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Optimal fuzzy control of electronic expansion valve-evaporator system

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ABSTRACT

In evaluating the efficiency of heat pump system, the efficiency of the superheat control process plays an important role. In this study, the mathematical model of superheat control of electronic expansion valve-evaporator system is developed, with the control strategy investigated. The model is identified by the least squares algorithm based on the minimized sum of squared residuals. The model consists of heat transfer relations concerning the fundamental equipment in the system such as thermal energy storage tank, electronic expansion valve, condenser, and evaporator. Different fuzzy control strategies, combined with optimal control algorithm, are investigated in detail to validate the deduced mathematical model of superheat control process.

KEYWORDS

Optimal control;
Fuzzy control;
Electronic expansion valve,
Evaporator.

INTRODUCTION

The ecological problems and energy crisis in the world have advanced the use of green technologies for residential, commercial, and industrial heating applications. Heat pump can combine the solar heat and the common air source or ground source heat to improve the coefficient COP of heat supply[1-4]. In evaluating the efficiency of heat pump system, the effi-ciency of the superheat control process plays an important role[5]. In this paper, superheat control process is investigated by electronic expansion valve-evaporator (EEVE) system of a solar heat pump (SHP) testing system. The basic schematic diagram for heat production system is given as Figure 1. When system makes heat, one way is to send hot air by ordinary air supply units, the other way is to realize water heating. If temperature of heat exchanger of indoor machine is overly low, auxiliary heater will be turned on to improve heat supply so as to meet consumer requirement.

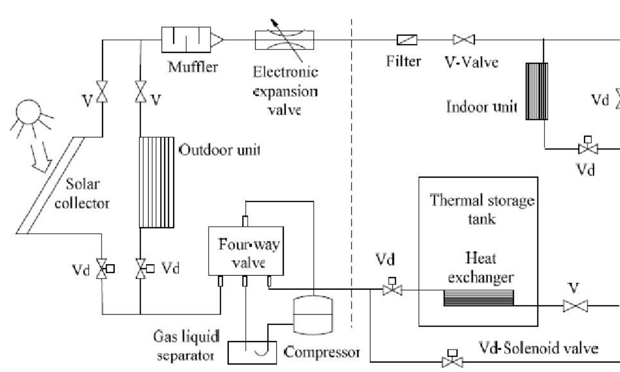

Figure 1 : Basic schematic diagram of SHP testing system

In general, as far as the control system is concerned, there are closed loop control for superheat degree, and compound control of feed-back & feed-forward. As far as the control algorithm is concerned, there are PID control and fuzzy control. In the paper, the two types of EEVE systems are identified, and the model objects are controlled by different fuzzy control strategies combined with optimal control algorithm.

SYSTEM IDENTIFICATION FOR EEVE SYSTEM

The actuator of electronic expansion valve is drove by stepper motor. If forward pulse or negative going pulse is given to stepper motor, turndown ratio of valve can continuously expand or shrink. So, cryogen feed can increase or decrease. The controller output is responding to valve location change. The EEVE system output is the superheat control parameter. The controller input is the practical superheat deviation signal and the desired value. By system identificationÿthe transfer function can be obtained. System identification for EEVE system is investigated by the least squares algorithm based on the minimized sum of squared residuals (LSR),which is expatiated on as follows[6]

$$\begin{aligned} y(t) + a_1 y(t-1) + a_2 y(t-2) + \cdots + a_n y(t-n) = b_1 x(t-d) + b_2 x(t-d-1) + \cdots \\ + b_m x(t-d-m+1) + \varepsilon(t) \end{aligned} \quad \textbf{(1)}$$

where $\varepsilon(t)$ can be regarded as the identification residuals. Here the shorthand notation $y(t)$ is used for the output superheat signal $y(kT)$, and $y(t-1)$ can then be used to describe the output superheat signal at the previous sample, i.e., $y[(k-1)T])$. Simultaneously $x(t)$ is used for the input opening activation signal for electronic expansion valve. For the purpose of reducing nonlinear effects of process of refrigeration, the results of sampling values of $x(t)$ and $y(t)$ in LSR method were applied after data smooth processing. Suppose that a set of input and output signals has been measured and written as

$$x = [x(1),\ x(2),\ \cdots,\ x(M)]^T \quad ,$$

$$y = [y(1),\ y(2),\ \cdots,\ y(M)]^T .$$

From Eqs. (1), it can be found that

$$\begin{aligned} y(1) &= -a_1 y(0) - \cdots - a_n y(1-n) + b_1 x(1-d) + \cdots + b_m x(2-m-d) + \varepsilon(1) \\ y(2) &= -a_1 y(1) - \cdots - a_n y(2-n) + b_1 x(2-d) + \cdots + b_m x(3-m-d) + \varepsilon(2) \\ y(M) &= -a_1 y(M-1) - \cdots - a_n y(M-n) + b_1 x(M-d) + \cdots + b_m x(M+1-m-d) + \varepsilon(M) \end{aligned}$$

where $y(t)$ and $x(t)$ are assumed to be zero when $t \leq 0$. The matrix form of the above equations can be written as

$$y = \Phi\theta + \varepsilon \quad \textbf{(2)}$$

where, Φ is the matrix of $x(i)$ and $y(i)$ defined as

$$\Phi = [F_1 \quad F_2]$$

$$F_1 = \begin{bmatrix} y(0) & \cdots & y(1-n) \\ y(1) & \cdots & y(2-n) \\ \vdots & \cdots & \vdots \\ y(M-1) & \cdots & y(M-n) \end{bmatrix} ,$$

$$F_2 = \begin{bmatrix} x(1-d) & \cdots & x(2-m-d) \\ x(2-d) & \cdots & x(3-m-d\_ \\ \vdots & \cdots & \vdots \\ x(M-d) & \cdots & x(M+1-m-d) \end{bmatrix}$$

$$\theta^T = [-a_1, -a_2, \cdots, -a_n, b_1, \cdots, b_m] ,$$

$$\varepsilon^T = [\varepsilon(1),\ \cdots,\ \varepsilon(m)]$$

To minimize the sum of squared residuals, the optimum estimation to the undetermined elements in θ can be written as

$$\theta = [\Phi^T\Phi]^{-1}\Phi^T y \quad \textbf{(3)}$$

It can be seen that the original system can be excited by the input signal sequence to generate the output superheat signal sequence. Based on these signals, the discrete-time model can be identified.

The value of the model order is determined by the number of measurement points; the vector contains the identified parameters, and the number of parameters to be identified. If the value is very small, the relevant process values can be used as the orders of the identified system. In general, this approach has different order combinations; however, the lowest possible orders are desirable for the system.

The paper deals with two types of EEVE systems, type one is that the expansion valve has the linear flow character and evaporator with smaller lag characteristic, the other type is that the expansion valve has the character of integration element and evaporator with large lag characteristic.

The discrete transfer function model converted from the identified results is in fact a double input transfer function matrix. The first one is the expected transfer function model, and the second is the transfer function from error signal to the output signal, which is discarded in the example. So the discrete transfer function models of the first type system $sys1$ and the second type sys-

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tem $sys2$ can be obtained respectively.

$$sys1 = z^{-150}\frac{8.374\times10^{-4}}{z-0.9968},$$

$$sys2 = z^{-300}\frac{-1.148\times10^{-5}z-1.147\times10^{-5}}{z^{2}1.999z+0.999} \quad \textbf{(4)}$$

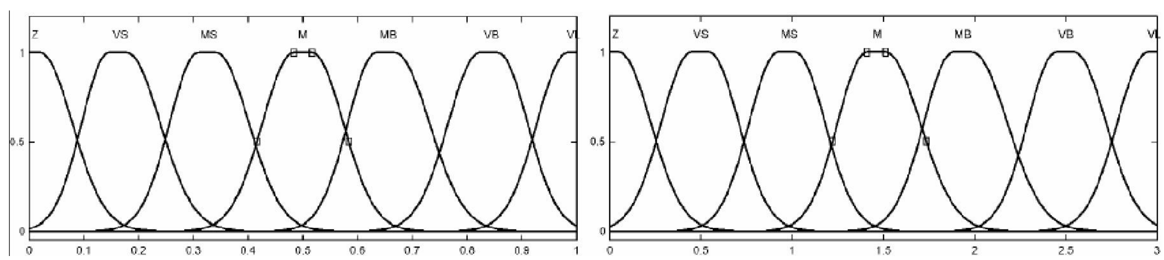
FUZZY CONTROL FOR EEVE SYSTEM

The PID controller for electronic expansion valve normally permits adjustments in the proportional, integral and derivative gains. Several control methods are available for controlling the superheat degree at the outlet of the evaporator using an electronic expansion valve. Ekren and Küçüka[7] proposed a fuzzy logic control to regulate the speed of a scroll compressor and to adjust the opening of an electronic expansion valve[7], and the importance of an effective controller was emphasized. Antônio et al.[8] developed an adaptive PID-controller to regulate superheat degree at the outlet of the evaporator, with the automatic robust tune rule proposed by Vilanova[9] employed to calculate the controller gains.

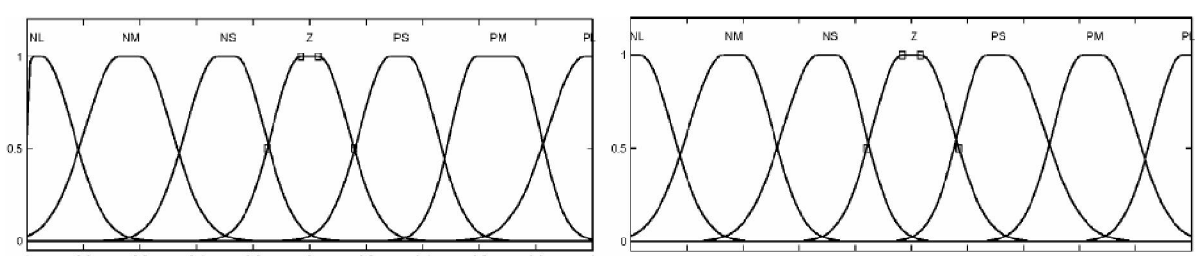
Considering the nonlinearity, time lag and time variation characteristics of air conditioning systems, Fuzzy Proportional Integral Derivative (FPID) controller for temperature control in EEVE system is usually employed[10,11]. In this paper, fuzzy PI (FPI) control strategy[12] is applied to deal with the first type system because of its linear flow character and smaller lag characteristic, and in view of potential integration element in and large lag characteristic, an extra integrator is not necessary in the controller to remove the steady-state error to a set point change, so different Fuzzy PD (FPD) controllers are proposed and simulated for the second type system. The controllers combine the fuzzy controller and optimal control algorithm with PID parameters tuned. The FPI controller and FPD controller with its modified models are employed to decrease the overshoot and stable time during the transient response period.

FPI controller devise for the first type system(FTS)

Fuzzy control depends on the fuzzy algorithm between the information of process and control input. Fuzzy controllers from their inception have demonstrated a vast range of applicability to processes where the plant transfer function is not defined but the control action can be described in terms of linguistic variables, and are often being used to improve the performance of a system where the plant transfer function is known[7]. For the FTS system, FPI controller is devised. Two input variables, error(E) and change in error(ED) and two output variables Kp and Ki of the PI controller with seven linguistic variables of gauss2mf membership function is used, which can be seen in Figure 2. The input linguistic variables are NL(Negative Large), NM(Negative medium), NS(Negative small), Z(Zero), PS(Positive small), PM(Positive medium), PL(Positive



Membership function plots for both input variables "E" and "ED"



Membership function plots for both output variables "Kp" and "Ki"

Figure 2 : Membership function plots for both input variables and output variables

large). The output linguistic variables for Kp and Ki are Z(Zero),VS(Very small), MS(Medium small), M(Medium), MB(Medium Big),VB(Very Big), VL(Very large), respectively. Ranges of input variables are (-1 to 1) for E and ED, respectively, and the ranges of output variables for Kp is from 0 to 1, and for Ki is from 0 to 3. Mamdani models are applied as structures of fuzzy inference. The control rules are built from the statement: if input 1 and input 2 then output 1and output 2. The aggregation and defuzzification method are used respectively max-min and centroid method. For the case of two-input and two-output, the control rules are shown in TABLE 1-2, where every cell shows the output membership function of a control rule with two input membership functions.

TABLE 1 : Rule for Kp

E\ED	NL	NM	NS	Z	PS	PM	PL
NL	VL	VL	VB	VB	MB	M	M
NM	VL	VL	VB	MB	MB	M	MS
NS	VB	VB	VB	MB	M	M	MS
Z	VB	VB	MB	M	MS	VS	VS
PS	MB	MB	M	MS	MS	VS	VS
PM	VB	MB	M	MS	VS	VS	Z
PL	M	MS	VS	VS	VS	Z	Z

TABLE 2 : Rule for Ki

E\ED	NL	NM	NS	Z	PS	PM	PL
NL	Z	Z	VS	VS	MS	M	M
NM	Z	Z	VS	MS	MS	M	M
NS	Z	VS	MS	MS	M	MB	MB
Z	VS	VS	MS	M	MB	VB	VB
PS	VS	MS	M	MB	MB	VB	VL
PM	M	M	MB	MB	VB	VL	VL
PL	M	M	MB	VB	VB	VL	VL

FPD controller devise for the second type system(STS)

FPD controller calculates the appropriate control at the input of the system according to the error and change of error at the input. While developing such a system the most important process is encoding the knowledge base of fuzzy controller. The knowledge base of the FPD controller consists of data and rule bases. Membership function distributions of system input and output variables are defined in data base[9].

In this study, a novel fuzzy rule type of the designed FPD controller is developed based on Sugeno model[13]. So there are 25 weight values. According to intuition method, list of linguistic rules is shown in TABLE 3. Error and change of error membership functions are denoted with mf1(negative very small), mf2(negative small), mf3(zero), mf4(positive big) and mf5(positive very big), respectively. Units of values are given according to practical ranges of opening activation for electronic expansion valve signals corresponding ranges of superheat signals.

The control precision depends on the units of values in TABLE 3. In addition, membership functions may be selected as a triangular, trapezoid or other appropriate forms. The numbers of membership functions change depending on the problem. The numbers of these linguistic variables specify the quality of control, which can be achieved using fuzzy controller. As the numbers of linguistic variables increase, the quality of control increases at the cost of increased computer memory and computational time.

TABLE 3 : Rule weight values of FPD controller

(de/dt)\(e)	mf1	mf2	mf3	mf4	mf5
mf1	-18.0	-15.3	-16.2	-10.8	0
mf2	-14.4	-13.5	-9.0	0	9.0
mf3	-2.7	-7.2	0	15.3	13.5
mf4	-9.0	0	11.7	14.4	17.1
mf5	0	12.6	18.0	17.1	18.0

In FPD controller, five triangular-membership function forms for and five triangular-membership function forms for , are determined the same, which are shown in Figure 3. Borders of both function sequences vary between ±3.

A general fuzzy controller consists of four modules: a fuzzy rule and data base, a fuzzy inference engine, fuzzification and defuzzification modules. The interconnections among these modules and the controlled process are shown in Figure 4. Aforehand introduce into previously-calculated parameters, Kp and Kd, of PD controller, simultaneously normalize and deal with and, then fuzzify the two signals to get signals E and Ed, do fuzzy reasoning with E and Ed, and solve fuzzification with the gained fuzzy quantities. Finally get accurate variable U, then get control signal u(t) after normalizing the fuzzy gain Ku.

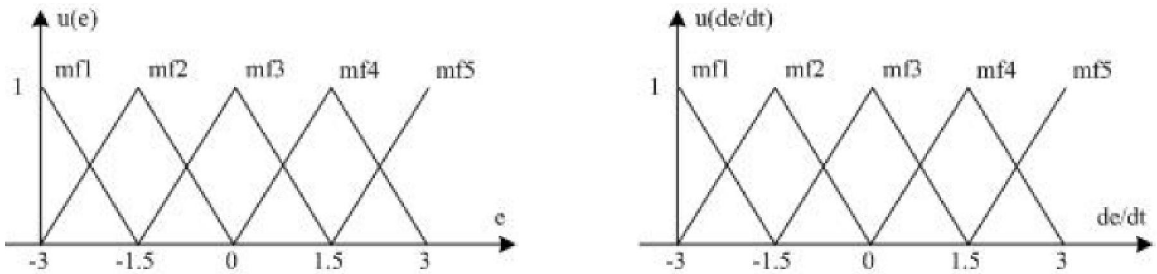


Figure 3 : Membership function plots for both function sequences

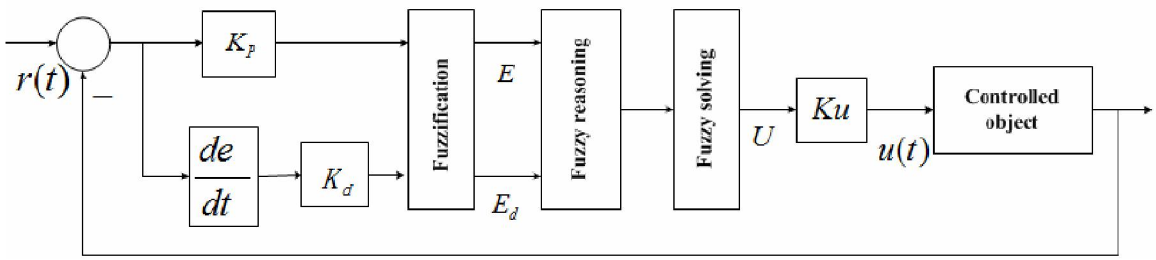


Figure 4 : The flow chart of fuzzy PD

Parameter tuning based on optimal control

For the fuzzy PID controller parameters tuning, it is necessary to determine universe ranges and perform tens or hundreds of simulation experiments until acceptable values is found. The optimal control is under certain concrete conditions, to achieve special control object, and to make selected target maximal or least.

From the optimal control, the PI parameters Kp and Ki, the PD parameters Kp and Kd, and the fuzzy gain Ku can be found during optimization. The target function used here adopts ITAE rule, defined as

$$J_{ITAE} = \int_0^\infty t\left|e(t)\right|dt \qquad (5)$$

when time is relatively big, to assure target value small, the steady error must be diminished, so as to make system speed in steady area.

Simulink block diagrams of EEVE simulation systems based on optimal FPI controller can be established in Figure 5 for the FTS system, where the ITAE criterion can be evaluated as shown.

Each parameter in target transfer function may be evaluated and initialized. The Matlab function, fminunc(), is applied to search for the optimal FPI and optimal FPD controller parameters for the system. During the simulation, the program codes below are used. The main program codes can automatically choose initial value of the optimized parameters, which are listed as,

```
global Kp Ki Kd t1 y1
x=fminunc(@optfun_name,rand(3,1)),
plot(t1,y1(:,2)),figure,plot(t1,y1(:,1))
```

Take the optimal FPI controller for example, in order to minimize the ITAE criterion, the following Matlab function can be written to describe the objective function,

```
function y=optfun_name(x)
global Kp Ki Ku t1 y1
Kp=x(1);
Ki=x(2);
Ku=x(3);
[t1,x1,y1]=sim(‘ Modelname.mdl ‘,[0,300]);
y=y1(end,1);
```

% where the third, fourth, and fifth lines in the codes will assign variables Kp, Ki and Ku in Matlab workspace, and the last two lines evaluate objective function.

The optimal search might better rationalize the choices for Kp, Ki and Ku. The point to be emphasized here is that simulation time is set as 300s, too small value of which might influence parameter tuning result. In addition, from the oscillograph, dynamic optimized process and result can be seen.

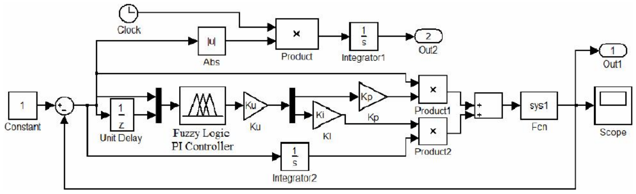


Figure 5 : Simulink block diagram of the first type system based on optimal FPI controller

It can be seen from the practice that the program is quite versatile in finding the optimal controllers. However, in some applications, it may not find a solution due to the poorly posed problem or because a good initial search point has not been found. This can be a drawback in conventional optimization algorithms, but many such problems can be avoided by setting parameter in Abs block to saturate on integer overflow and performing more times of continuous optimization process, or by intelligent use based on an understanding of the system behavior[6].

The unit step responses of the optimal FPI and conventional PI are illustrated in Figure 6(a). Superheat responses of evaporator are demonstrated based on the optimal FPI and conventional PI, respectively. Figure 6(b) displays exactly the superheat response fluctuation corresponding to the given desired values of superheat degree, cycling values of 8 °C and 12°C. A simulation comparison of the optimal FPI and conventional PI indicates that the optimal FPI has more advantages in aspects of overshoot and stability, and may perform well for the first type system.

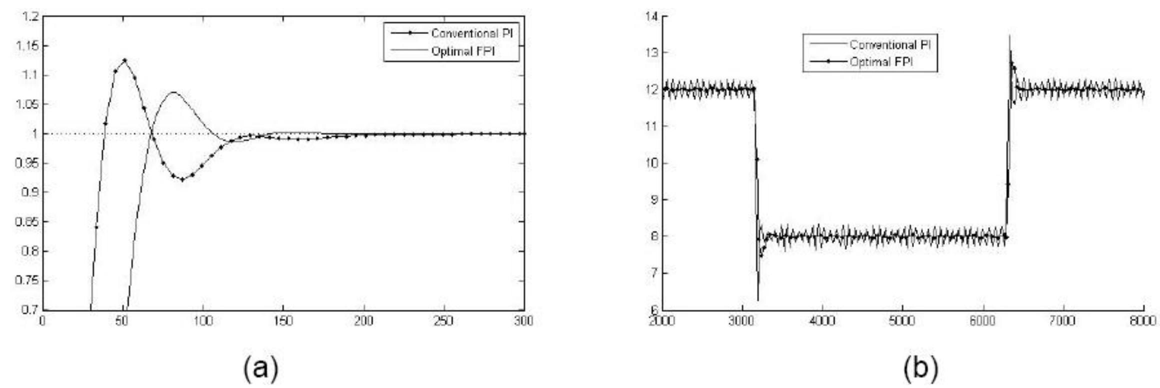


Figure 6 : The unit step responses(a) and superheat responses(b) of optimal PI controller and conventional PI controller

Modified FPD controller

Figure 7 shows the unit step response of optimal FPD controller, and it can be seen that the optimal FPD algorithm has a larger overshoot with long adjustment time. So a modified FPD algorithm, optimal fuzzy and PD dual-mode control(FDM), is applied. The optical FDM controller might compromise advantages of conventional PD controller and FPD controller by fuzzy switch. The unit step response of the optimal FDM simulation is also illustrated in Figure 7.

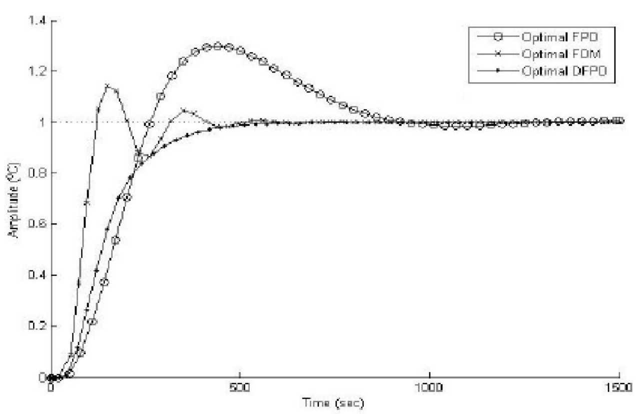


Figure 7 : The Unit step responses of different optimal fuzzy PD controllers

Obtained results show that the proposed optimal FDM controller is not only effective with fast rise time, but also it gives excellent characteristics of overshoot and adjustment time compared with the optimal FPD controller. However, from the unit step response of the optimal FDM simulation, a transient sudden change in overshoot takes place, and the peak of the curve is too close to the valley, which might make sudden rapid change of response in practice, when the given desired value varying by a large margin.

So another fuzzy and dual-mode control with derivative forward PD (DFPD) model is proposed in Figure 8. The advantages of DFPD lie in derivative operation only for output signal rather than input signal. So the output value won't change with the input value, therefore the varying of the controlled variable is moderate. This kind of DFPD controller is applicable to frequently lifting occasions of the given desired value, which can avoid system oscillation so as to apparently improve system dynamic behavior.

The unit step response of the optimal DFPD simulation is also illustrated in Figure 7, which shows moderate rise time and adjustment time, and without over-

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shoot.

It should be stated that when optimization finished, the parameter values obtained can be directly used as a substitute for set of Kp, Ki Kd and Ku in Figure 5,and Figure 8, respectively. So the optimization process is performed only in the first simulation.

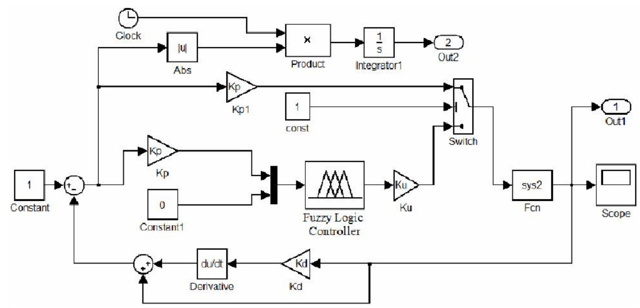

Figure 8 : Simulink block diagram of optical DFPD simulation

Superheat responses of evaporator are demonstrated from the three controllers: FPD, FDM, and DFPD, respectively. Figure 9 displays exactly the superheat response fluctuation corresponding to the given desired values of superheat degree, cycling values of 9 ^{o}C and 11 ^{o}C.

Figure 9(a) shows that the optimal FPD controller might produce big overshoot and long adjustment time as demonstrated in its simulation. However, the overshoot might take place when the given desired value jumps from smaller one to larger one, whereas the overshoot might be slight when the desired value jumps inversely. At the same time, in stable region, the response is more accurate. Figure 9(b) shows that the optimal FDM controller might bring about considerable instantaneous impact no matter how the desired value jumps, and in sable region, there is small fluctuation. However, it gives excellent characteristics of overshoot and adjustment time compared with the optimal FPD controller.

The point to be emphasized from Figure 9(c) is that the optimal DFPD controller shows moderate results not only for rise time and adjustment time, but also for stability fluctuation, and almost with no overshoot, and in general the optimal DFPD control strategy is recommended for the second type system.

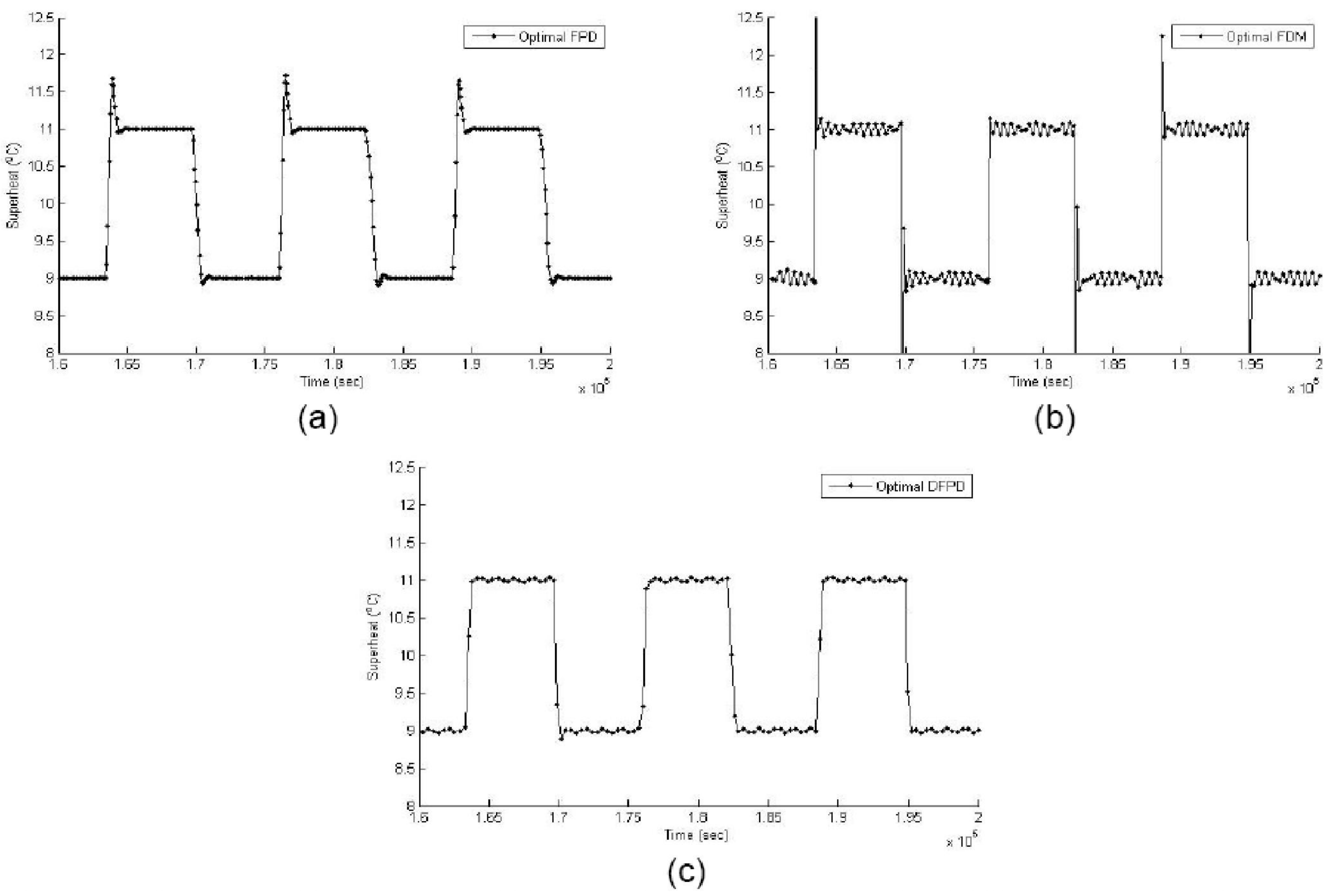

Figure 9 : Superheat response of evaporator based on optimal fpd controller(a), optimal fdm controller(b),and optimal dfpd controller(c), respectively

CONCLUSIONS

In this study, the modeling and simulation approaches of refrigerant feed fuzzy control of a solar-assisted heat pump system are investigated. A fuzzy PI control and three different fuzzy PD control strategies combined with optimal control algorithm for two types of EEVE systems are put forward and discussed in detail. Some concluding remarks can be drawn from the results:

1) If ignore evaporator system nonlinearity and work in stable external environment conditions, the LSR method can be used for identification for the two types of EEVE systems. In view of the same control idea[14], it might be used for multi-evaporator air-conditioners as well.
2) FPI controller may perform well for the first type system, and FPD controller may play an important role in second type system control not only in identifiable system here, but also in processes where the plant transfer function is not defined, because the control action can be described in terms of linguistic Sugeno variables just like what is described here.
3) All things considered, the optimal DFPD controller shows moderate results for the second system, and is applicable to frequently lifting desired value, which can avoid system oscillation so as to apparently improve system dynamic behavior.
4) The optimal control algorithm based on ITAE criterion is of significance in aspect of solutions for parametric objective functions, not only for PID controller parameter tuning, but also for fuzzy system parameter estimation, as described here.
5) It should be stated that this article is not meant to be an effect analysis of thermal characteristics, but rather a technical demonstrating on how the fuzzy PID control strategies combined with optimal control algorithm can be used to a heat pump to analyze the different EEVE system control problems. The modeling and simulation approaches presented in the paper might be of positive significance on the intelligent control of SHP system.

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