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CONTROLLER DESIGN FOR A PILOT-SCALE HEATING AND VENTILATION SYSTEM USING FUZZY LOGIC APPROACH

NURUL ADILLA MOHD SUBHA[1*], MOHD FUA'AD RAHMAT[2] & KASHIF M. ISHAQ[3]

Abstract. In this paper, a Single-input fuzzy logic controller (SIFLC) is designed and applied on a nonlinear heating and ventilation plant VVS-400 developed from Instrutek, Larvik, Norway. VVS-400 is modeled using Auto-regressive with exogenous input (ARX) model structure and linear black-box technique. The proposed SIFLC offers significant reduction in rule inferences and simplify the tuning of control parameters. To verify its effectiveness, this control method is simulated with an approximated VVS-400 model. An approximated VVS-400 model is obtained using System Identification toolbox in Matlab. The SIFLC provides several advantages over conventional fuzzy logic controller (CFLC) due to its simple inference rule mechanism, require very minimum tuning effort and mininizing the computational time to accomplish the controller algorithm. Simulations validate the equivalency of both controllers. Results reveal that SIFLC and CFLC have almost similar output performance. However SIFLC requires very minimum tuning effort and has less computational time.

Keywords: Fuzzy logic controller; VVS-400; signed distance method; single-input fuzzy logic controller; ARX

Abstrak. Dalam kajian ini, pengawal masukan tunggal logik kabur (SIFLC) direka bentuk dan dilaksanakan ke atas sistem VVS-400 dari Instrutek, Larvik, Norway. VVS-400 ini dimodelkan menggunakan struktur model ARX dan model kotak hitam untuk menerbitkan anggaran model matematik bagi sistem tersebut. Reka bentuk SIFLC menawarkan pengurangan yang signifikan dalam peraturan yang digunakan serta memudahkan proses mengawal parameter kawalan. Untuk mengesahkan keberkesanannya, kaedah pendekatan ini disimulasikan dengan anggaran model matematik bagi sistem VVS-400. Anggaran model matematik ini boleh di terbitkan menggunakan perisian pengenalpastian sistem di dalam Matlab. SIFLC telah memberikan beberapa kebaikan dan pembaikan prestasi jika dibandingkan dengan pengawal logik kabur (CFLC) kerana memerlukan peraturan yang mudah serta usaha yang sangat minimum ketika mengawal parameter kawalan. Ini dapat memendekkan masa pengkomputeran untuk menyelesaikan algoritma pengawal. Dalam simulasi, persamaan SIFLC dan CFLC dapat di lihat pada keluaran

[1,2&3] Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
* Corresponding author: adilla@fke.utm.my

sistem. Kedua-duanya menghasilkan keluaran yang hampir sama. Namun, kebaikan SIFLC jelas membuktikan keluaran yang sama dapat dihasilkan dengan sedikit pengubahsuaian dari CFLC.

Kata kunci: Pengawal logik kabur; VVS-400; kaedah jarak bertanda; pengawal masukan tunggal logik kabur; ARX

1.0 INTRODUCTION

The heating and ventilation system (HV) plays an important role in any working environments for maintaining the healthy and safe environment to the conditioned space. Therefore, an optimum operation of these systems is needed to provide the occupants with a comfortable and productive working environment which satisfies their physiological needs and minimizing the energy consumptions. Temperature is an essential factor in maintaining a desired comfort level. Therefore, a HV system plays an essential role to a building for supplying treated air with a specified temperature to the conditioned space.

During system's operation, the interaction between the temperature and humidity is significant which results high nonlinearity to the system. Consequently, it is difficult to develop the mathematical model that accurately describes this particular system. Due to this, the choice of control technique of this system is very challenging task due to its unpredictable condition and interaction with the humidity.

During the past years, both classical and modern control techniques have gain wide interest in HV system. Each control techniques have different control methodology. A popular classical proportional-integral-derivative (PID) controller is widely used in HV system due to its simple implementation and robustness. However, PID controller has fixed tuning parameters, the effectiveness of this controller is limited especially when the system is nonlinear [9, 11, 15]. Under these circumstances, frequent tuning is required to achieve a satisfactory performance. Proper tuning rules may allow the easy set up of the PID controllers and ease of re-tuning when the process characteristic is changed [13].

To solve the PID's tuning problem, some researcher has demonstrated a various combination techniques of classical PID and intelligent control in order to eliminate the limitation of PID. Liu has proposed fuzzy immune PID control that copes with nonlinear dynamic behavior of HVAC system which produces a good result of controller stability [11].

Due to the learning capability of artificial intelligence techniques in a varying environment, these control techniques are very promising to provide an excellent environmental control. Artificial intelligence controls strategies will be based on the control concepts have been proposed in attempts to improve the system performance. Fuzzy logic control and neural network are the most famous techniques of intelligent control. Over the years, there has been growing interest in using fuzzy logic control. Among these works, a fuzzy logic controller (FLC) with genetic algorithm tuning strategy is proposed to control the HVAC systems that exhibits good results compare to classical controller [1]. Using a similar approach, Gottschalk has employed a genetic algorithm (GA) to control a climate of potato bulk store [8]. Some improvement in tuning approach of GA was further explored in [2], where the tuning system was developed at rule level. This approach proposed a combination of weighted linguistic fuzzy rules together with a rule selection process in heating and ventilation system to maintain its indoor temperature. With the widespread use of fuzzy logic controller, Etik has proposed fuzzy expert system control with a prototype operating room control [6]. In many cases, some researchers use an adaptive and predictive control scheme. A fuzzy model-based predictive control scheme is presented by Thompson for controlling the supply air temperature in an air conditioning system [14]. Furthermore, a multiple fuzzy model predictive control (MMPC) is proposed by He to cope with strongly nonlinearity and time varying characteristic of the HVAC process [9]. An adaptive control with combination of fuzzy and neural network has been proposed by Chen to model the thermal comfort with experimental data [4].

Nevertheless, a more computation effort is required due to various process involve in FLC structure like fuzzification, rule base, inference engine and defuzzification operation. Hence, larger sets of fuzzy rules will produce longer computational time. In addition, a complicated system like heating and ventilation system would required many rules, at expands of longer processing time. Therefore, it may not practical to use the CFLC with a real plant, particularly when the real-time control is considered. Despite these issues, it is known that FLC requires simpler mathematics and offers higher degree of freedom in tuning its control parameters compared to other nonlinear controllers [10]. The simplification of CFLC could improve the computational time by applying the "signed distance method". In this paper, this approach called Single Input Fuzzy Logic Controller (SIFLC) is proposed where distance, d represents as soli input variable for the SIFLC. Choi [5] and Ishaq [10] have presented the ideal framework to apply the SIFLC in two different plants via computer simulation. However, so far, no reports have described the application of the Signed Distance method for heating and ventilation system. To verify the SIFLC method, simulation of the VVS-400 pilot scale heating and ventilation system using SIFLC is performed.

2.0 VVS-400 MODELING

In this study, VVS-400 is used as a model system. The VVS-400 plant is a pilot scale of heating and ventilation system developed by Instrutek A/S, Larvik, Norway. The system is represented in 2x2 multi-input, multi-output (MIMO) form. A black-box model identification technique was used to model temperature process over a range of operating conditions. The schematic diagram of this system is shown in Figure 1.

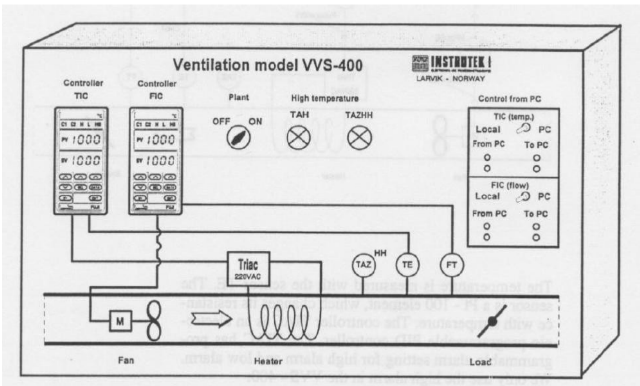

Figure 1 Schematic diagram of the VVS-400 heating and ventilation model

The mathematical modeling of this system can be obtained using MATLAB's System Identification (SI) Toolbox. SI technique provides a competent approach and proved to be very significant in practical applications. In this paper, an open-loop single-input single-output (SISO) identification experiment was performed with Pseudo-Random Binary Sequences (PRBS) signals as inputs. The purpose of conducting this experiment is to obtain the output temperature that corresponds to its input. The arrangement of the experiment includes VVS-400 plant, data acquisition hardware (PCI-1711 card) and computer. The PCI-1711 card that developed by Advantech is used to read and write data to and from the VVS-400 plant. In this experiment, the persistently excitation of input signal is crucial, since it influences the data sufficiency. Often, Pseudo-Random Binary Sequences (PRBS) input are chosen due to its large energy content in a large frequency range [7]. Further details in choosing the appropriate input can be found in [3]. From Fig. 2, both Analog Output and Analog Input from Real-time Windows Target (RTWT) toolbox will directly connect the Matlab/Simulink to the VVS-400 plant using PCI-1711. The plant is connected to the Analog Input of PCI-1711 and input to the plant is connected to the Analog Output of PCI-1711.

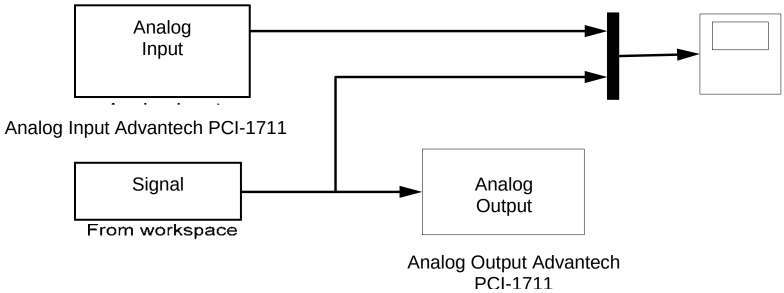

Figure 2 Open-loop identification experiment using Simulink block diagram

Through this experiment, a system model is identified using data collected when the Pseudo Random Binary Sequence (PRBS) is perturbed into the system using Matlab/Simulink. There are 2297 samples of data taken at 2 seconds sampling interval. The PRBS input is generated in Matlab. The collection of data was performed by PCI-1711 interface card. Then, data will be analyzed by System Identification toolbox in Matlab [12].

The VVS-400 system is modeled based on Autoregressive with exogenous input (ARX) model structure which the general equation of ARX can be represented as

$$A(q)y(t) = B(q)u(t-n_k) + e(t) \tag{1}$$

Based on equation (1), its polynomial structure can be written as equations (2) and (3).

$$A(q) = 1 - 0.4776q^{-1} - 0.441q^{-2} - 0.774q^{-3} + 0.4322q^{-4} + 0.1352q^{-5} + 0.1308q^{-6} \tag{2}$$

$$B(q) = 0.0002502\,q^{-3} + 0.0008348\,q^{-4} + 0.0003908\,q^{-5} + 0.0003052\,q^{-6} + 0.0006835\,q^{-7} + 0.000266\,q^{-8} \tag{3}$$

Therefore, the pilot scale heating and ventilation VVS-400 plant can be approximated modeled by this following equation

$$\frac{B(q)}{A(q)} = \{0.0002502\,q^{-3} + 0.0008348\,q^{-4} + 0.0003908\,q^{-5} + 0.0003052\,q^{-6} + 0.0006835\,q^{-7} \ldots + 0.000266\,q^{-8}\} / \{1 - 0.4776\,q^{-1} - 0.441\,q^{-2} - 0.774\,q^{-3} + 0.4322\,q^{-4} + 0.1352\,q^{-5} + 0.1308\,q^{-6}\} \tag{4}$$

3.0 SINGLE-INPUT FUZZY LOGIC CONTROLLER (SIFLC)

In CFLC design, it is common to have an error, e and change of error, $\dot{e}$ as an input variable. Its two-dimensional input space rule table is constructed as can be seen in Table 1. The L_{NL}, L_{NM}, L_{NS}, L_{Z}, L_{PS}, L_{PM}, and L_{PL} represent seven diagonal lines with L_{Z} as main diagonal line. Then, each diagonal line has a magnitude which proportional to the distance from its main diagonal line, L_{Z}. It can be noted that rule table represents same output membership function in a diagonal direction where there is an opportunity to simplify the table. The proposed SIFLC simplifies the number of input using Signed distance method by deriving new soli input variable known as signed distance, d.

The distance, d represents the absolute distance magnitude of the parallel diagonal lines (in which the input set of e and $\dot{e}$ lies) from the main diagonal line L_Z. To derive the distance, d variable, let $T(e_0, \dot{e}_0)$ be an intersection point of the main diagonal line and the line perpendicular to it from a known operating point $U(e_1, \dot{e}_1)$, as illustrated in Figure 3.

Table 1 Rules table of fuzzy

e \ $\dot{e}$	PL	PM	PS	Z	NS	NM	NL
NL	Z	NS	NM	NL	NL	NL	NL
NM	PS	Z	NS	NM	NL	NL	NL
NS	PM	PS	Z	NS	NM	NL	NL
Z	PL	PM	PS	Z	NS	NM	NL
PS	PL	PL	PM	PS	Z	NS	NM
PM	PL	PL	PL	PM	PS	Z	NS
PL	PL	PL	PL	PL	PM	PS	Z

Saturation region
LNL
LNM
LNS
Saturation region
LPL
LPM
LPS
LZ

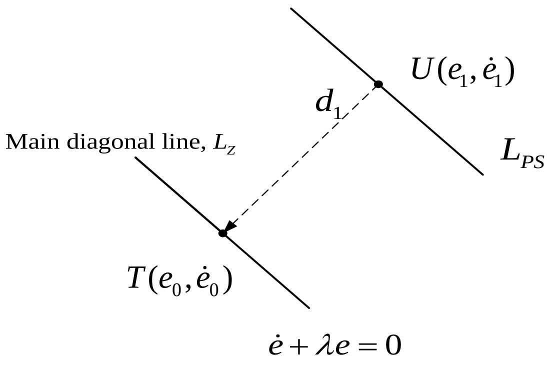

Figure 3 Derivation of distance variable

From Figure 3, the absolute distance magnitude from point T to U can be obtained by using the Pythagoras theorem as follows

$$d = \sqrt{(e_1 - e_0)^2 + (\dot{e}_1 - \dot{e}_0)^2} \tag{5}$$

It also can be noted that main diagonal line, L_z can be represented as follows

$$\dot{e} + \lambda e = 0 \tag{6}$$

In equation (6), variable λ is the slope magnitude of the main diagonal line, Lz. The distance, *d* from point $T(e_0, \dot{e}_0)$ to point $U(e_1, \dot{e}_1)$ can be expressed as

$$d = \frac{\dot{e} + \lambda e}{\sqrt{\lambda^2 + 1}} \tag{7}$$

Based on equation (7), the magnitude distance, *d* can have positive or negative sign. The derivation of input variable distance, *d* resulted in one-dimension rule table as depicted in Table 2.

Table 2 The reduced table using Signed distance method

$d = \dfrac{\dot{e} + \lambda e}{\sqrt{1 + \lambda^2}}$	L_{NL}	L_{NM}	L_{NS}	L_Z	L_{PS}	L_{PM}	L_{PL}
$\dot{u}_o = \dot{e} + \lambda e$ (rule table)	NL	NM	NS	Z	PS	PM	PL

As can be realized, the L_{NL}, L_{NM}, L_{NS}, L_Z, L_{PS}, L_{PM}, and L_{PL} are the diagonal lines of Table 1 which correspond to the new input variable of the reduced table in Table 2 while NL, NM, NS, Z, PS, PM, and PL represent the output of the corresponding diagonal lines. The final output of this SIFLC is obtained by multiplying the $\dot{u}_o$ (k) with output scaling factor, denoted as K. The output equation can be written as

$$\dot{u} = \dot{u}_o(k)K \tag{8}$$

In Signed distance method, the number of input variable s been simplified into soli input variable. The soli input gives a significant reduction in number of rules since it has one-dimensional rule table instead of two-dimensional rule table in CFLC. Consequently, less number of fuzzy rules gives an advantage to SIFLC in faster computational time [5, 10].

3.1 SIFLC Control Surface

For CFLC, the correlation between the input and output is normally represented by a three-dimensional plot, known as control surface, ψ. The control surface is the graphical representation of the combined effects of the tuning parameters. These parameters can be identified as membership function, inference methods, fuzzification and defuzzification operator selections. Different settings of tuning parameters yield different control surfaces, which result different control actions by CFLC. Clearly, the optimum tuning of these parameters is the crucial issue faced by the designers. In contrast, control surface of SIFLC has two-dimensional plot. It can be achieved when the rules table is reduced to a one-dimensional rules table as derived in Table 2. Therefore, it is possible to produce an effective control surface for SIFLC without having to look into complex computations coupled with fuzzification, rules inferences and defuzzification processes. In fact, it is possible for nonlinear control surface to be approximated based on piecewise linear by met a several operating conditions as follows:

1. The input membership function is triangular shape
2. The output membership function is singleton shape
3. The fuzzification and defuzzification process uses Center of Gravity (CoG) method.

3.1.1 Linear Piecewise Linear (PWL) Control Surface

Once the operating conditions to obtain a linear control surface are determined, the output equation $\dot{u}_o$ can be derived. To derive the output equation, consider the triangular shape input and singleton shape output memberships as Figures 4 and 5, respectively. If LDL_{-3}, LDL_{-2}, LDL_{-1}, LDL_0, LDL_1, LDL_2 *and* LDL_3 are the input membership functions and S_{-3}, S_{-2}, S_{-1}, S_0, S_1, S_{-2} and S_3 are the output singleton membership functions, its rules inference can be written as in Table 3.

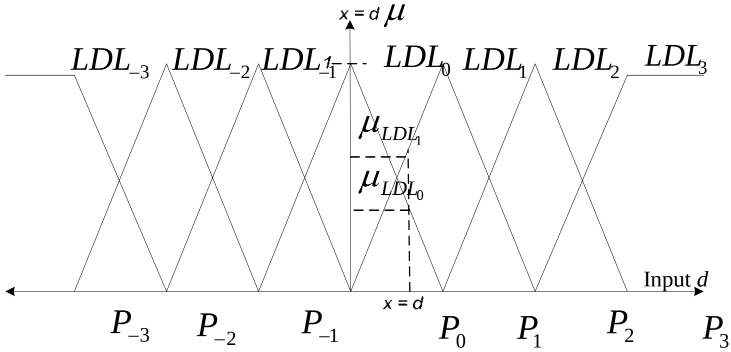

Figure 4 Input Membership function

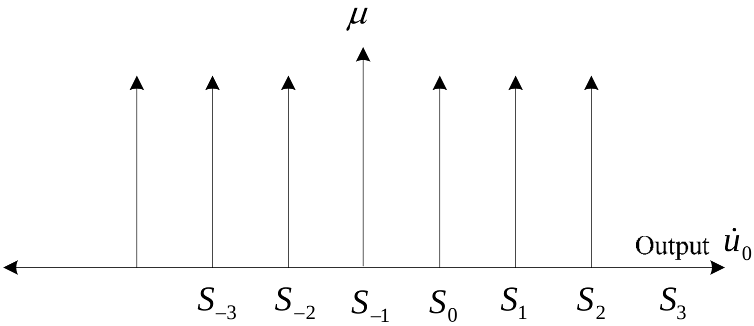

Figure 5 Output membership function

Table 3 Rule table of the above example

d	LDL_{-3}	LDL_{-2}	LDL_{-1}	LDL_0	LDL_1	LDL_2	LDL_3
$\dot{u}_o$	S_{-3}	S_{-2}	S_{-1}	S_0	S_1	S_2	S_3

Referring to Fig. 4, $P_{-3}, P_{-2}, P_{-1}, P_0, P_1, P_2,$ and P_3 are denoted as the peak locations of *LDL*$_{-3}$, *LDL*$_{-2}$, *LDL*$_{-1}$, *LDL*$_0$, *LDL*$_1$, *LDL*$_2$ *and LDL*$_3$ membership functions, respectively. Consider *x* as the measured distance *d* input within the Universe of Discourse (UoD). It can be noted that *x* is a member to *LDL*$_0$ and *LDL*$_1$ membership functions. By using the Centre of Gravity (CoG) defuzzification operator, the output $\dot{u}_0$ can be calculated

$$\dot{u}_o = \frac{\sum_{i=-2}^{2} \mu_i S_i}{\sum_{i=1}^{n} \mu_i} \tag{9}$$

In equation (9), μ_i is the membership degree value for i^{th} membership function. Since *x* is a member of *LDL*$_0$ and *LDL*$_1$ membership functions, the other membership functions will have zero membership degree value. Hence, equation (9) can be written as

$$\dot{u}_0 = \frac{\mu_0 S_0 + \mu_1 S_1}{\mu_0 + \mu_1} \tag{10}$$

$$\dot{u}_0 = \left(\frac{S_1 - S_0}{P_1 - P_0} \right) x + \left(\frac{X_1 S_0 - X_0 S_1}{P_1 - P_0} \right) \tag{11}$$

As can be seen in equation (11), linear function of output equation is obtained. It can be rewritten in a more generalised form as

$$\dot{u}_o = \alpha d + \gamma \tag{12}$$

where *d* is the input distance variable and α is the slope of the line. The variable γ is the output value when input *d* is zero. Both α and γ parameters are defined as

$$\alpha = \left(\frac{S_1 - S_0}{P_1 - P_0} \right) \tag{13}$$

$$\gamma = \left(\frac{X_1 S_0 - X_0 S_1}{P_1 - P_0} \right) \tag{14}$$

As can be observed from equations (13) and (14), the output equation is a function of *peak locations* of input and output membership functions. Therefore, a PWL control surface can be obtained. Then, PWL control surface can be simply constructed using a look-up table. In this case, faster computation time can be achieved since fuzzification, rules inferences and defuzzification processes are eliminated. Figure 6 shows a linear PWL control surface which has a constant slope throughout the UoD.

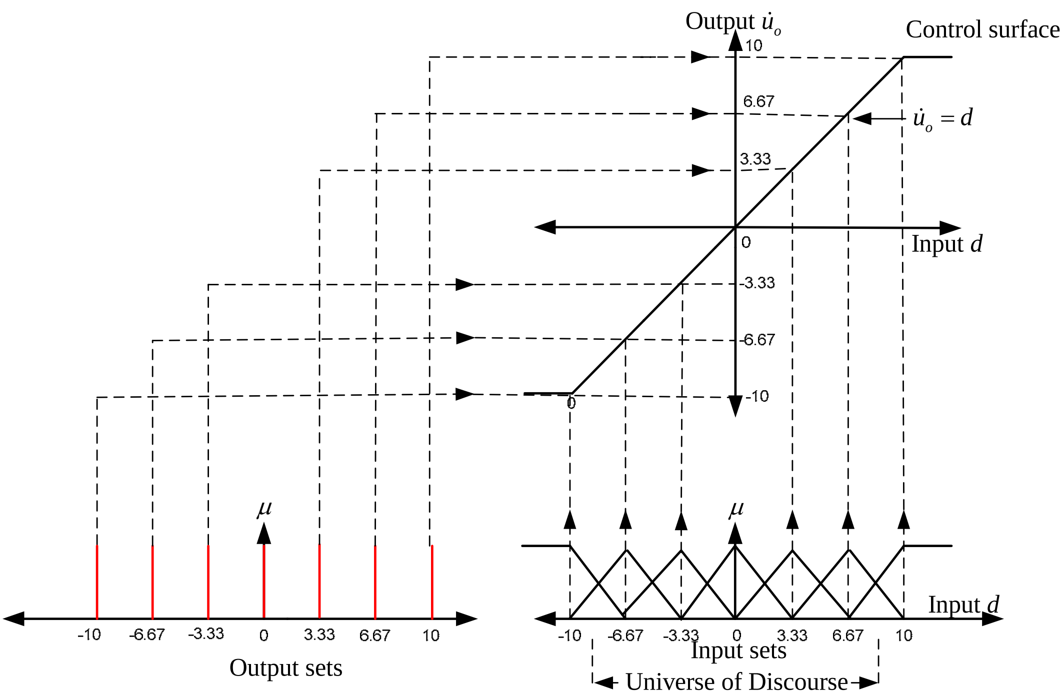

Figure 6 Linear PWL Control surface for an equal space of input and output membership functions

3.1.2 Nonlinear Piecewise Linear (PWL) Control Surface

To obtain a multiple linear regions in a PWL control surface, input and output membership function can be arranged in unequal space as depicted in Figure 7. The location of triangular input and singleton output membership function can be changed to produce a multiple linear surface with different slope. The transition point between two different PWL slope is called break-point (d_{bp}).

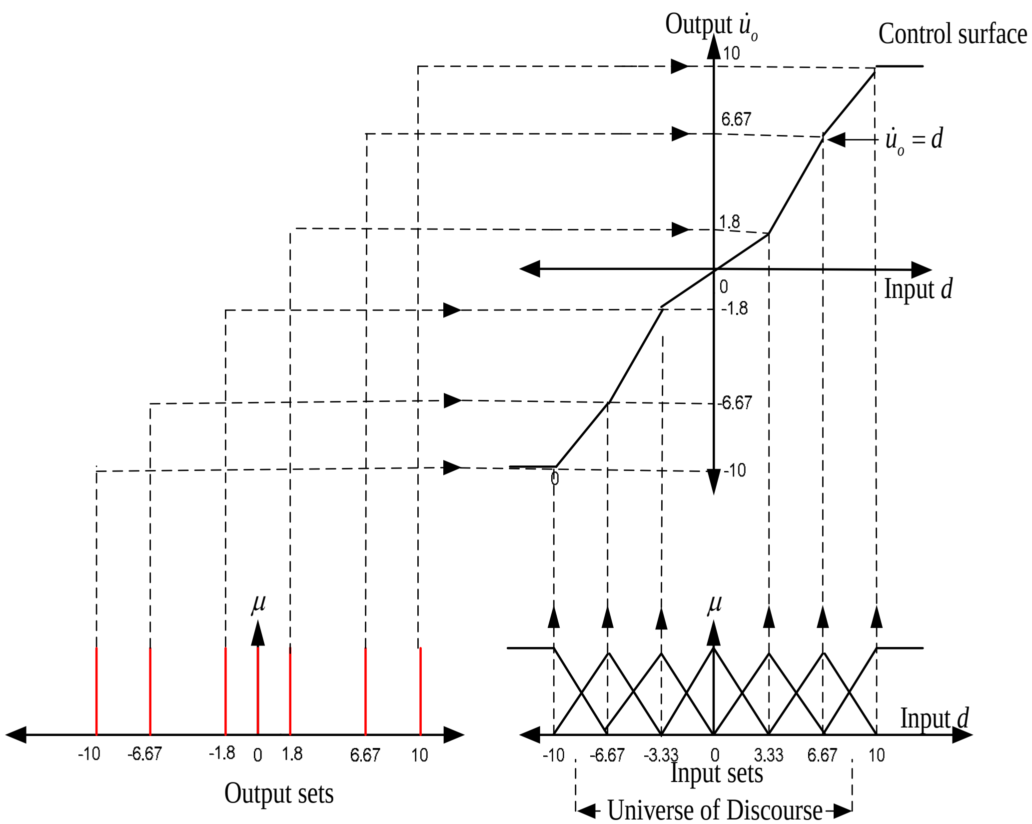

Figure 7 Nonlinear PWL control surface with peak locations of the output membership function is adjusted

4.0 SIFLC DESIGN FOR VVS-400

In this section, two types of SIFLC for a VVS-400 is designed. The proposed SIFLC is employed with two different PWL control surface to control the temperature of VVS-400. First, with linear PWL control surface, all input and output membership function is in equal space. Second, nonlinear PWL control surface, with two different slopes and one break-point.

Table 4 is the rule table for the CFLC where the outputs of each diagonal line correspond to its input values is obtained using equation (6). The diagonal line that result "0" is called main diagonal line.

Table 4 Rule Table for conventional FLC

$\dot{e}$ \ e	PL “10”	PM “6.67”	PS “3.33”	Z “0”	NS “-3.33”	NM “-6.67”	NL “-10”
NL “-10”	0	-3.33	-6.67	-10	-10	-10	-10
NM “-6.67”	3.33	0	-3.33	-6.67	-10	-10	-10
NS “-3.33”	6.67	3.33	0	-3.33	-6.67	-10	-10
Z “0”	10	6.67	3.33	0	-3.33	-6.67	-10
PS “3.33”	10	10	6.67	3.33	0	-3.33	-6.67
PM “6.67”	10	10	10	6.67	3.33	0	-3.33
PL “10”	10	10	10	10	6.67	3.33	0

Saturation region

Saturation region

The equivalent single-input single-output (SISO) table will be derived using Table 4. In order to derive this table, the input distance, *d* will be calculated using equation (7) for seven diagonal lines. Then, the derived reduced SISO is given in Table 5.

Table 5 The reduce rule table of SIFLC

$d = \dfrac{\dot{e} + \lambda e}{\sqrt{1+\lambda^2}}$	-7	-4.66	-2.33	0	2.33	4.66	7
$\dot{u}_0 = \dot{e} + \lambda e$ (rule table)	-9.9	-6.6	-3.3	0	3.3	6.6	9.9

The derivation of distance, *d* input variable resulted in single-dimension rule table compared to CFLC which has two-dimension rule table. All input, *d* and output,

$\dot{u}_0$ values are formed using a look-up table in Matlab Simulink. This simplification allows the control surface to be approximated as a linear PWL control surface as depicted in Figure 6. Then, the nonlinear PWL control surface is generated by changing the peak locations of output membership function, S_{-1} from -3.33 to -1.8 and S_1 from 3.33 to 1.8 as depicted in Figure 7. Both types of SIFLC control surface which can be simply generated using look-up table.

5.0 RESULTS AND DISCUSSIONS

5.1 Comparison Between CFLC and SIFLC

Figure 8 shows the output performance via simulation for CFLC and SIFLC with linear control surface. As can be seen, the simulated output response of SIFLC provides almost similar result with the CFLC. The initial value of the temperature is determined by the room temperature which is 22ºC. Furthermore, with less number of rules in SIFLC, a faster computation time is expected to accomplish the control algorithm. This is in contrast to CFLC approach where large computational time with many rules. Table 6 compares the computational time for linear control surface of CFLC and SIFLC.

From Table 6, it can be seen that SIFLC performed much faster to compute the control algorithm compared to CFLC in simulation. It has proved that by reducing the number of rules, the computational time can be minimized. Other than that, SIFLC also provide an advantage in the tuning process to provide a similar output as CFLC. The complex tuning process of CFLC with fuzzification, defuzzification and inference can be simplified and replaced by properly tuned the slope of the piecewise linear segment and the break-point in SIFLC.

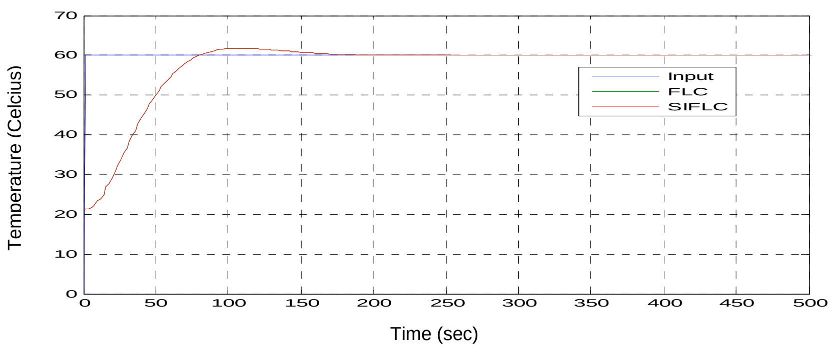

Figure 8 The output performance of FLC and SIFLC via simulation

Table 6 Computation time comparison

CONTROLLER	COMPUTATION TIME (SIMULATION)
Conventional FLC	95 seconds
SIFLC	Less than 1 second

5.2 Comparison Between Linear and NONLINEAR SIFLC

Figure 9 shows the responses obtained for linear and nonlinear types SIFLC for simulated results. The control surfaces used are shown in Figure 6 for linear PWL control surface and Figure 7 for nonlinear PWL control surface, respectively. As expected, the nonlinear PWL control surface exhibit better overshoot transient and steady state performance. From Figure 9, it can be seen that the overshoot of the response can be reduced by re-tuning the location of output membership function. It shows that the SIFLC has very easy tuning method instead of CFLC in order to achieve a satisfactory performance.

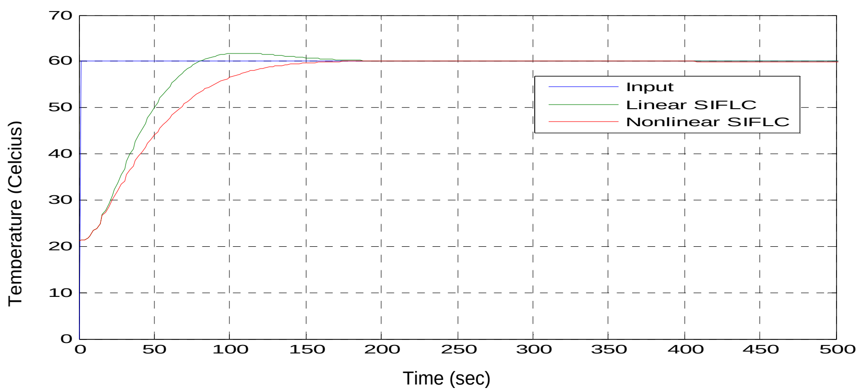

Figure 9 The simulated output response

Table 7 compares the settling time and overshoot between linear and nonlinear types SIFLC controllers. From the table, it can be observed that nonlinear SIFLC improved the overshoot of the output response. However, the transient responses tend to be slower which results larger settling time. For that reason, it is important to choose the right value of break-point for a particular application.

Table 7 Transient response (Simulation) comparison

CONTROLLER	LINEAR	NONLINEAR
Settling time	80 seconds	145 seconds
Overshoot	2ºC	No overshoot

6.0 CONCLUSION

In this paper, linear and nonlinear types of Single-input fuzzy logic controller (SIFLC) are proposed for the pilot scale of heating and ventilation VVS-400 system. Both types are designed via simulation with approximated VVS-400 model to verify the SIFLC design. Furthermore, the SIFLC design is basically derived from CFLC using Signed distance method which has reduces the number of controller's input. From this study, it can be clearly seen that this proposed control technique provides reduction in number of rules, small computational time, easy implementation using look-up table and simple tuning as compared to CFLC. In addition, simulated output response of the VVS-400 system have proven that the proposed SIFLC scheme give the similar results as the CFLC when the control surface is linear.

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