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Development an Adaptive Incremental Fuzzy PI Controller for a HVAC System

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Abstract: This paper presents an adaptive incremental fuzzy PI controller (AIFPI) for a heating, ventilating, and air conditioning (HVAC) system capable of maintaining comfortable conditions under varying thermal loads. The HVAC system has two subsystems and is used to control indoor temperature and humidity in a thermal zone. As the system has strong-coupling and non-linear characteristics, fixed PI controllers have poor control performance and more energy consumption. Aiming to solve the problem, fuzzy control and PI control are combined together organically. In the proposed control scheme, the error of the system output and its derivative are taken as two parameters necessary to adapt the proportional (P) and integral (I) gains of the PI controller based on fuzzy reasoning according to practical control experiences. To evaluate the effectiveness of the proposed control methods in the HVAC system, it is compared with a fixed well-tuned PI controller. The results demonstrate that the AIFPI controller has more superior performance than the latter.
Keywords: HVAC system, adaptive control, fuzzy logic control, PI control.

1 Introduction

Commercial and industrial HVAC applications use electric and mechanical control system to maintain the desired temperature humidity level, and static pressure within a given area or zone. Good HVAC control schemes help reduce energy used and maintain occupant comfort. In spite of many advance in control theory, simply controllers of PI/PID type are still widely used in the majority of HVAC control loops [1]. There are three common methods for determine "good" values for the gain, integral time constant and derivative time constant of a PI/PID controller: manual tuning, auto tuning and adaptive control method [2]. For thermal load disturbances, variation of fluid flowrate, heat exchangers fouling or wear on valves, most HVAC systems have nonlinear, strong-coupling and time-varying dynamics [3]. A problem using conventional PI controllers in HVAC control systems is that control performance varies as conditions change and loops may become sluggish or oscillatory at certain times [2].

According to Åström, a fixed gain controller should be used for systems with constant dynamics, and adaptive control methods should be used for processes with time varying dynamics [4]. Consequently, we should use adaptive control methods in the HVAC industry. Some work has already been done in this area. For example, the development of control strategies for improving the performance of PID controllers using self tuning and adaptive control PI control techniques for HVAC systems has been studied in recently years [5]. The controllers normally have two parts: online identification and controller tuning. And the Recursive Least Square (RLS) method is commonly used by the identification part. However, it has been reported that unmodeled process disturbances and actuator hysteresis limit the effectiveness of the RLS [6]. Then, the traditional adaptive control methods based on the identification have limitations in HVAC control applications, such as absence of robustness.

Intelligent adaptive control using AI (Artificial Intelligence) techniques don't need the identification procedure and can also adapt to the various situations in real time [7]. It has both adaptability and robustness characteristics. Therefore, the adaptive control based on AI techniques has acquired more attention in application to HAVC systems since the end of last century [8]. Zaheer-Uddin [9] has utilized a Neuro-PID algorithm for tracking control of a discharge air temperature (DAT). The ANN (Artificial Neural Network) is used to calculate the gain coefficient of PID controller. Results show that the controller is able to track set point trajectories efficiently in the presence of disturbances. Seem [10] has described a method for automatically adjusting the gain and integral time of PI controllers based upon patterns that characterize the closed-loop response for HVAC systems. This new pattern recognition adaptive controller (PRAC) is easy to use and can provides near-optimal performance for a range of systems and noise levels.

Fuzzy logic control, also a method of AI techniques, is proposed by Zadeh in 1973 and has been widely applied to industry areas [11]. It presents a good tool to deal with complicated, non-linear and time-variant systems. To utilize the advantages of fuzzy control and the existing PI controllers in HVAC control systems, we design an adaptive incremental fuzzy PI (AIFPI) controller, within which the parameters of the PI controllers can be updated online as a function of operational conditions to adapt to various load disturbances in HVAC systems.

2 HVAC System and System Models

A single thermal zone HVAC system for control analysis is considered [12]. The schematic diagram of the HAVC system and its control system is shown in Fig.1. The HVAC system consists of the following main components: a cooling coil, a supply air fan, a thermal zone, connecting ductwork, water pipe, and filter. The control system includes temperature sensors, humidity sensors, a Variable Frequency Drive (VFD), a water valve and a centralized controller, etc.

The basic operation mode of the HVAC system is considered as follows: initially, 25% fresh air enters the system and is mixed with 75% of the recirculated air, the remained air is exhausted. Then, the mixed air passed through the cooling coil where it is conditioned according to the thermal zone designed temperature. Next, the conditioned air is delivered by a supply fan and the flow rate of the air is adjusted to maintain the thermal zone humidity. Furthermore, the supply air enters thermal space to offset sensible and latent loads acting on the system. Finally, the air in the room space is recirculated and the remained air is exhausted to the outside environment. During the operation, the flow rate of the water and the air is modulated to maintain the setting points of the temperature and the humidity in the thermal space.

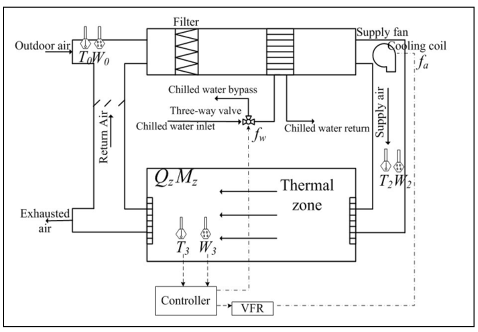

Figure 1: Schematic diagram of the HVAC system and its control system

According to the energy and mass balance of the HVAC system, the differential equations of the system mathematical model can be described as follows [12]:

$$\begin{cases} \frac{dW_3}{dt} = \frac{(W_2-W_3)f_a}{V_z} + \frac{M_z}{\rho_a V_z} \\ \frac{dT_3}{dt} = \frac{(T_3-T_2)f_a}{V_{he}} + \frac{0.25(T_0-T_3)f_a}{V_{he}} - \frac{h_w(0.25W_0+0.75W_3-W_2)f_a}{C_{pa}V_{he}} \\ \frac{dT_3}{dt} = \frac{(T_2-T_3)f_a}{V_z} - \frac{h_{fg}(W_2-W_3)f_a}{C_{pa}V_z} + \frac{1}{\rho_a V_z C_{pa}}(Q_z - h_{fg}M_z) \end{cases} \tag{1}$$

where C_{pa} is the specific heat of air (1.004kJ/kg.K);C_{pw} is the specific heat of water (4.183kJ/kg.K); f_a is the flow rate of air(m^3/s);f_w is the flow rate of water(m^3/s);h_w is the enthalpy of liquid of water(790.84kJ/kg);h_{fg} is the enthalpy of water vapor(2500.45kJ/kg);M_z is the moisture load (0.021kg/s);Q_z is the sensible heat load (84.93kJ/s);T_0 is the temperature of outside air (K);T_2 is the temperature of supply air (K);T_3 is the controlled temperature of thermal space(K);V_{he} is the volume of cooling coil (1.72m^3);V_z is the volume of room space (1655.11m^3);W_0 is the humidity of outside air (0.018kg/kg);W_2 is the humidity of supply air(0.007kg/kg);W_3 is the controlled humidity of thermal space (kg/kg); ρ_a is the density of air (1.185kg/m^3); ρ_w is the density of Water(1000kg/m^3).

3 Design of an Adaptive Increment Fuzzy PI Controller

Fig.2 shows the schematic diagram of the proposed controller and its application to the HVAC system. The control system is composed of two control loops. One is to control the indoor humidity (W_3) by regulating the frequency of the supply fan. The other is to control the indoor temperature (T_3) by regulating the opening of the bypass valve. Due to the complex characteristics of the HVAC system, it is difficult for fixed PI controllers to maintain the indoor environment and keep comfort situations

Fig.3 shows the infrastructure of the AIFPI controller. The control scheme is mainly composed of two parts: Fuzzy controller and PI controller, the increment of proportional and integral gains of the PI controller can be adjusted by the Fuzzy controller in real-time according to the error of the system output and the change of the error.

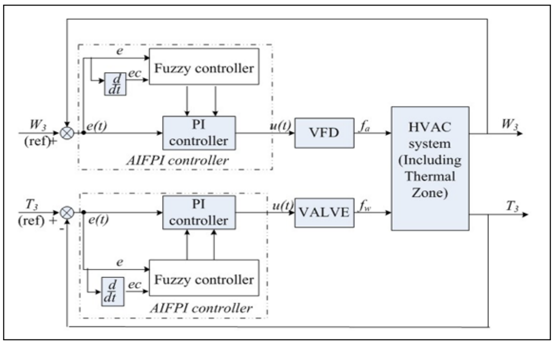

Figure 2: Schematic diagram of the AIFPI controller for the HVAC system

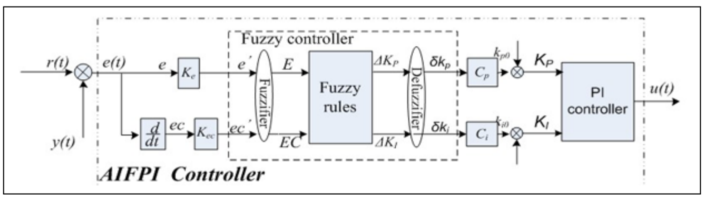

Figure 3: Infrastructure of the AIFPI controller

In Fig.3, $r(t)$ is the desired setpoint for process output and $y(t)$ is real process output; $u(t)$ is the fuzzy PI controller output;e is the error at sampling time t defined as $e= r(t)$; ec is the change of the error; K_e and K_{ec} are input scaling factors of the fuzzy controller; Multiplied by K_e and K_{ec} separately, e' and ec' are the input variables of the fuzzy controller, which can be regarded as equivalent to e and ec. C_P and C_I are output scaling factors of the fuzzy controller;k_{p0} and k_{i0} represent initial proportional and integral gains of the PI controller;E and EC are Fuzzy sets of e' and ec'separately; ΔKP and ΔKI are fuzzy sets of δk_p and δk_i. They are the increment of proportional and integral gains of the PI controller. And K_P and K_I are proportional and integral gains of the PI controller. As the kernel of the fuzzy controller, the fuzzy rules are composed of the generalized forms "if –then" to describe the control policy and can be represented as follows.

R$^{(n)}$: If z Then{ δk_p is $\Delta KP_i^{(n)}$ and δk_i is $\Delta KI_i^{(n)}$} i=1, ...,m;

where $E_i^{(n)}$,$E_j^{(n)}$,$\Delta KP_i^{(n)}$ and $\Delta KI_i^{(n)}$are linguistic terms of E ,EC, $\Delta KP$and ΔKI .

According to the Mamdani inference rule, the fuzzy vector-matrix composition relation of ΔKP and ΔKI can be described as in follows:

$$\begin{cases} R_P = R_1 \cup R_2 \cdots \cup R_n = \bigcup\limits_{m=1}^{n} R_i \ \ (m = 1, \cdots, 49) \\ R_I = R_1 \cup R_2 \cdots \cup R_n = \bigcup\limits_{m=1}^{n} R_i \ \ (m = 1, \cdots, 49) \end{cases} \tag{2}$$

Then, the fuzzy rule bases for determination of $\Delta KP$and ΔKI can be presented as

$$\begin{cases} \Delta KP = (E \times EC) \cdot R_p, \\ \Delta KI = (E \times EC) \cdot R_i, \end{cases} \tag{3}$$

As shown in Fig.3, the proposed fuzzy PI controller can be formulated as

$$\begin{cases} K_P = k_{p0} + \delta k_p \cdot C_p \\ K_I = k_{i0} + \delta k_i \cdot C_i \end{cases} \tag{4}$$

where the output crisp values, δk_p and δk_i can be calculated by the center of gravity methods. Thus, the output of the fuzzy PI controller can be given by

$$u(t) = K_P e(t) + K_I \int_0^{\tau} e(t)dt \tag{5}$$

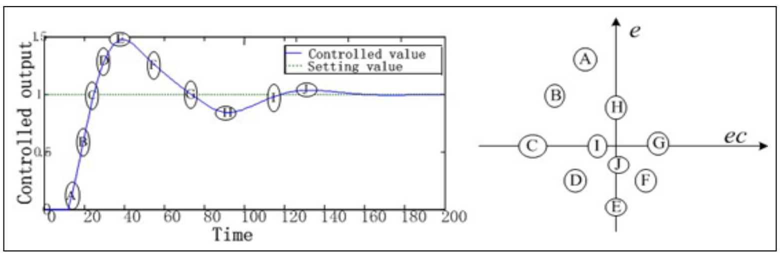

Figure 4: Infrastructure of the AIFPI controller

Fig.4 shows the diagram of controlled output regions at a step response and these regions' positions in a rectangular coordinate. The controlled output can be divided into ten regions. In the control scheme, the variation of incremental parameters of the PI controllers is relevant with the e and ec.And each of input and output variables are fuzzified using seven fuzzy sets. The linguistic terms of the fuzzy sets are negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), positive big (PB). The shape of the fuzzy sets, i.e. member functions, is chosen to be either triangle or Z-shape curve ones. The relation between ΔKP, ΔKI and E, EC can be summarized as the fuzzy rules in Table1, where the content in the first and second brackets represents the ΔKP and ΔKI separately.

Table 1 Fuzzy rule base for determination of ΔKP ,ΔKI based on E *and* EC

E	***EC***						
	PB	PM	PS	ZE	NS	NM	NB
PB	(NB)(PB)	(NB)(PB)	(NM)(PM)	(NM)(PM)	(NM)(PS)	(Z)(Z)	(Z)(Z)
PM	(NB)(PB)	(NM)(PB)	(NM)(PM)	(NM)(PS)	(NS)(PS)	(Z)(Z)	(PS)(Z)
PS	(NM)(PB)	(NM)(PM)	(NS)(PS)	(NS)(PS)	(Z)(Z)	(PS)(NM)	(PS)(NS)
Z	(NM)(PM)	(NM)(PM)	(NS)(PS)	(Z)(Z)	(PS)(NS)	(PM)(NM)	(PM)(NM)
NS	(NS)(PS)	(NS)(PS)	(Z)(Z)	(PS)(NS)	(PM)(NS)	(PM)(NM)	(PM)(NB)
NM	(NS)(Z)	(Z)(Z)	(PS)(NS)	(PS)(NS)	(PM)(NM)	(PB)(NB)	(PB)(NB)
NB	(Z)(Z)	(Z)(Z)	(PS)(NS)	(PM)(NM)	(PM)(NM)	(PB)(NB)	(PB)(NB)

4 Application of the AIFPI Controller to the HVAC System

The AIFPI controller is applied to the HVAC system described in section 2. In the control system, there are two control loops to maintain the indoor temperature and humidity separately. There are hence two controllers in the control scheme (Fig.2).They have the same member functions of E, EC , ΔKP and ΔKI depicted in Fig.5. However, other parameters of the two AIFPI controllers, such as K_e, K_{ec}, C_p and C_i have different values to achieve good performance. From Fig.5, it can be found that the input variables of the fuzzy controller in the proposed control

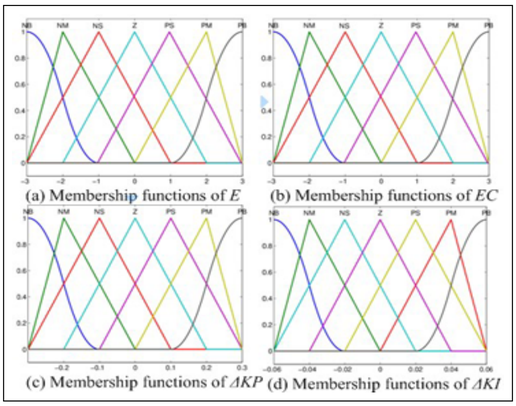

Figure 5: Member functions of the proposed AIFPI controller

scheme, e' and ec',which are equivalent to the error e and the change of error ec are all quantized inside [-3, 3]. The output of the fuzzy controller, δk_p and δk_i, which are incremental proportional and integral gains of the PI controller are quantized inside [-0.06, 0.06] and [-0.3, 0.3] separately. A proper choice of input and output scaling factors K_e, K_{ec}, C_p and C_i is important for the AIFPI controller to achieve good performance of the two control loops. After plenty of trials, the values of K_e, K_{ec},C_p and C_i for controlling the indoor temperature are set as 6.5, 3, 1.6 and 10. And that for controlling the indoor humidity are 2.2, 4, 1.5 and 10. To evaluate the effectiveness of the proposed AIFPI controller, its control performance is compared with a fixed well-tuned PI controller, which adopts the PI/PID tuning rules proposed by Wang [13]. It has been proved that the auto-tuning controller using the PI/PID tuning rules has good performance for HVAC systems [14]. Their behavior is all evaluated with MATLAB/Simulink simulation using the HVAC system model described by Eq.(1) and predefined load disturbances, which are used to simulate non-linear, strong coupling and time-variable characteristics of the HVAC system.

(1)Comparison with different moisture load in the HVAC system

Fig.6 shows the controlled temperature and humidity subjected to different moisture load during the simulation. In the beginning, the moisture load is 0.021kg/s, the setting points of the humidity and the temperature are 0.009kg/kg and 298.15K. At the 400^{th} sampling time, the moisture load is improved to 0.031kg/s to evaluate the control performance of the proposed controller.As shown in Fig.6, it can be found that the variation of the load disturbances is one of the important factors which will influence the stability of the controlled loops in the HVAC system. Good controllers can recover the stability and accuracy of the controlled variable quickly. It can be seen that the proposed controller achieves more superior performance than the well-tuned PI controller considering the transition time and the overshoot subjected to different moisture load disturbances. Fig.7 and Fig.8 also present the variation of the proportional and integral gains of the proposed controller during the simulation. It can be also found that the proportional and integral gains can adapt to the different load disturbances and attain new stable status when offsetting them.

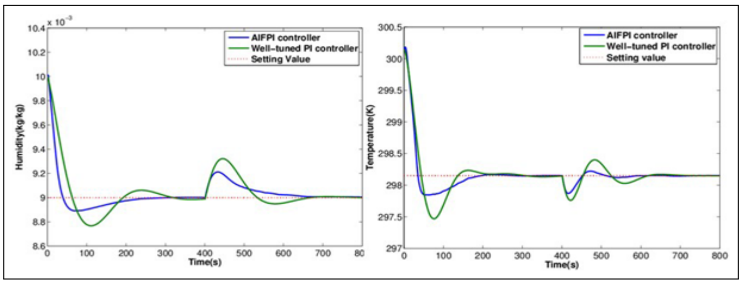

Figure 6: Controlled humidity and temperature with moisture load disturbances

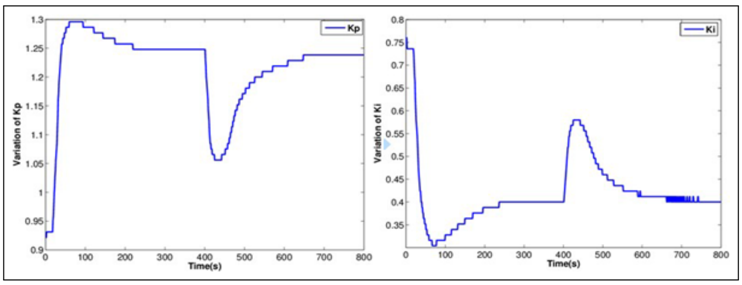

Figure 7: Variation ofK_p and K_i of the AIFPI controller for controlling the humidity

(2)Comparison with different cooling load in the HVAC system

In HVAC systems, cooling load is changing all the time during a day. The variation of the cooling

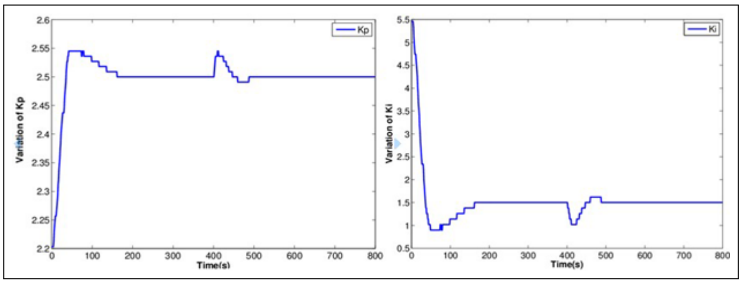

Figure 8: Variation of K_p and K_i of the AIFPI controller for controlling the temperature

load will lead to oscillation and drift of the controller variable, the indoor comfort then will be reduced. In order to evaluate the control performance subjected to cooling load disturbances for the proposed controller followed situations were simulated. In the beginning, the cooling load in the thermal zone is set as 84.93kJ/s, and the setting point of the humidity and the temperature is 0.009 kg/kg and 298.15K. At the 400^{th} sampling step, the cooling load is increased by 40kJ/s.

Fig.9 shows the temperature and the humidity response of the two control loops. It can be seen that the proposed controller has less overshoot and quicker response speed than the well-tuned PI controller. It can be also found that the humidity will not be influenced subjected to the cooling load in the HVAC system. The variation of the proportional and integral gains of the controller controlling the temperature is shown in Fig.10. It can be concluded that the proposed controller has good adapt ability and control performance subjected to the cooling load disturbances.

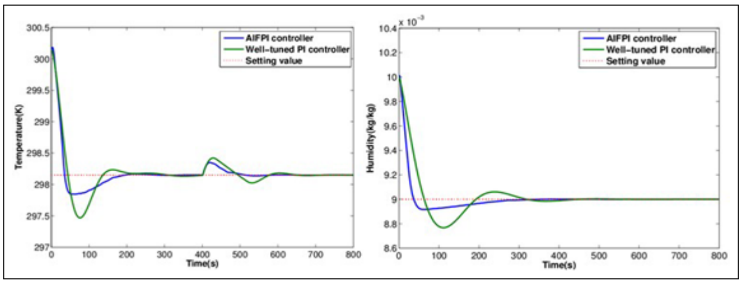

Figure 9: Controlled humidity and temperature with different cooling load disturbances

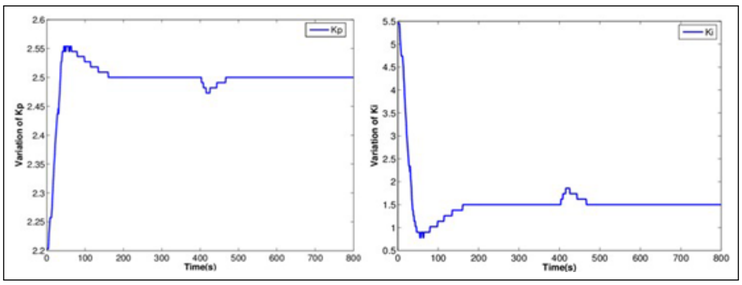

Figure 10: Variation of K_p and K_i of the AIFPI controller for controlling the indoor temperature

5 Conclusion

In this paper, an AIFPI controller is developed and applied to a HVAC system, which has two subsystems and is used to maintain temperature and humidity in a thermal zone. Taking full advantage of fuzzy logic control and PI control together, the proposed AIFPI controller uses Fuzzy logic to supervise PI controller parameters. In the control scheme, the incremental parameters of a PI controller are updated online as a fuzzy function of the operating conditions to improve the behavior of classical fixed PI controllers. The results demonstrate the AIPFI controller has good adaptability to the non-linear, strong coupling characteristics of the HVAC system. It performs significantly better control performance than the well-tuned PI controller considering response time and overshoot subjected to different moisture load disturbances or cooling load disturbances during the simulation. The AIFPI controller can be widely used in the HVAC industry.

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