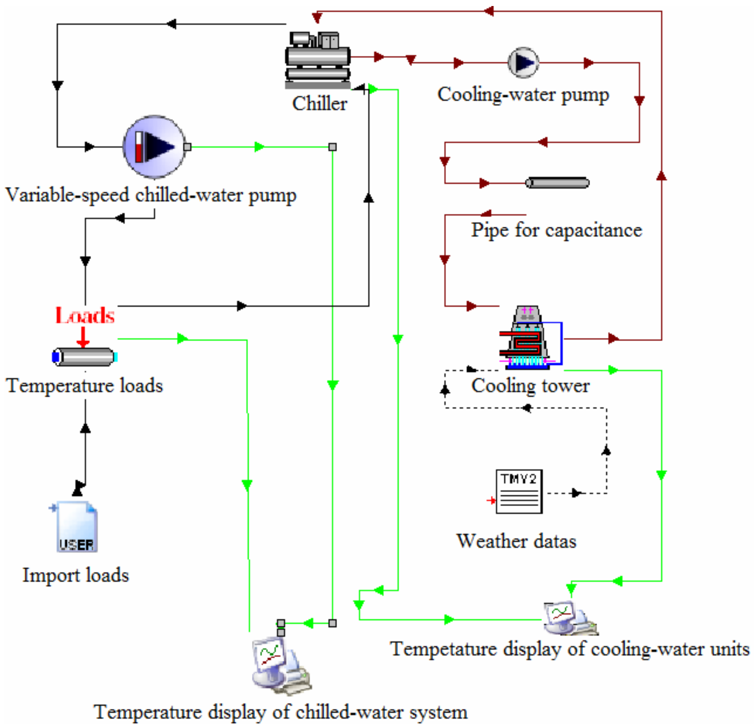

Fig. 4. Schematic diagram of an air-conditioning refrigeration-station system established by TRNSYS

4.3 Load Data

In order to study control strategies, the changing load data is introduced, which is shown at Fig. 5. The measured weather data mentioned is the monitoring data of annual weather for a building in Beijing.

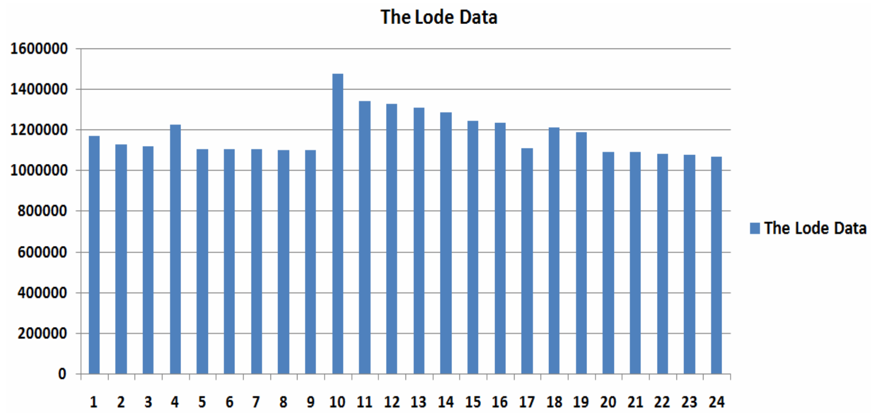

Fig. 5. The load data of a building in one day of late July (0hr-24hr)

The optimization methodology for global optimal operation of a refrigeration-station system takes account of dynamic data of the building, system components and the operation schedules of refrigeration-station systems. Current practice in the refrigeration system usually involves tuning the experimental hysteresis settings to some desired threshold of temperature control. Note that the desired temperature of chilled return water in this study is set at 7℃ considering actual project, and the control objective is to make the temperature difference maintained at the set-point 5℃ in the case of load changing.

5 Control Strategy

Currently, most of refrigeration-station systems are running in low-load conditions, and it often occurs that the chiller runs in large flow but small temperature difference. However, because of its high nonlinearity, large hysteresis, and the dynamic interactions between the building and all refrigeration-station system components, control system have not been developed. Therefore, to obtain satisfactory control performance, iterative feedback control is more suitable. On the one hand, IFT method has no use for a precise mathematical model. And on the other hand, the parameters of IFT method adjust conveniently. For the large hysteresis characteristics on refrigeration station systems, IFT method can be timely to tune the controller parameters by recursive computation. And compared with PID algorithm, it can achieve the desired control performance more quickly.

5.1 Performance Assessment

The iterative feedback controller calculates the control signal (u) required to maintain the controlled variable (y) at the set-point (y_{set}). It uses TRNSYS iterations to provide accurate set-point tracking. This controller can be used to model a real feedback controller that would adapt its control signal continuously or using a discrete time step much shorter than the TRNSYS simulation time step. The controller has an on/off signal and bounds can be fixed for the control signal.

In this section, attention is focused on the performance of algorithm, and the performance index to be minimized is defined as:

$$J = (y - y_{set}) \tag{6}$$

Wherein, y is the temperature difference between chilled supply and return water. And y_{set} is the set point of temperature difference(This thesis sets it at 5℃).

5.2 Optimization Algorithm

Iterative feedback turning method for solving nonlinear equations is successive approximation algorithm. The iterative feedback controller tracks the tracking error x_k (x_k=y-y_{set}) with secant method. The secant method calculates output signal $f(x_k)$ of controller for minimizing tracking error. In terms of extremely complex refrigeration-station systems, the iterative algorithm is extremely complicated. As to obtain the first derivative of the calculation function $f(x_k)$, the roots can be obtained by secant method. Secant method can improve the initial value by using linear interpolation or extrapolation.

Typically, the derivative is more difficult because of complex function $f(x_k)$. This section describes an iterative algorithm for identifying the parameter x_{k+1}. It can be noted that the Newton's formula (7) $f'(x_k)$ is substituted of (8), i.e., the difference approximation.

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)} \tag{7}$$

$$f'(x_k) = \frac{f(x_k)-f(x_{k-1})}{x_k - x_{k-1}} \tag{8}$$

So get formula:

$$\begin{cases} 初値 x_0, x_1 \\ x_{k+1} = x_k - \dfrac{f(x_k)}{f(x_k)-f(x_{k-1})}(x_k - x_{k-1}) \\ (k=1,2,...) \end{cases} \tag{9}$$

Wherein, $x_{k+1}$is the root approximation of $f(x) = 0$, x_0, x_1 are the initial values of secant method.

The secant method is an optimization algorithm proposed in the case which some functions of derivation are extremely difficult or inconvenient. In numerical analysis, the secant method is a root-finding algorithm that uses a succession of roots of secant lines to better approximate a root of a function $f(x)$. For large and complex systems, such as refrigeration stations, secant method can be used to solve derivative. Derivatives typically use the finite difference quotient for approaching, as shown in Fig. 6.

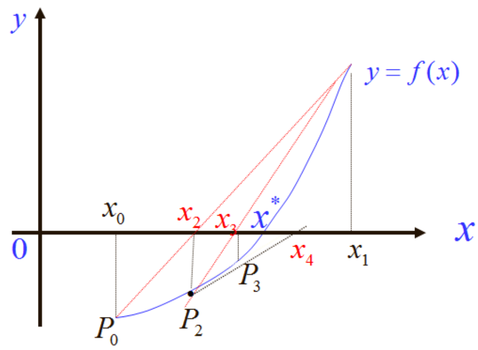

Fig. 6. Illustrates of secant method

6 Simulation Results

It is apparent that the dynamic model developed in this study can be suitably tuned to reflect the actual building-system parameters and then can be used to simulate different operating scenarios. With this knowledge of zone temperature responses, the air-conditioning refrigeration-station system could be started ahead of time to bring the zone temperature back to comfort set-points. Such results will be of great value in assessing several different operating strategies which will translate into significant energy savings when implemented on real systems.

It is apparent that the dynamic model developed in this study can be suitably tuned to reflect the actual building-system parameters and then can be used to simulate different operating scenarios. Note that compared to the full-off case, this thesis respectively use PID algorithm and IFT method as simulated operating strategies for control of chilled water system with variable flow rate in the refrigeration station using the developed control system model. As shown in Fig. 7, the PID control module is introduced to the refrigeration-station control system. In this thesis, in order to obtain better tuning parameters of PID controller by trial and error, and the optimal PID parameters finally set at K_p = 0.05, T_i = 0.001s, T_d = 0.001. In this case, the temperature difference between chilled supply and return water can be controlled at 5 ℃. Fig. 9 shows the typical space temperature oscillation performance based on PID control. And it can be seen from the curve that, although it achieves the objectives, it has an adjusting time of 8hr, and the temperature of chilled return water still fluctuates at 12 ℃. As a result, the system response is slow, and parameter tuning of the controller is extremely difficult.

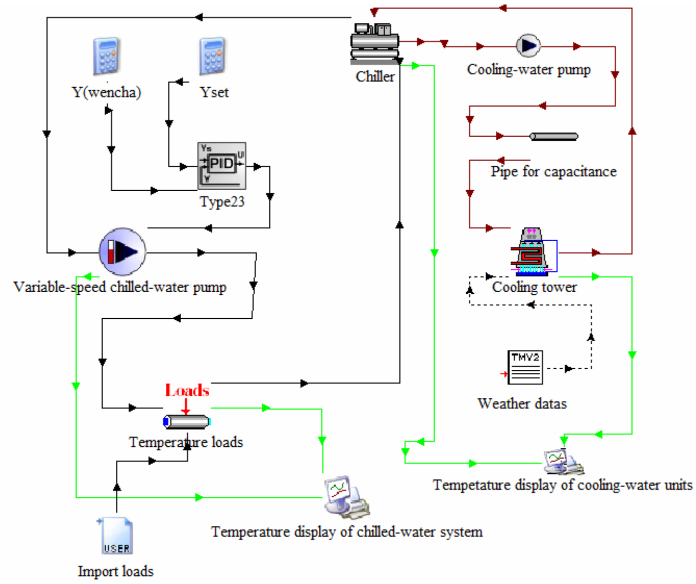

Fig. 7. Schematic diagram of the air-conditioning refrigeration-station system with PID algorithm

For optimized parameters, algorithms of these equipment modeling programs is designed in MATLAB. And optimization parameters are transferred to the corresponding modules in TRNSYS. Fig. 8 shows the general layout of the co-simulation platform for MATLAB and TRNSYS.

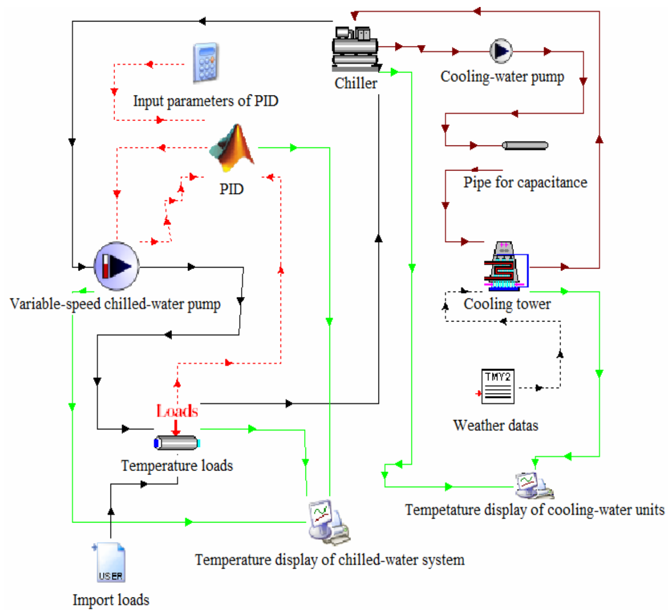

Fig. 8. Co-simulation platform for MATLAB and TRNSYS

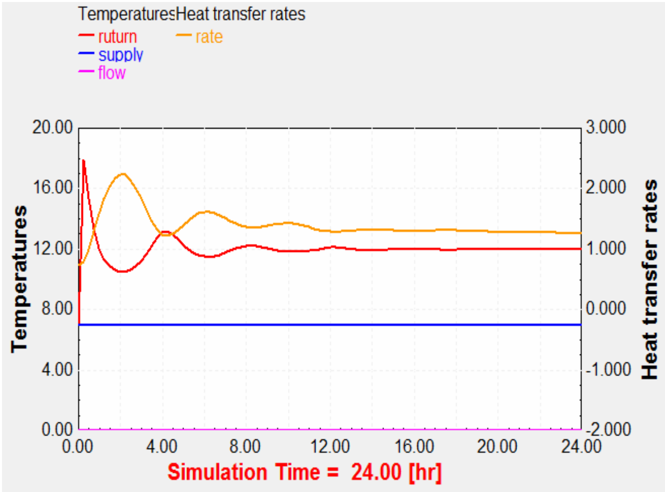

Fig. 9. System temperature response with PID algorithm

The co-simulation between MATLAB with TRNSYS is implemented through the module Type155, which calls the MATLAB program in TRNSYS main program processing. Unusually, this called program mentioned above is a M-files having fixed format which written depending on a particular control strategy. It is noted that the data communication of two software simulation is achieved through the COM component.

Since the parameter tuning process of PID algorithm is extremely difficult, and the control effect is not satisfactory. Retaining the same set of parameters, the system introduces iterative feedback control module. This developed control system is shown in Fig. 10 and the simulation time is set at one day of late July (0hr-24hr). The result of this simulation is shown in Fig. 11. The curve of temperature difference between chilled supply and return water is obtained by TRNSYS simulation.

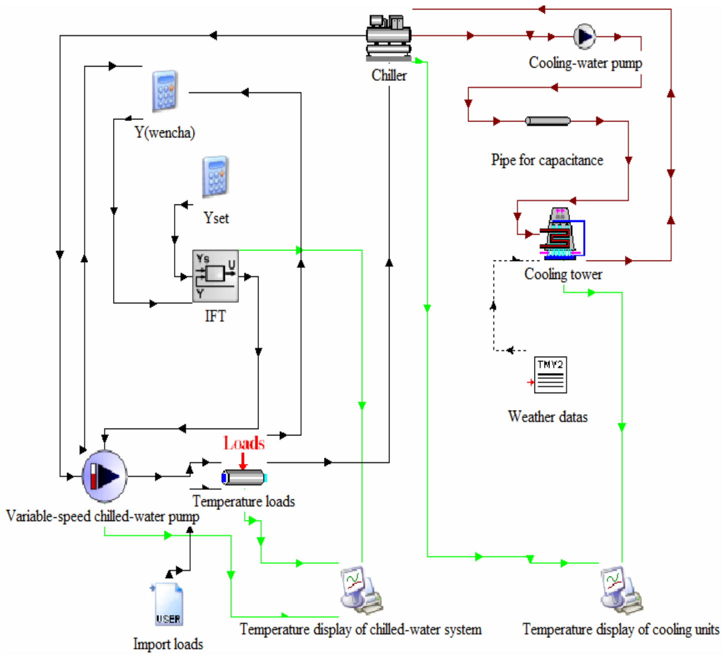

Fig. 10. Schematic diagram of air-conditioning refrigeration-station system with IFT method

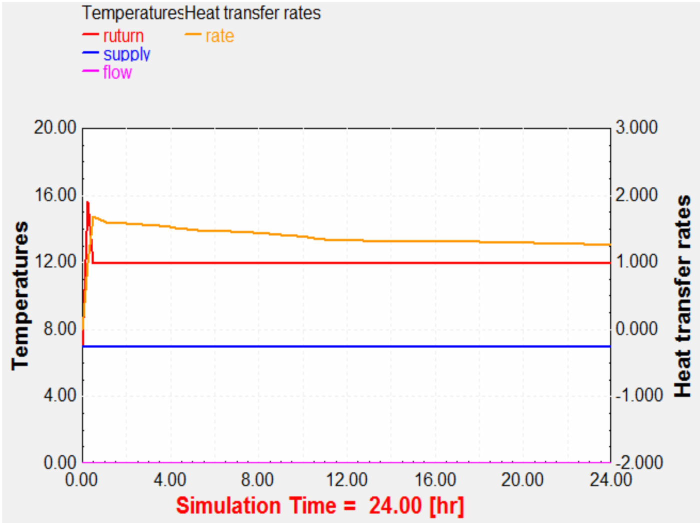

Fig. 11. System temperature responses by using IFT method

It can be noted that, compared to PID control, the system with IFT method has only slight difference between set-points with actual operation results. In other words, the control system can make temperature difference between chilled supply and return water immune to affecting of load changes. In addition, temperature difference is very close to the set-point, and the system has the adjusting time of 0.5hr.

In addition, it can be noted from the simulation results, the iterative-feedback-control system adjusts and regulates the zone temperatures at 02:00. And the system has shorter adjusting time and can obtain more stable responses. Therefore, compared with PID algorithm, IFT method is more suitable for temperature difference control of the chilled water system with variable flow rate.

7 Conclusions

Development of a comprehensive modeling and optimization methodology for air-conditioning refrigeration-station system has been presented in this thesis. Compared classical PID algorithm with the IFT method, it should be noted that IFT method performs much better than PID algorithm in the case of achieving constant-temperature-difference control of chilled-water systems with variable flow rate. Simulation results shows that, compared with PID algorithm, IFT method has shorter adjusting time and excellent stability, and it applicable for the constant-temperature-difference and variable flow control in centralized air-conditioning refrigeration stations.

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