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Fuzzy Logic Controller Design for a Small Scale Industrial Hot Air Blower Heating and Ventilation System

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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. Instead of using two inputs $(e, \dot{e})$ in the conventional FLC, this method simplifies the number of input by deriving new solitary input variable known as signed distance, d. To verify its effectiveness, this control method is simulated and performs an online control with an approximated and real VVS-400 plant respectively. An approximated VVS-400 model is obtained using System Identification approach while the real plant model is developed by interfacing the Real-time Windows Target toolbox in Matlab with real VVS-plant using data acquisition (DAQ) card PCI-1711. The SIFLC provides several advantages over conventional FLC due to its simple inference rule mechanism, require very minimum tuning effort and minimizing the computational time to accomplish the controller algorithm. However, simulations and experiments validate the equivalency of both controllers. Results reveal that SIFLC and conventional FLC have almost similar output performance but SIFLC found to be better than FLC due to its less computational time compared to conventional FLC.

Key words: Fuzzy logic controller · VVS-400 · Signed distance method · Single-input fuzzy logic controller

INTRODUCTION

In heating and ventilation system, the temperature control plays an important role for maintaining the healthy and safe environment to the conditioned space. This system has a time-varying nature and high nonlinearity. Therefore, it is difficult to develop the mathematical model that accurately describes this particular system. Moreover, the choice of control technique of this system is very challenging task due to its unpredictable condition and interaction with the humidity. The classical control techniques such as PID controller have fixed tuning parameters where the effectiveness of this controller is limited when applied to heating and ventilation system with high nonlinearity [1]. Due to this reason, the PID controller is not possible to give a satisfactory performance. Therefore, an artificial intelligent control is most applicable rather than classical control techniques since it can provides better performance with less time consuming [2, 3].

Over the years, there has been growing interest in using fuzzy logic control. Among those works, [4] has proposed a combination of weighted linguistic fuzzy rules together with a rule selection process in heating and ventilation system to maintain its indoor temperature. However, it is known that conventional FLC has to deal with fuzzification, rule base, inference engine and defuzzification operation. Larger sets of fuzzy rules will produce longer computational time for conventional FLC. Generally, a complicated system like heating and ventilation system requires many rules to develop a conventional FLC. These will results large computational time in order to accomplish the control algorithm. Therefore, the simplification of conventional FLC using Signed distance method has been made called Single input fuzzy logic controller (SIFLC). The proposed SIFLC

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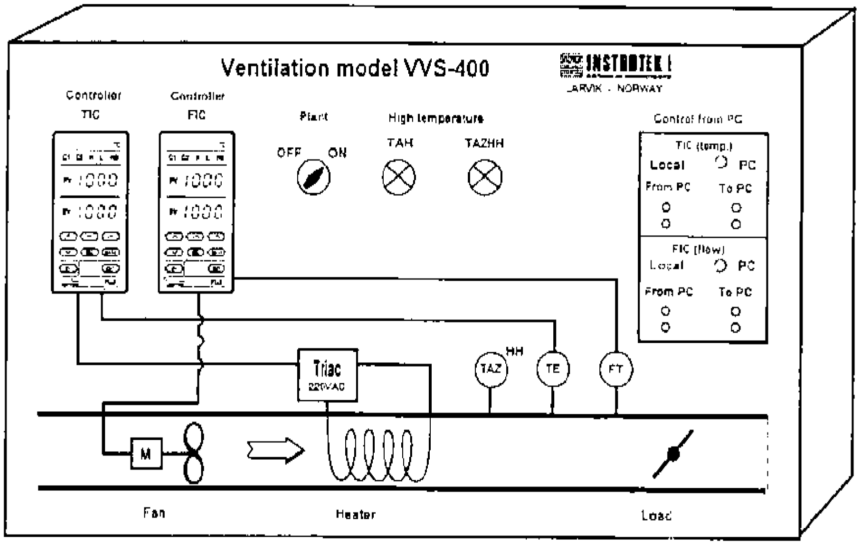


Fig. 1: Schematic diagram of the VVS-400 heating and ventilation model

is introduced to solve the conventional FLC problem. The SIFLC has only one single input variable with distance, *d*. The distance, *d* represents the absolute distance magnitude of the parallel diagonal lines from the main diagonal line. In addition, each point of the diagonal lines has its magnitude that proportional to the distance from its main diagonal line. Then, single-dimension of rule table is constructed from the conventional fuzzy rule table. This will lead to less number of rules compared to conventional FLC and eliminates the fuzzification and defuzzification process. For example, SIFLC has been successfully designed via computer simulation using two nonlinear plants by [5]. The SIFLC has only single input variable which offer less number of rules compared to conventional FLC. [6] has designed the SIFLC which was shown to have very effective due to its less computation time in the real time application. The SIFLC also can be combined with self-tuning scheme in order to achieve better results in output performance as proposed by [2]. To verify the designed controller, simulations and hardware results of a VVS-400 are acquired. The results are compared with the conventional FLC developed on the same system.

However, in order to design a very efficient controller with high quality system performance, the system must be modeled in a proper way. For unknown system which has unknown parameters, it can be called as black-box model. The mathematical modeling of this black-box model system can be obtained using System Identification (SI) technique. SI technique provides a competent approach and proved to be very significant in practical applications. There are two methods to perform the system modeling, which are using theoretical and experimental design. Only experimental approach is considered in this paper where the system model is referred as a black-box model (Section II). In this approach, 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 [8]. Further details in choosing the appropriate input can be found in [9]. Controller design is also included in this paper through Matlab simulation (Section III) and online implementation using Real-time Windows Target toolbox (Section IV). Finally, discussion and conclusion are drawn.

System Modeling

System Description: 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 schematic diagram of this system is shown in Fig. 1. This plant can operate in three different modes: 1) Temperature control, 2) Flow control and 3) Cascade control. In this paper, only temperature control is studied (constant air flow rate). This model consists of a fan and heating element which is controlled by TRIAC. The fan blows air through the flow tube over the heating element. The temperature sensor, RTD platinum is located at the end of the tube. This plant model is also equipped by two independent local PID controllers to control the temperature and flow processes. However, in this study, local PID controller

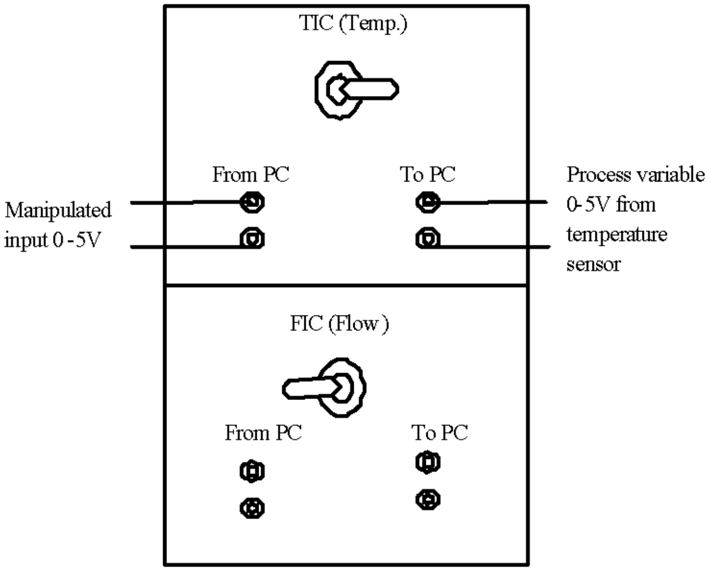


Fig. 2: Local panel on VVS-400

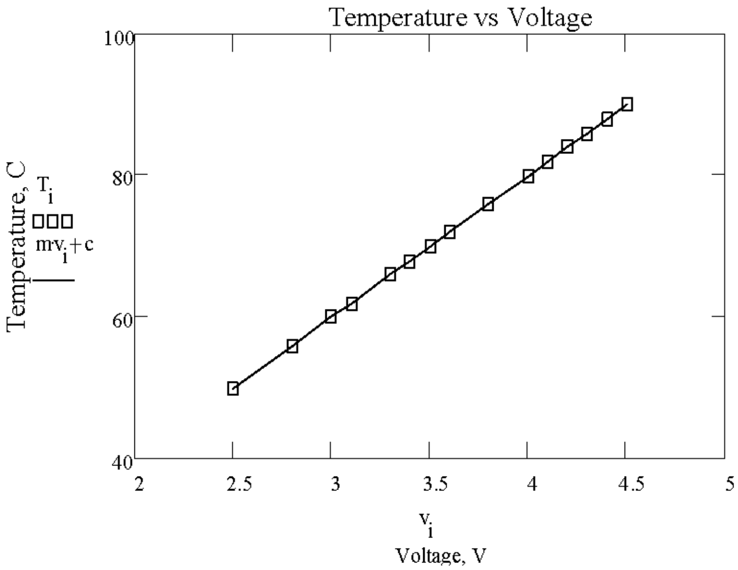


Fig. 3: Temperature Calibration Curve from the Process Rig

for temperature will be set as “off mode” which creates an open loop system for temperature while the air flow rate is fixed to a certain number and controlled by flow local PID controller. The local PID controller for temperature can be set as “off” by setting the switch “local-PC” is set to “PC” position at local panel on VVS-400 as shown in Fig. 2.

The manipulated input can be set manually to simulate the PC 0-5 volt output. If the manipulated variable is connect with a particular input, the feedback signal will acquire the output from the temperature sensor. The PCI-1711 card will be as an interface between the local panel on VVS-400 and the Matlab software on the computer.

System is calibrated by injecting the step input signal into the system through the local panel with an open-loop control. After system calibration, the relationship between voltage and temperature is obtained and plotted as shown in Fig. 3. This is done by observing the output temperature with different input voltage as shown in Table 1.

From Fig. 3, it can be noted that the relationship between voltage and temperature can be expressed as (1) and (2).

Table 1: Input voltage and output temperature

Voltage (V)	Temperature (Celcius)
2.5	50
2.8	56
3.0	60
3.1	62
3.3	66
3.4	68
3.5	70
3.6	72
3.8	76
4.0	80
4.1	82
4.2	84
4.3	86
4.4	88

$$\text{Temperature}(^\circ\text{C}) \propto K \times \text{Voltage(V)} \qquad (1)$$

$$K = \text{constant} = \text{gradient} = 20$$

Hence,

$$\text{Temperature } (^\circ\text{C}) = 20 \times \text{Voltage (V)}$$

$$T_i = 20V_i \qquad (2)$$

Where: i = nth data

According to (2), the process output must be multiplied with constant 20 since the output from the approximated plant and data acquisition (DAQ) card is in voltage. Temperature process study of VVS-400 plant has been conducted in [10] which reveal the temperature process is continuously nonlinear.

System Model: Initially, system model must be determined before control technique is applied. The system modeling part is the most challenging and vital part in designing the control system of VVS-400 due to its large time constant and slow process response. In order to obtain a particular model for this system, the open-loop single-input single-output (SISO) identification experiment has been done using parametric approach where the model is described in terms of difference and differential equation. The purpose of conducting this experiment is to obtain the output temperature that corresponds to its input. In this experiment, VVS-400 plant, data acquisition hardware (PCI-1711 card) and computer are connected as shown in Fig. 4. The PCI-1711 card that developed by Advantech is used to read and write data to and from the VVS-400 plant. From Fig. 5, 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.

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 as can be seen in Fig. 6. From Fig. 6, there are 2297 samples of data with 2 seconds sampling interval. The PRBS input is generated in Matlab. The collection of data was performed by PCI-1711 interface card. The input-output data is then be analyzed by System Identification toolbox in Matlab [11].

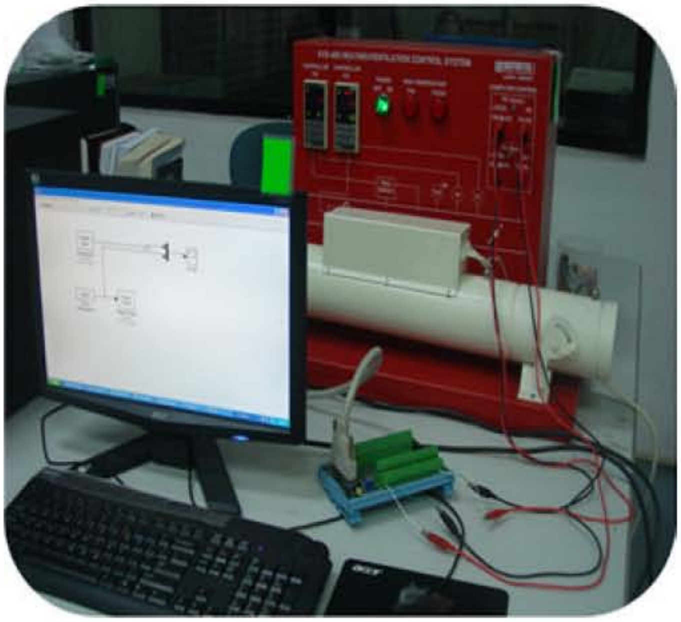


Fig. 4: VVS-400, computer and data acquisition hardware

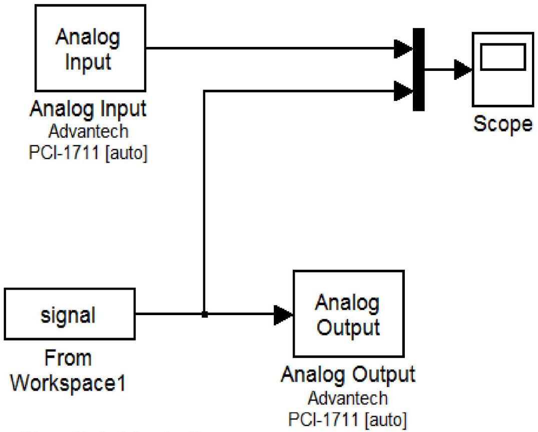


Fig. 5: Open-loop experiment using Simulink block diagram

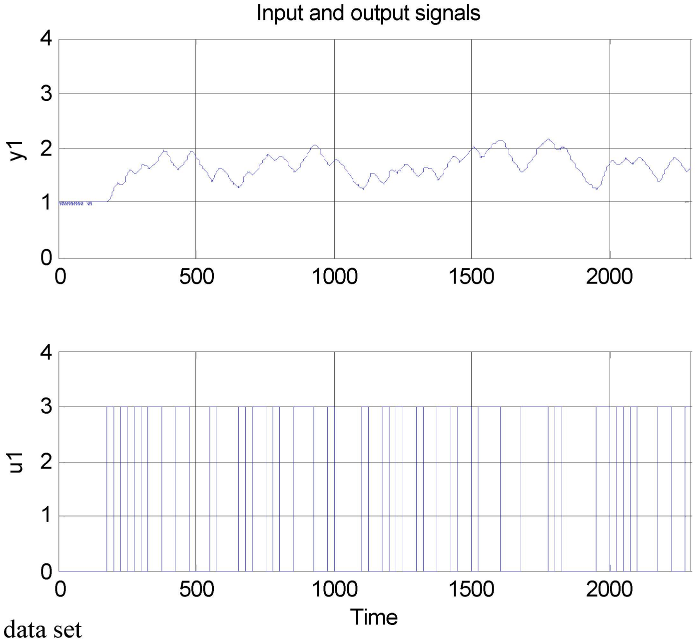


Fig. 6: The input-output data set

Fig. 6 shows the training and validation data. The VVS-400 system is modeled based on Autoregressive with exogenous input (ARX) model structure with sixth order. The general equation of ARX model structure can be written as follows

$$A(q)y(t) = B(q)u(t) + e(t) \tag{3}$$

The ARX model parameters are estimated based on input and output data. From equation (3), y and u is the output and input sequences, respectively and e is a white noise sequence with zero mean value. The best fit of output model is 82.84% as depicted in Fig. 7. Its polynomial structure can be written as equation (4) and (5).

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

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

Loss function and Akaike's Final Prediction Error (FPE) are 0.0000123078 and 0.000012567 respectively. Therefore, the pilot scale heating and ventilation VVS-400 plant can be approximated modeled by this following equation.

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

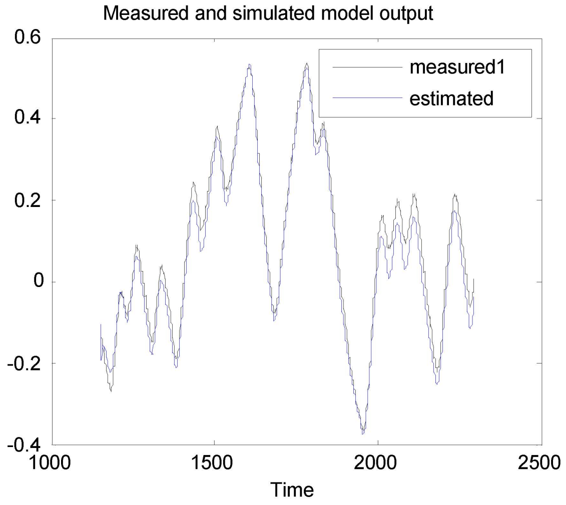


Fig. 7: Measured and simulated model output

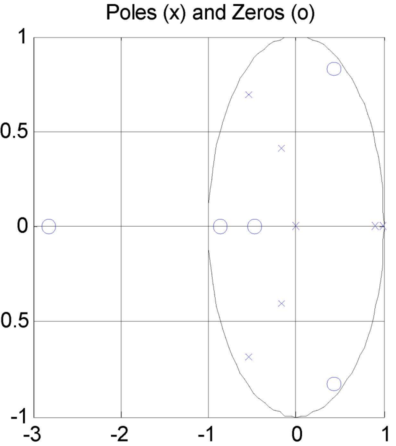


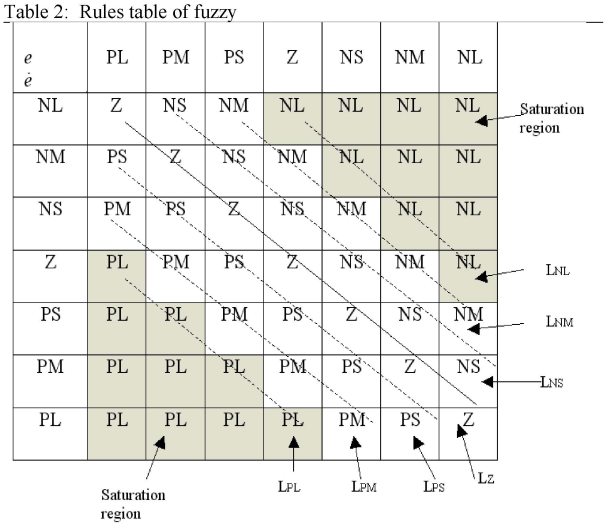
Fig. 8: Pole-zero plot

As can be seen in equation (6), the approximated plant gives a higher order model where an excess model order is usually represent the noise. Since the ARX model incorporated with the noise in the system model, the model might be influenced by this noise [8].

From Fig. 8, it can be noticed that there is one zero outside the unit circle of the z-domain. This specific zero is called non-minimum phase model. System is assumed to be stable since all the poles have negative real parts.

Single-Input Fuzzy Logic Controller (SIFLC): In conventional FLC design, it is common to have error, e and change of error, $\dot{e}$ as an input variable. Then, a two-dimensional input space rule table is constructed as can be seen in Table 2. 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.

Table 2: 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

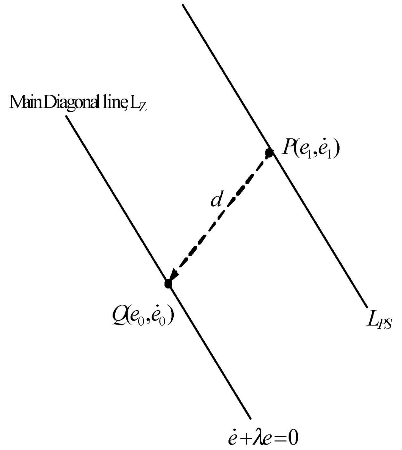


Fig. 9: Derivation of distance variable

It can be noted that rule table represents same output membership function in a diagonal direction. Instead of using two inputs $(e, \dot{e})$ in the conventional FLC, this method simplifies the number of input 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 $Q(e_0, \dot{e}_0)$ be an intersection point of the main diagonal line and the line perpendicular to it from a known operating point $P(e_1, \dot{e}_1)$, as illustrated in Figure 9. The absolute distance magnitude from point P to Q can be obtained by using the Pythagoras theorem as follows

$$d=\sqrt{(e_1-e_0)^2+(\dot{e}_1-\dot{e}_0)^2} \qquad (7)$$

From Figure 9, it can be noted that main diagonal line, L_z can be represented as follows

$$\dot{e}+\lambda e=0 \tag{8}$$

In equation (8), variable ë is the slope magnitude of the main diagonal line, Lz. Since the distance, d from point P and Q (denoted as PQ) is perpendicular to the Lz, the PQ can be describe as a straight line function as follows.

$$\dot{e}=\frac{1}{\lambda}e+c \tag{9}$$

Substituting P(e_1, $\dot{e}_1$) into equation (9) and solving for c, gives a line function for PQ is

$$\dot{e}=\frac{1}{\lambda}e+(\dot{e}_1-\frac{1}{\lambda}e_1) \tag{10}$$

By solving equation (8) and (10), value of e_0 can be obtained as follows

$$-\lambda e_0=\frac{1}{\lambda}e_0+(\dot{e}_1-\frac{1}{\lambda}e_1) \tag{11}$$

$$e_0(\frac{-\lambda^2-1}{\lambda})=\dot{e}_1-\frac{1}{\lambda}e_1 \tag{12}$$

$$e_0=\frac{\dot{e}_1-\frac{1}{\lambda}e_1}{\frac{-\lambda^2-1}{\lambda}}=\frac{-\dot{e}_1\lambda+e_1}{\lambda^2+1} \tag{13}$$

Then, to solve for $\dot{e}_0$, substituting the value of e_0 in equation (13) into (8)

$$\dot{e}_0=-\lambda e_0=-\lambda(\frac{-\dot{e}_1\lambda+e_1}{\lambda^2+1})=\frac{\dot{e}_1\lambda^2-e_1\lambda}{\lambda^2+1} \tag{14}$$

Finally the distance, d between point P and Q can be obtained by replacing e_0 and $\dot{e}_0$ in equation (13) and (14) into (7), gives.

$$d=\sqrt{(e_1-(\frac{-\dot{e}_1\lambda+e_1}{\lambda^2+1}))^2+(\dot{e}_1-(\frac{-\dot{e}_1\lambda^2+e\lambda}{\lambda^2+1}))^2} \tag{15}$$

Simplifying equation (15) gives

$$d=\sqrt{\left(\frac{\lambda^2+1}{\left(\lambda^2+1\right)^2}\right)(\lambda e_1+\dot{e}_1)^2}=\frac{\lambda e_1+\dot{e}_1}{\sqrt{\lambda^2+1}} \tag{16}$$

Table 3: The reduced table using Signed distance method

$d=\frac{\dot{e}+\lambda e}{\sqrt{1+\lambda^2}}$	LNL	LNM	LNS	LZ	LPS	LPM	LPL
$\dot{u}_0=\dot{e}+\lambda e$(rule table)	NL	NM	NS	Z	PS	PM	PL

Table 4 Rule Table for conventional FLC

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

In general form for any states (e and $\dot{e}$), distance, d can be expressed as

$$d=\frac{\dot{e}+\lambda e}{\sqrt{\lambda^2+1}} \tag{17}$$

Based on equation (17), 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 3.

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 2 which correspond to the new input variable of the reduced table in Table 3 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 $\dot{u}_0$(k) with output scaling factor, denoted as K as can be seen in Figure 10.

Therefore, the design of SIFLC for this system employs the signed distance method which has only one input variable as shown in Fig. 10 [5, 7, 12].

SIFLC Design for VVS-400: In this section, a SIFLC for a VVS-400 is designed. This proposed SIFLC is employed to control the temperature of VVS-400. Table 4 is the rule table for the conventional FLC where the outputs of each diagonal line correspond to its input values is obtained using equation (8). The diagonal line that result "0" is called main diagonal line.

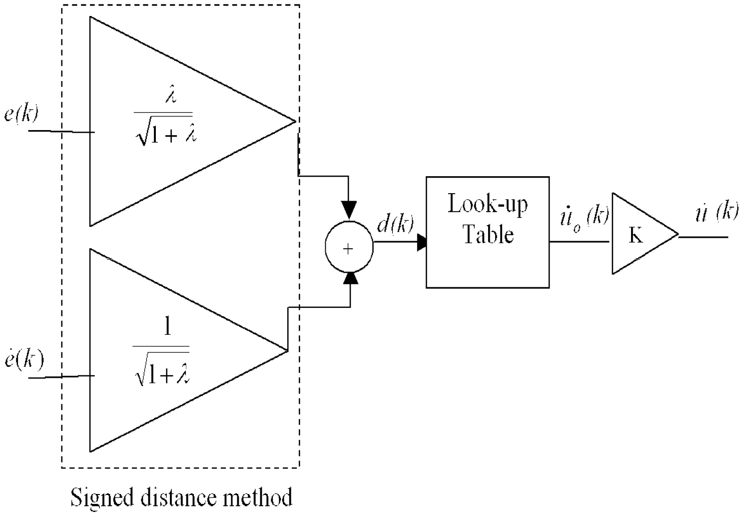


Fig. 10: The SIFLC control structure

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 (17) for seven diagonal lines as calculated below.

For diagonal line L_{NL}, the d is equal to "-7"
For diagonal line L_{NM}, the d is equal to "-4.66"
For diagonal line L_{NS}, the d is equal to "-2.33"
For diagonal line L_{Z}, the d is equal to "0"
For diagonal line L_{PS}, the d is equal to "2.33"
For diagonal line L_{PM}, the d is equal to "4.66"
For diagonal line L_{PL}, the d is equal to "7"
Then, the derived reduced SISO is given in Table 5.

The derivation of distance, d input variable resulted in single-dimension rule table compared to conventional FLC which have many rules. This simplification allows the control surface to be approximated as a linear which can be simply generated using look-up table. All input, d and output, $\dot{u}_0$ values are formed using a look-up table as can be shown in Simulink block diagram in Fig. 11. Fig. 12 shows the output of the system with SIFLC with less overshoot.

Table 5: The reduce rule table of SIFLC

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

An Online Control with Siflc: In the previous section, the SIFLC has been designed via simulation. However, it is not enough to ensure that the design controllers are exactly capable to control the VVS-400 system in online control. This real system implementation is done using Real Time Windows Target (RTWT) toolbox in Matlab [13]. Two blocks called Analog Output and Analog Input from RTWT connect the Simulink Matlab to the VVS-400 plant using data acquisition (DAQ) card PCI-1711. The controller will respond to the online process with 2 seconds sampling interval. The output of the controller will be fed into the Analog Output and the process output is generated from the Analog Input. Since only voltage is applicable in this RTWT toolbox, the output from the Analog Output need to be converted into temperature by multiply with a constant, 20 as given in the previous section. The simulink block diagram of the system with SIFLC and the system output performance are shown in Fig. 13 and 14 respectively. However, to optimize the output, tuning parameter requires a little adjustment since the simulation tuning parameter is designed based on the approximated plant.

Comparison Between Conventional Flc and Siflc: Fig. 15 and Fig. 16 show the overall output performance via simulation and online control. It is obvious when comparing output result from both simulation and online control that settling time is different. These are inherent difference that could not be changed. An extra disturbance might be occurring during online control since it can be varying with time. Besides, it can be noted that simulation and online control have validated the performance of the proposed SIFLC showing almost similar result with the conventional FLC. The initial value of the temperature is determined by the room temperature which is 22°C. Furthermore, with less number of rules, a faster computation time is expected to accomplish

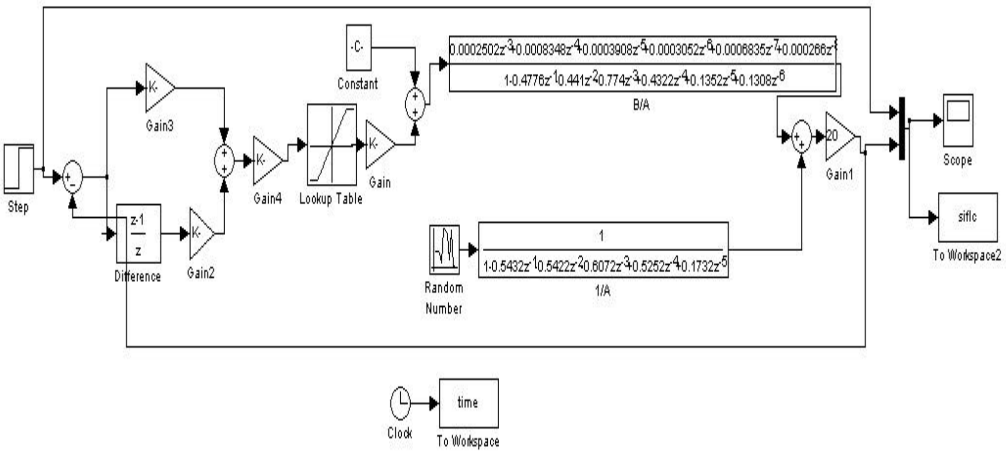


Fig. 11: Simulink block of the system and SIFLC

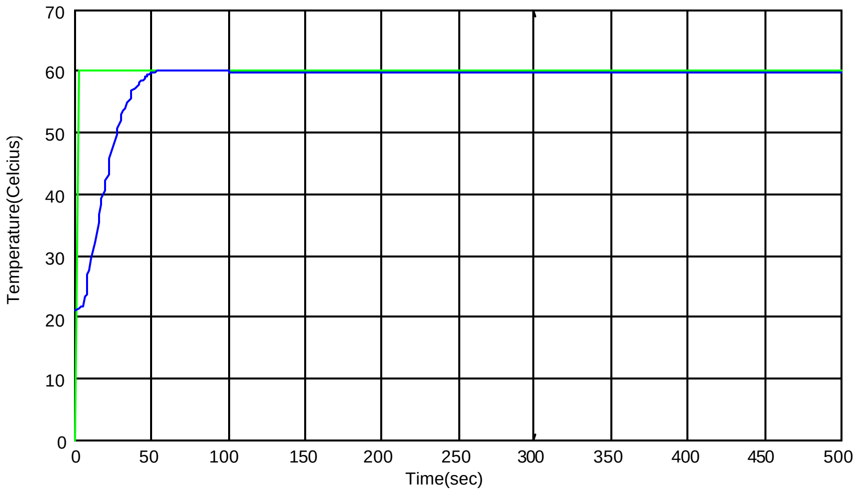


Fig. 12: Temperature process response from simulation with SIFLC

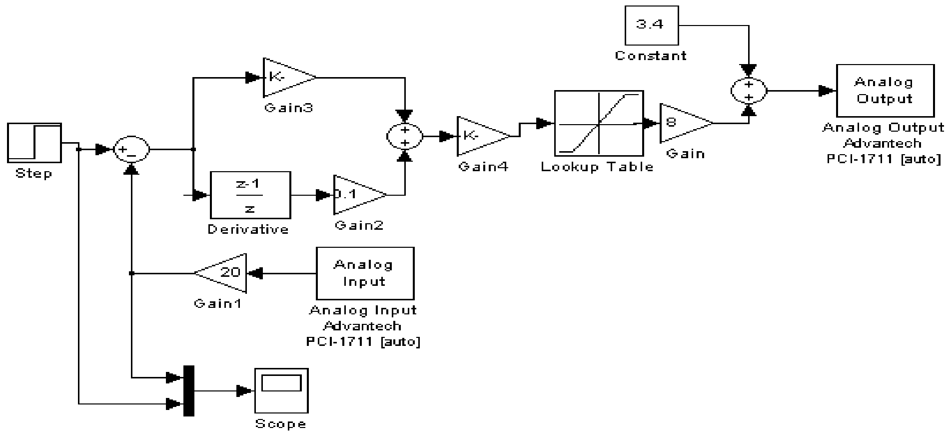


Fig. 13: Simulink block diagram of real plant implementation with SIFLC

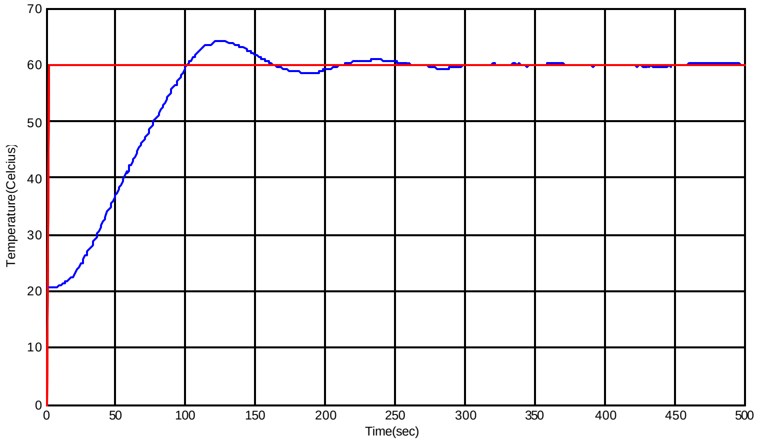


Fig. 14: Temperature process response from experiment with SIFLC

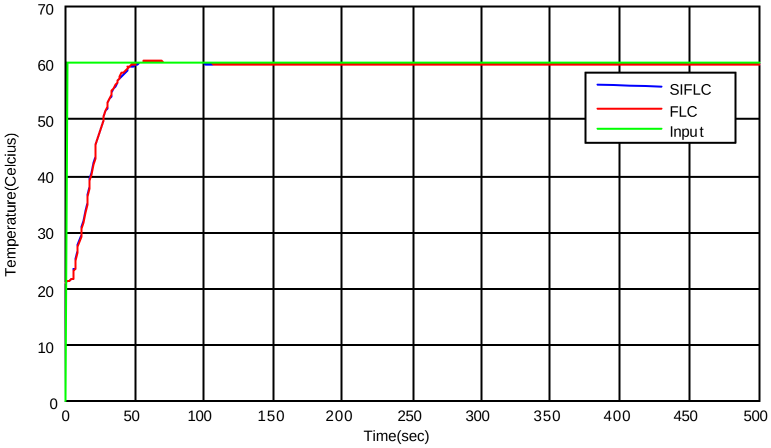


Fig. 15: The output performance of FLC and SIFLC via simulation

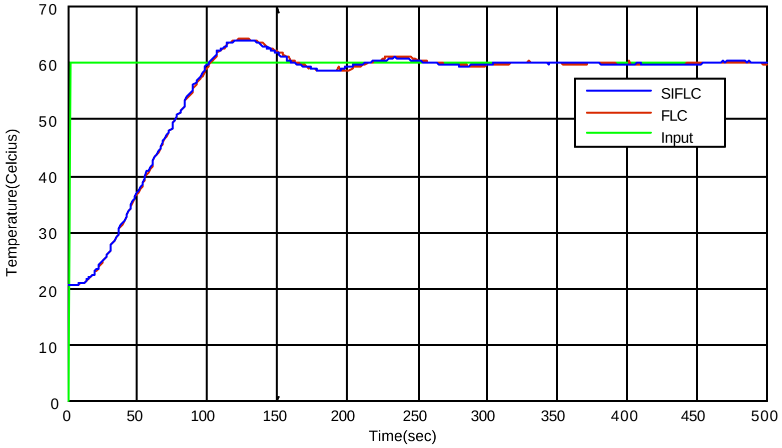


Fig. 16: The output performance of FLC and SIFLC in online control

Table 6: Computation time comparison

Controller	Computation time (Simulation)	Computation time (Online control)
Conventional FLC	95 seconds	1002 seconds
SIFLC	Less than 1 second	974 seconds

the control algorithm. This is in contrast to conventional FLC approach where large computational time with many rules. Table 6 compares the computational time for conventional FLC and SIFLC.

CONCLUSION

In this paper, the pilot scale of heating and ventilation VVS-400 plant has been successfully modeled by ARX model structure using system identification approach. The SIFLC controller is developed on this plant. In addition, SIFLC is also designed by online control to a real VVS-400 plant to verify the SIFLC design. From this study, it can be clearly seen that SIFLC produces almost similar output performance as conventional FLC. However, SIFLC gives small computation time due to the reduction in the number of fuzzy rules and has simple structure with no fuzzification and defuzzification process as compared to conventional FLC. Though, both controllers produced almost similar results, but in real world, the computation time plays a vital role in choosing a suitable controller.

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