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Operation of Compressor and Electronic Expansion Valve via Different Controllers

Orhan Ekren[1], Savas Sahin[2] and Yalcin Isler[3]
[1]Southern Illinois University,
Mechanical Engineering Department, Edwardsville,
[2]Ege University, Ege Technical College,
Department of Control and Automation, Bornova, Izmir,
[3]Zonguldak Karaelmas University,
Department of Electrical and Electronics Engineering,
Incivez, Zonguldak
[1]USA
[2,3]Turkey

1. Introduction

The most critical problem in the world is to meet the energy demand, because of steadily increasing energy consumption. Refrigeration systems` electricity consumption has big portion in overall consumption. Therefore, considerable attention has been given to refrigeration capacity modulation system in order to decrease electricity consumption of these systems. Capacity modulation is used to meet exact amount of load at partial load and lowered electricity consumption by avoiding over capacity using. Variable speed refrigeration systems are the most common capacity modulation method for commercially and household purposes. Although the vapor compression refrigeration designed to satisfy the maximum load, they work at partial load conditions most of their life cycle and they are generally regulated as on/off controlled. The experimental chiller system contains four main components: compressor, condenser, expansion device, and evaporator in Fig.1 where this study deals with effects of different control methods on variable speed compressor (VSC) and electronic expansion valve (EEV). This chiller system has a scroll type VSC and a stepper motor controlled EEV.

There are electronic parts in the control system: DAQ (data acquisition), Controllers, and Inverter. Data acquisition part reads distinct temperature values of the water outlet (T_{wo}), evaporator input (T_{ei}), and the evaporator output (T_{eo}) points from the evaporator. Controllers drive both expansion valve and compressor, which are named Controller #1 and Controller #2 throughout the paper, respectively. Inverter, which is commanded by controller #1, drives the compressor speed frequency (f) using $f(V)$. Common controllers are on-off, proportional (P), proportional-integral (PI), and PID respectively. "On-off" control method is the most used conventional technique to control refrigeration systems. This method has a big drawback of undesired current peaks during its state transitions (Aprea et al., 2009). PID controller has been found wide usage in industrial applications since it is very simple to design, to implement, and to use (Katsuhiko, 2002; Astrom and Hagglund, 1995). Therefore, it has been widely used in Heating Ventilation Air Conditioning and Refrigeration (HVAC&R) systems (Jiangjiang et al., 2006). Recently, energy consuming is a strict issue in designing new refrigeration system (Aprea and Renno, 2009; Ekren et al., 2010, 2011; Nasutin and Hassan, 2006, Sahin et al., 2010). EEV and VSC have important effect on efficiency of system energy consumption. Hence designing an eligible controller for these parts will improve energy consuming. Conventional controllers cannot deal with nonlinear behaviors including uncertainties in system parameters, time delays and limited operation point of refrigeration systems, which may reduce the energy efficiency. Nonlinear controllers based on Fuzzy Logic (FL) and Artificial Neural Network (ANN) may overcome these issues (Aprea et al., 2006a,b). The most important advantage of these algorithms is to enable solving control problems without any already-known mathematical model (Narendra and Parthasarathy, 1990; Narendra, 1993; Aprea et al., 2004; Ross, 2004).

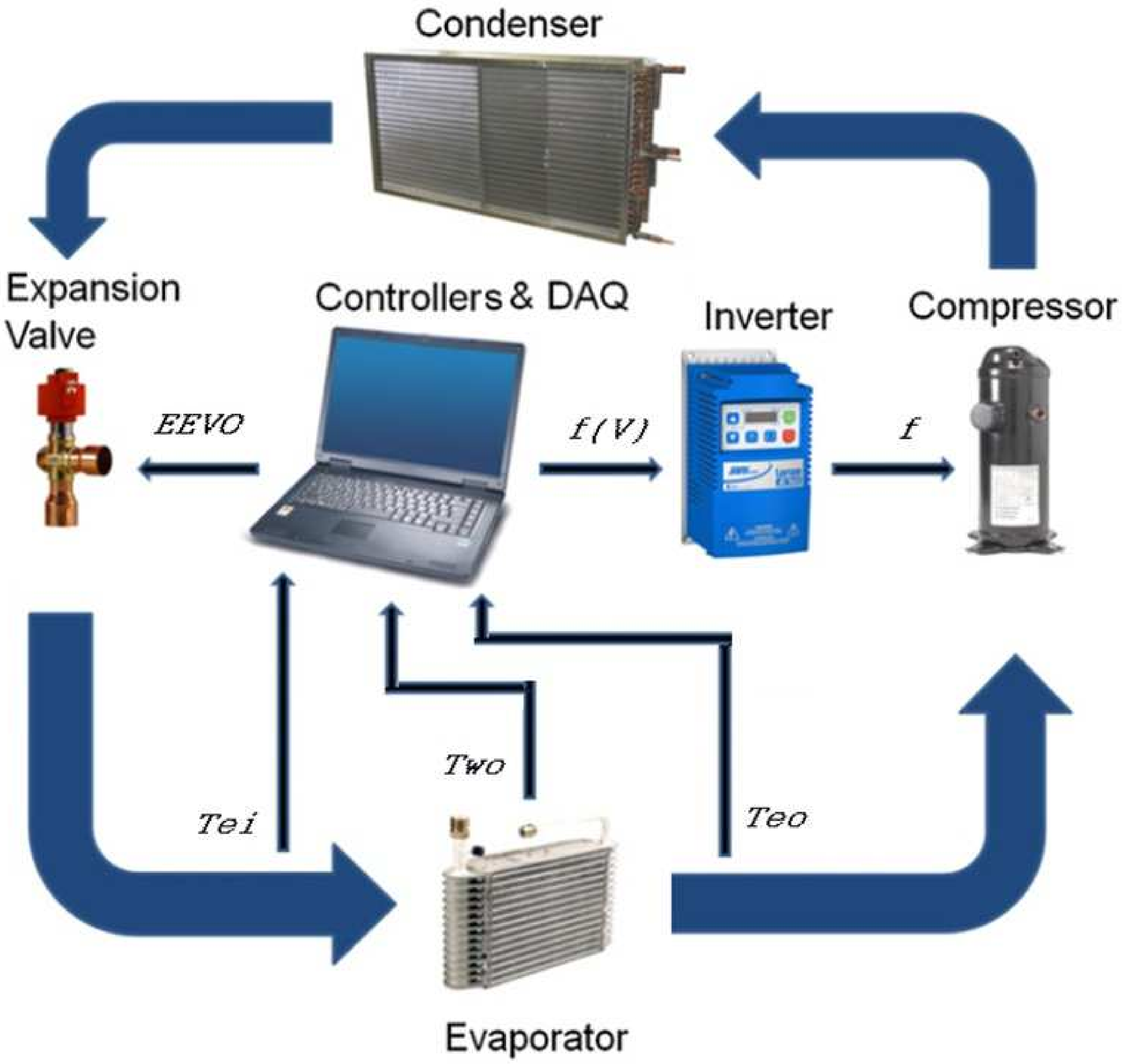

Fig. 1. Schematic of the refrigeration and control system

In this chapter, different control algorithms, based on proportional-integral-derivative (PID), fuzzy logic (FL), artificial neural network (ANN) for compressor speed and opening percentage of electronic expansion valve, were compared by means of achieving their desired output and energy demands.

2. Control methods of the VSRS

There are three parts in a closed-loop control system: error calculation, controller, and plant (Fig. 2). Error calculation part calculates the difference between the desired output, r(k), and the actual output, y(k), of the system. This difference is called error signal, e(k). A controller finds out a control signal, u(k), by considering this error signal. A plant, the system itself under investigation, generates the actual output, y(k), in reply to the u(k). The most important problem is generating the most suitable control signal that derives the plant to minimize the error, which means that the actual output and the desired output are almost equal in the closed-loop control system.

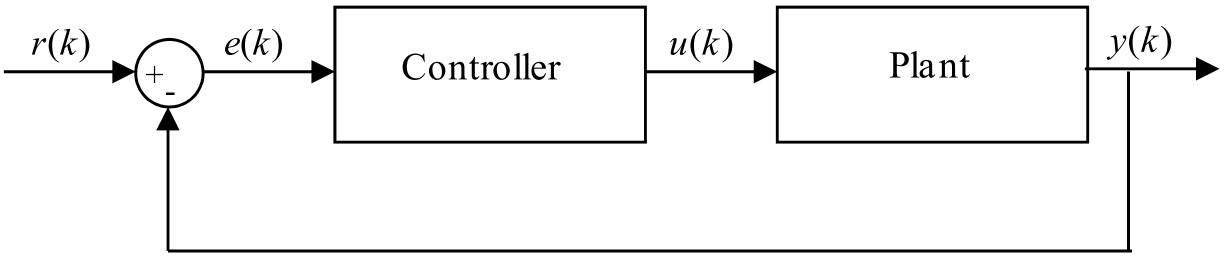

Fig. 2. A general closed-loop control system

In the variable speed refrigeration system (VSRS), which is a typical closed-loop control system, contains VSC and EEV controllable components. The frequency of the compressor and the opening amount of the expansion valve are control parameters in order to drive the water outlet temperature and the degree of superheat respectively to desired values in VSRS (Ekren et al., 2010). By considering controllable parts in the experimental setup, after adapting closed-loop control system into the setup, a detailed block diagram of controllers and system parts for the VSRS are also shown in Fig. 1.

In the following subsections, certain control methods are given in control refrigeration systems. These methods are itemized two main groups: i) linear controller such as PID and ii) nonlinear controllers such as FL and ANN controllers.

2.1 PID control

PID is the most commonly used control technique for industrial applications since it is very simple to design, to implement, and to use (Astrom and Hagglund, 1995). It has also been widely used in Heating Ventilation Air Conditioning and Refrigeration (HVAC&R) systems (Jiangjiang et al., 2006). This controller is tuned by its three variables: proportional (K_p), integral (K_i) and derivative (K_d) parameters. The control action $u(t)$ in time domain can be calculated as

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \dot{e}(t) \tag{6}$$

by means of the error, which is the difference between the desired and the actual output of the plant (e), and the derivative of this error ($\dot{e}$). PID parameters can be determined in using either the step response or the self-oscillation methods from Ziegler-Nichols (Ziegler and Nichols, 1942) are widely used in the literature (Astrom and Hagglund, 1995). In the step response method, if the output response of the plant can be obtained in time domain, PID parameters can be determined. This output response can be approximated as a first-order system

$$H(s) = \frac{K}{Ts+1} e^{-Ls} \tag{7}$$

where T is time constant, L is delay time and K is gain. The T and L give the PID controller design parameters (Katsuhiko, 2002; Astrom and Hagglund, 1995).

The template plot is represented in Fig.3 to find out L and T values. The parameters can be determined from the output plots with respect to step input. The constant gain K indicates the amount of output variation from one steady-state to another, with respect to the input variation. L represents the past time to observe the initial response changes after applying the input. In addition, T denotes the time necessary to reach the output equal to 63.2% of its final value for the first-order systems.

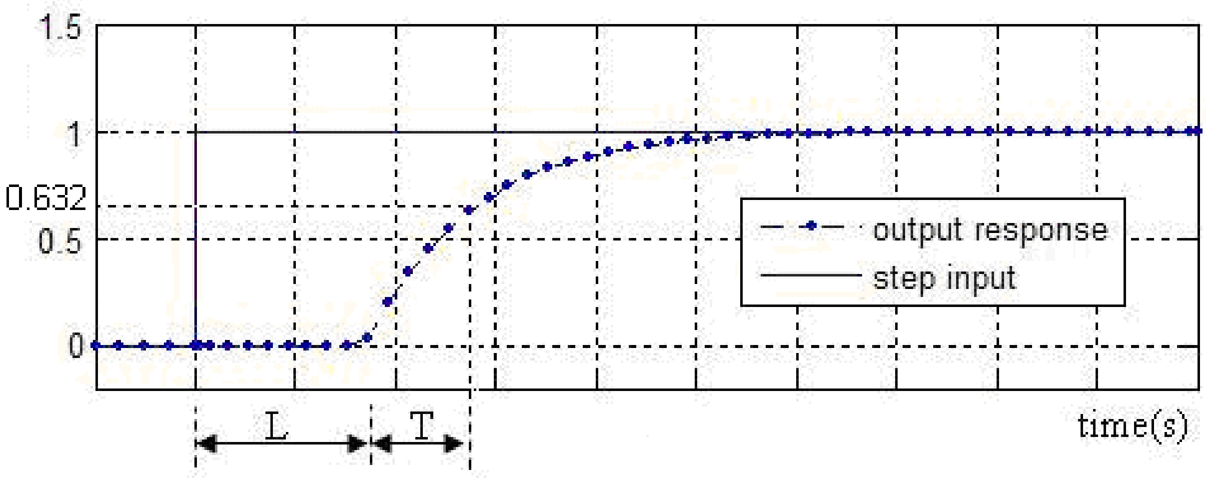

Fig. 3. Output response plots with respect to step function input

In the self-oscillation method, PID controller design parameters are calculated by critical gain and critical period variables. These variables are computed when a stable limit cycle of the closed-loop system is satisfied by using only the proportional gain. This gain is increased slowly, and then the PID parameters are determined. This method possesses very important advantage for the plant because self-oscillation experiment could be in reasonable operating bounds of the plant (Yuksel, 2006; Katsuhiko, 2002; Astrom and Hagglund, 1995).

Although there are some other methods to find out the PID parameters, Ziegler Nichols' methods are still the most used and preferred methods in the literature. In this study, Ziegler Nichols' step response method is used to find out the PID parameters by regarding the plot of the system output.

2.2 Fuzzy logic control

FL controllers consist of certain rules and membership functions. The certain rules is to determine the decision process and the membership functions is to bring up the relation between linguistic and the precise numeric values. These membership functions define input-output variables of any system and formulate control rules. A membership function can be defined by a geometric shape such as triangular, trapezoidal, etc. The selection of the membership functions depends on expert's knowledge about the process (Aprea et al., 2004; Ross, 2004).

The operation procedure of the FL controller can be itemized into three main steps: i) fuzzification, ii) inference, and iii) defuzzification (Zadeh, 1965; Ross, 2004). In the fuzzification step, system inputs-outputs and membership functions are well defined. In the inference step, a rules table is prepared according to the human expertise and these rules calculate the outputs (Ross, 2004). In the last step, defuzzification transforms fuzzy outputs into real world values. A detailed explanation of these steps and their implementation details can be found in the literature (Ross, 2004). In this study, the minimum-maximum method and the center of gravity method were used in the inference and the defuzzification steps, respectively.

EEV is the first controllable equipment in VSRS (Aprea et al., 2006a,b; Lazzarin and Noro, 2008, Ekren et al., 2010, 2011). For this controller, two inputs and one output variable were defined (Ekren et al., 2010) in Fig. 4.

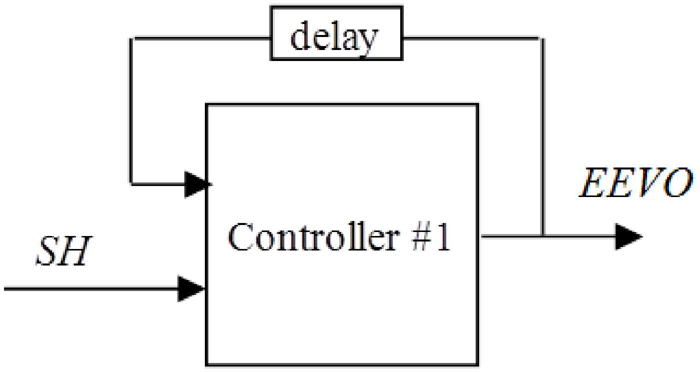

Fig. 4. Inputs and output of the first controller in VSRS.

The first input was the difference between desired and actual superheat (SH) values, of which linguistics were marked as negative high (NH), negative medium (NM), zero (Z), positive medium (PM), positive high (PH). The second one was the previous value of the EEV opening. The output was the value of EEV opening (EEVO). The second input and the output of the system had similar membership functions where linguistics were marked as very closed (VC), closed (C), medium (M), opened (O) and very opened (VO). The membership functions can be seen in Fig. 5.

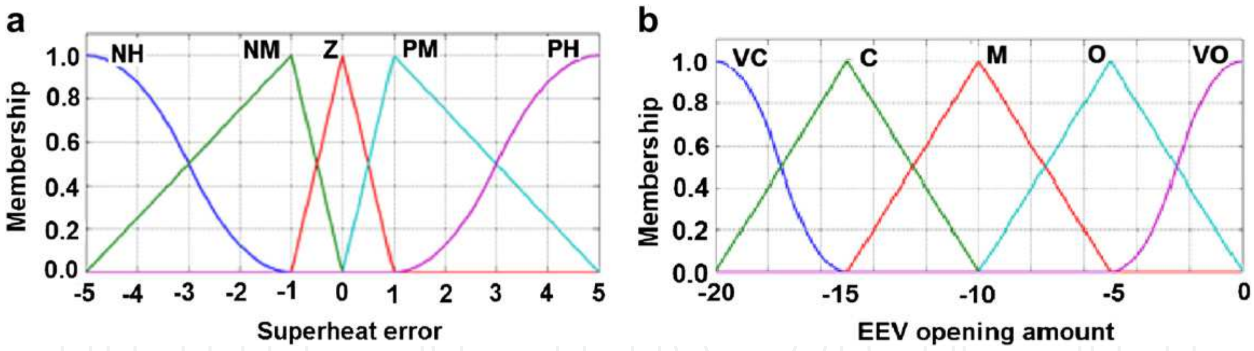

Fig. 5. Membership functions of (a) the superheat error input, (b) the previous opening value of EEV input and the EEV opening amount output.

Fuzzy rules for the EEV control were experimentally verified by using some trials, and it is given in Table 1.

	Previous Opening Value of EEV				
Superheat Error	***VO***	***O***	***M***	***C***	***VC***
NH	*O*	*M*	*C*	*VC*	*VC*
NM	*O*	*M*	*C*	*VC*	*VC*
Z	*VO*	*O*	*M*	*C*	*VC*
PM	*VO*	*VO*	*O*	*M*	*C*
PH	*VO*	*VO*	*O*	*M*	*C*

Table 1. EEV Fuzzy logic control rules

For the second controller, two inputs and one output variable were defined (Ekren et al., 2010) in Fig. 6.

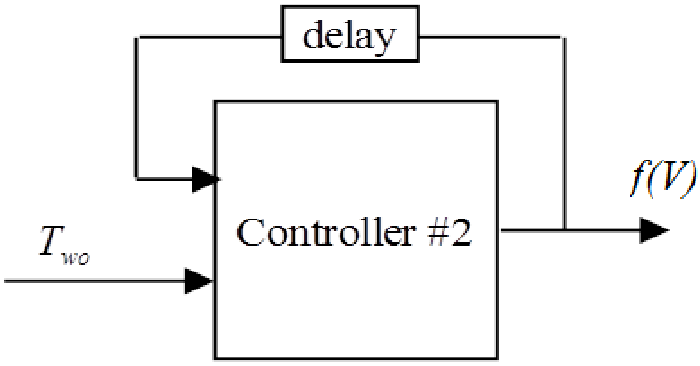

Fig. 6. Inputs and output of the second controller in VSRS.

The first input was the temperature difference between the desired temperature and actual temperature at outlet of the evaporator (T_{wo}), of which linguistics were marked as negative high (NH), negative medium (NM), zero (Z), positive medium (PM), and positive high (PH). The second input was the previous change of frequency value, sent to the inverter by the control unit. The output for this controller was the frequency change of the supply voltage of the compressor electric motor, *f(V)*. The second input and the output of the system had similar membership functions where linguistics were marked as very small (VS), small (S), medium (M), big (B) and very big (VB). The membership functions can be seen in Fig. 7.

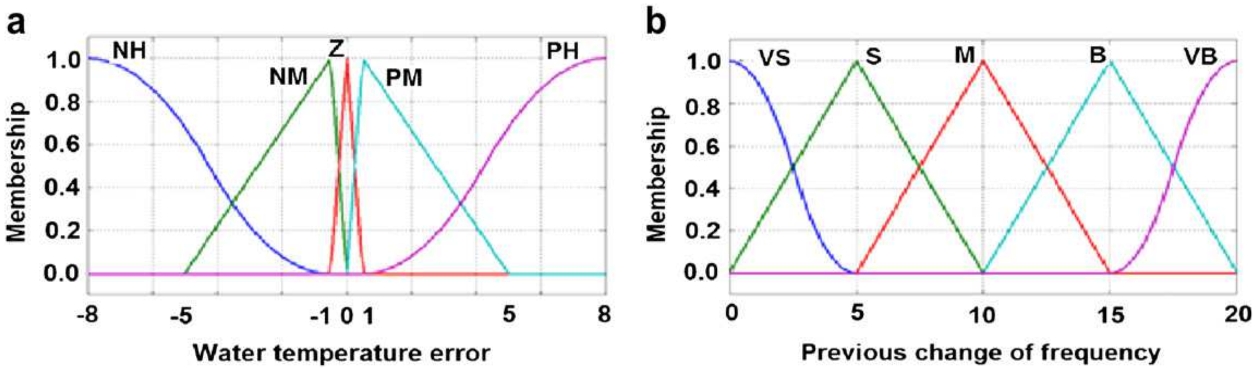

Fig. 7. Membership functions for (a) water temperature error input, (b) for the previous change of frequency input and the frequency change output.

Fuzzy rules for the compressor control were experimentally verified by using some trials, and it is given in Table 2.

	Previous Change of Frequency				
Water Temperature Error	***VS***	***S***	***M***	***B***	***VB***
NH	*S*	*M*	*B*	*VB*	*VB*
NM	*S*	*M*	*B*	*VB*	*VB*
Z	*VS*	*S*	*M*	*B*	*VB*
PM	*VS*	*VS*	*S*	*M*	*B*
PH	*VS*	*VS*	*S*	*M*	*B*

Table 2. Compressor fuzzy logic control rules

2.3 ANN Control

The most important features of the ANN developed by inspiring from biological neural networks are learning, generalizing and making a decision. ANNs are widely used in many industrial applications such as identification, control, data and signal processing area since 1980s. Since ANNs define, in general, a nonlinear algebraic function, they can cope with nonlinearities inherent in control systems possessing complex dynamics. As in the general ANN literature, the mostly widely used ANN model in identification and control is the Multi Layer Perceptron (MLP) due to its function approximation capability and the existence of an efficient learning algorithm (Ahmed, 2000; Lightbody & Irwin, 1995; Meireles et al., 2003; Noriega & Wang, 1998; Omidvar & Elliott, 1997). MLP is a multilayer, algebraic neural network of neurons, called as perceptrons, which are multi-input, single-output functional units taking firstly a weighted sum of their inputs and then pass it through a sigmoidal nonlinearity to produce its output shown in Fig. 8.

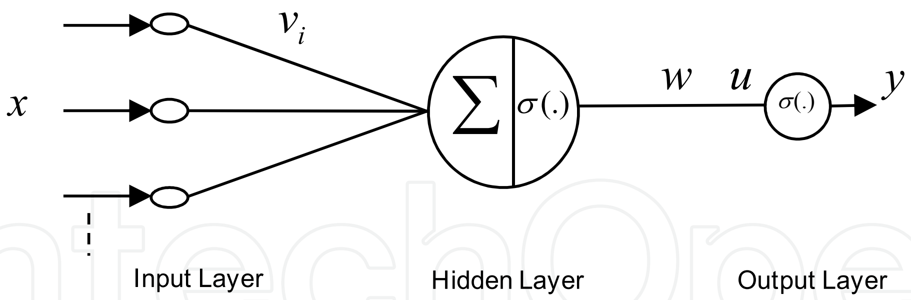

Fig. 8. Perceptron as a hidden neuron

Although MLP-ANNs are algebraic models, MLP-ANNs can define nonlinear discrete-time dynamical system due to the fact that its inputs can be connected with delayed outputs. As shown in Fig. 9, a multi-input, multi-output MLP with one hidden layer can be used as a Nonlinear Auto-Regressive-Moving-Array (NARMA) model. Input vector of this NARMA model $x = [y(k-1),...,y(k-n),u(k-1),...,(k-n)]$ where n is the finite value and v and w are weights of the layers.

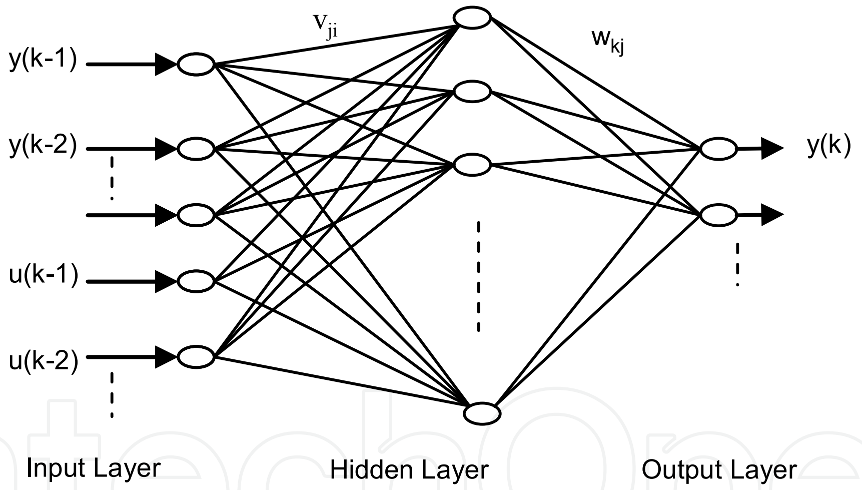

Fig. 9. MLP implementing NARMA model

In most industrial cases, an ANN is an adaptive system that changes its internal information in the learning phase. A general feed-forward inverse control system contains two MLP-ANNs such as identification and control structures, which are shown in Fig. 10 (Narendra and Parthasarathy, 1990). In this study, for the identification stage, serial-parallel identification is used for inputs of ANN. These inputs are the actual input with its past values $(u(k) = [u(k-1),...,u(k-15])$ and the actual output with its past values $(y(k) = [y(k-1),...,y(k-15)])$. The output of ANN identification block is $\hat{y}(k)$. After ANN identification is completed, ANN controller weights are tuned with respect to overall closed-loop error function (Narendra and Parthasarathy,1990).

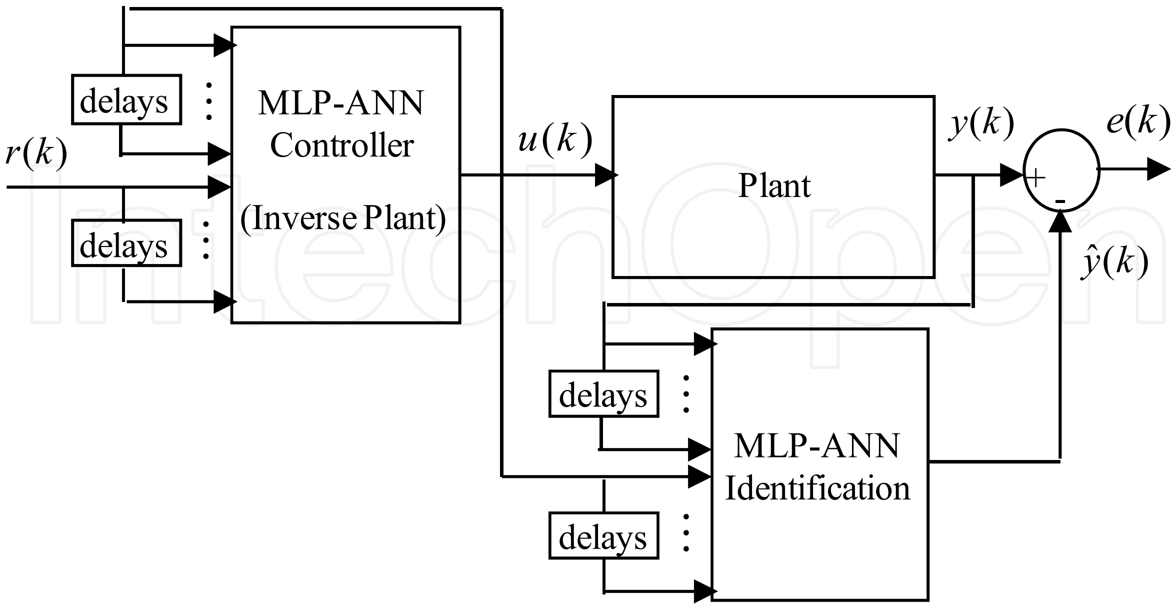

Fig. 10. Feed-forward inverse control system using MLP-ANN.

One of the most important problems in real world applications is the delay time defined the time required before observing the output change after applying a control input. To overcome delay time problem, Smith compensator structure can be used in ANN-based controllers (Ekren et al., 2010; Huang and Lewis, 2003; Lin et al., 2008; Slanvetpan et al., 2003). Inverse system MLP-ANN controller with Smith predictor was used for compensation of the delay time of the plant in Fig. 11. The MLP in both EEV and compressor controllable parts are trained with the gradient algorithm. The number of neurons in the hidden layer of MLP was selected as 20 experimentally. The EEV was controlled using an inverse system ANN controller with Smith compensator. Inputs of the first controller were EEV opening values and SH error with their 15 past values. The output of this controller was EEVO. On the other hand, compressor was controlled using an inverse system ANN controller. Inputs of this controller were compressor frequency and T_{WO} error values with their 15 past values. The output of this controller was the frequency change of the supply voltage of compressor electric motor (*f*).

3. Applications of the controllers

In this study, the controllers are designed as decoupled ones without interfering loops (Li et al., 2008). In the experimental setup used in this study, there were some limitations of the equipment. EEV opening value is restricted between 0% and 20% since its limits are 15% and 35% to prevent the low pressure alert and to avoid liquid entrance into the compressor. Instantaneous frequency change is restricted between 0 Hz and 20 Hz to prevent system from the vibration and the unsuitable lubrication since the frequency limits are 30 Hz and 50 Hz. By considering these limitations, three different controllers such as PID, FL, and ANN were examined in the VSRS.

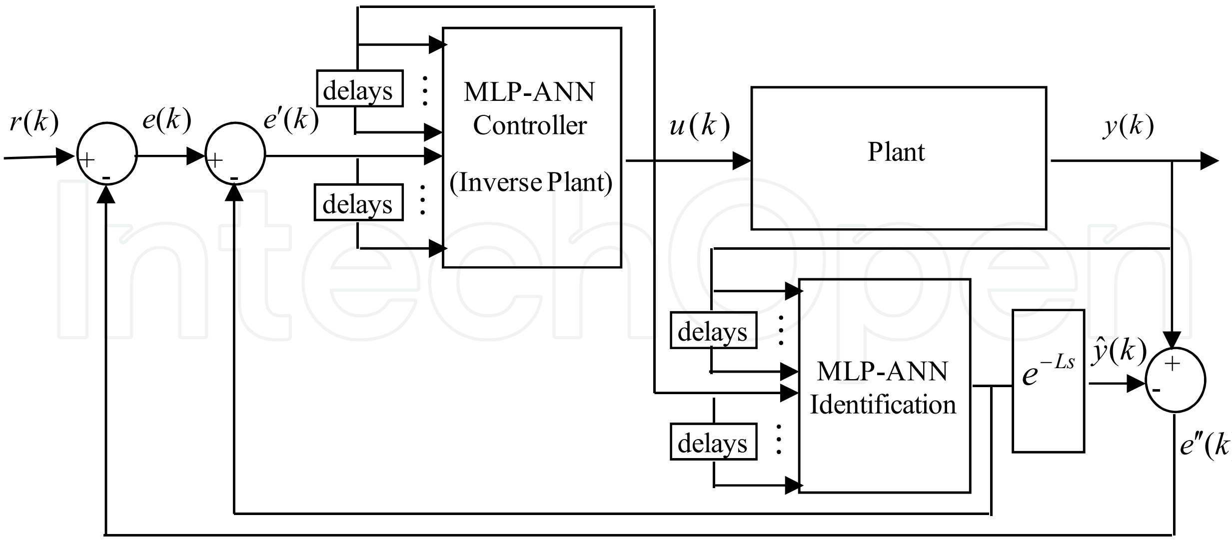

Fig. 11. Smith delay time compensator configuration using MLP-ANN.

Control experiments, conducted during the study, have been classified in three groups. The first was controlling EEV opening, the second one was controlling compressor frequency, and the last one was controlling both together. For the first and second groups, the other controllable part was operated at a constant value. All cases were tested using three different control algorithms of PID, FL and ANN. In addition, the cooling load was decreased 40% of full load to simulate a disturbance input in all cases. This is presumed to be by a change in water flow.

All controller algorithms were implemented using the most famous software of Matlab version 2011a. No ready-made toolbox routines were used throughout the study. The personal computer with a dual-core processor, 2 GB DDR Ram, and a special internal data acquisition board were used to implement controllers and to read system outputs.

3.1 EEV opening control with fixed compressor frequency

EEV opening amount was controlled to drive SH degree to a desired value. Scroll compressor frequency was fixed at 50 Hz and desired SH value was set to 6°C in order to test only EEV control algorithm. Variations of the SH degree at the outlet of the evaporator were compared and visualized in Fig. 12. The vertical dotted line in this figure shows the moment of the disturbance.

3.2 Compressor frequency control with fixed EEV opening

Compressor speed was controlled to drive water temperature at the outlet of the evaporator. EEV opening amount was fixed at 30% to obtain effects of the compressor control algorithm alone. This value was chosen since it gives better COP value for this system (Ekren and Kücüka, 2010). Water temperature variations can be seen in Fig. 13. The vertical dotted line in this figure shows the moment of the disturbance.

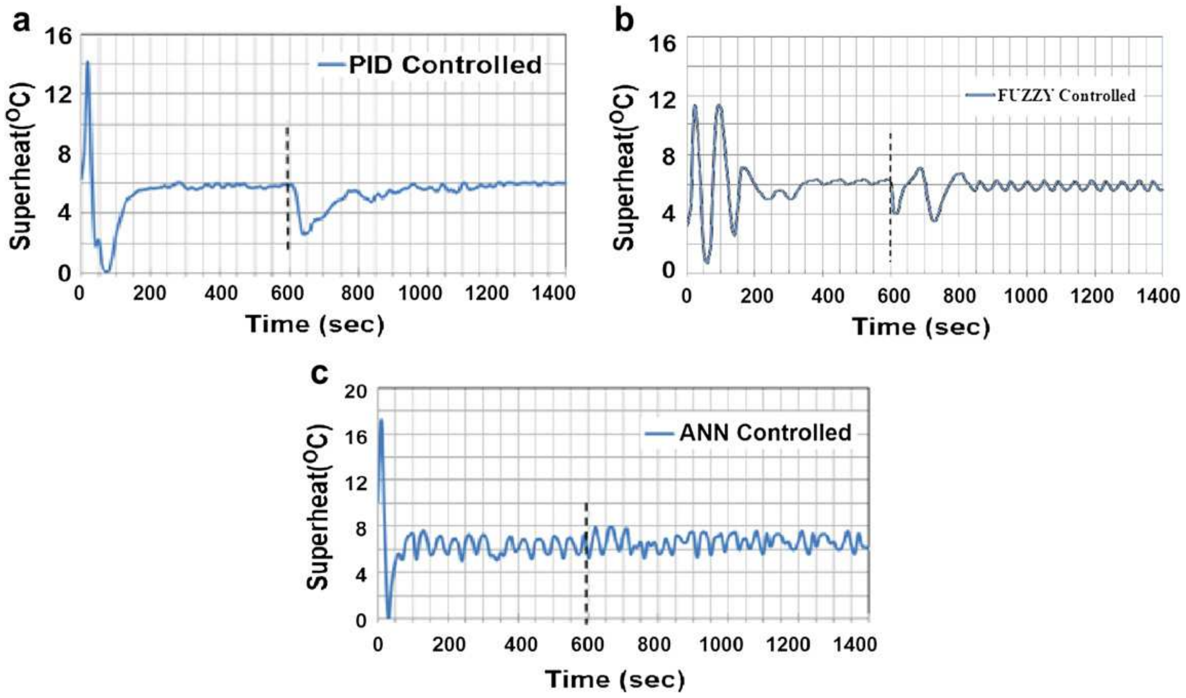

Fig. 12. Superheat change according to control method (the first case).

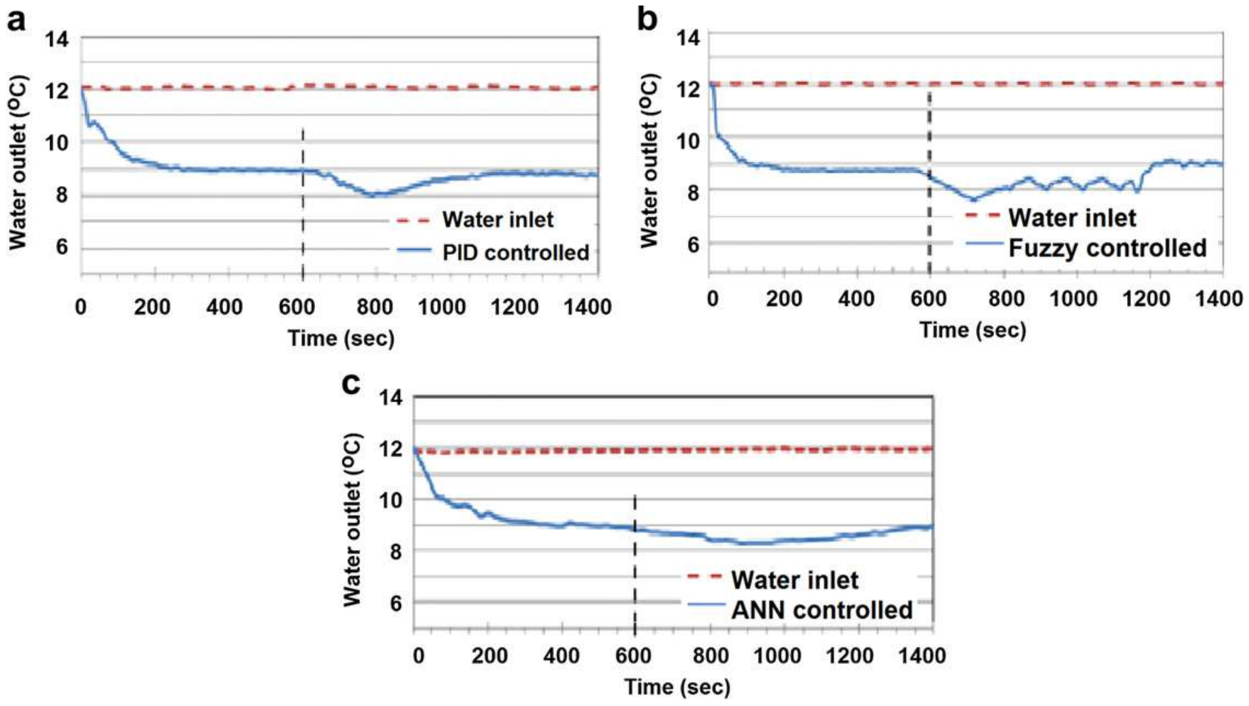

Fig. 13. Water outlet temperature change according to control method.

3.3 Both compressor and EEV control

The system was tested with the set value for SH degree of 7°C and T_{wo} of 9°C using all controller combinations. Results for SH can be seen in Fig. 14. Since the T_{wo} results were similar to results obtained in Fig. 13, T_{wo} graphs were not re-plotted here. The vertical dotted line in the Fig. 14 shows the moment of the disturbance.

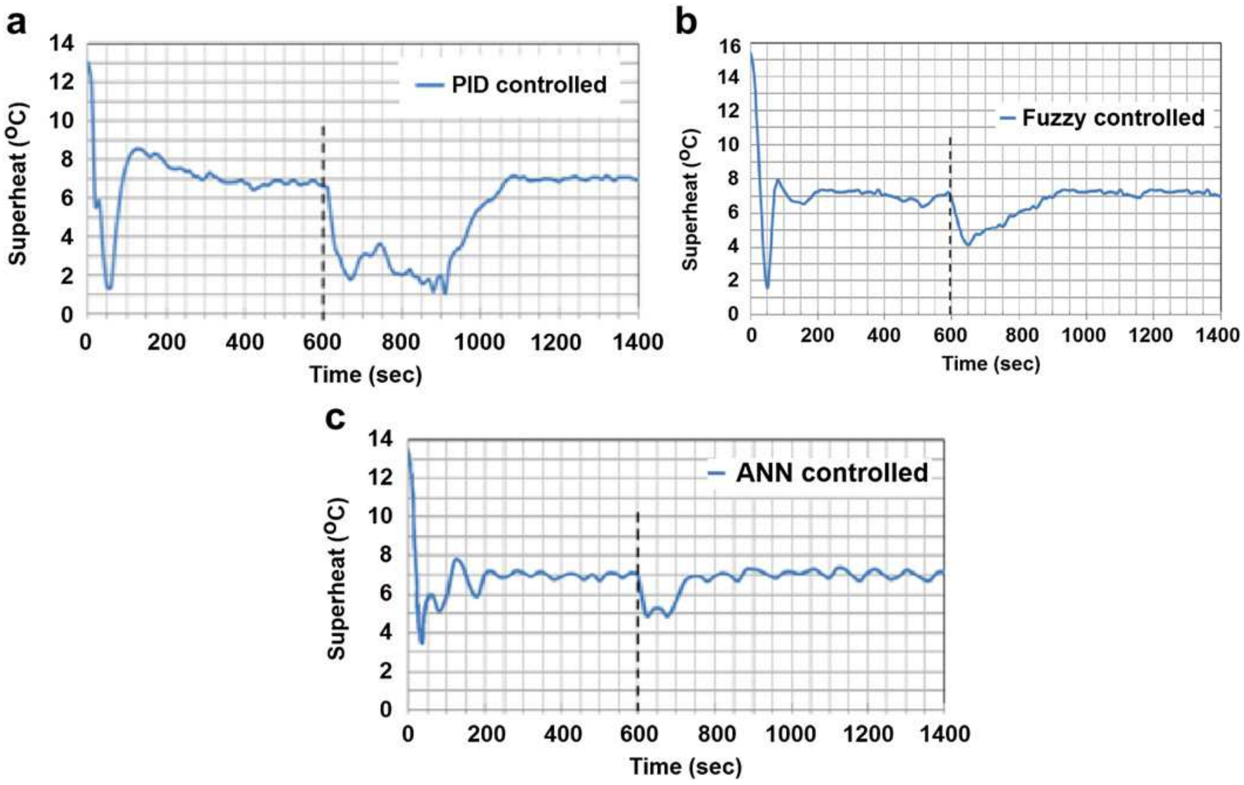

Fig. 14. Superheat change according to control method (the second case).

In addition, power consumptions were measured using wattmeter for the same duty, which can be seen in Fig. 15. Lower power consumption was obtained via ANN control algorithm.

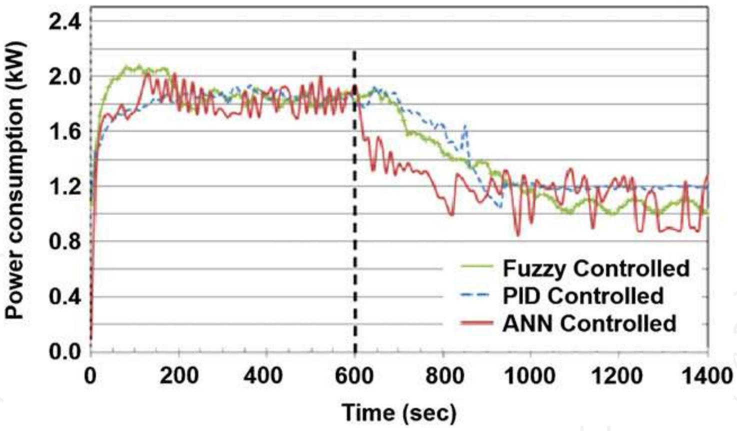

Fig. 15. Power consumptions of the compressor.

4. Conclusion

In this study, effects of different control methods (PID, FL, and ANN) on variable speed compressor (VSC) and electronic expansion valve (EEV) in a VSRS were examined. Two different procedures were applied to control EEV and VSC: controlling each part individually while the other was set to a constant value and controlling both parts together using the same algorithm. In both cases, the results of the three controllers satisfied for the set values of SH and T_{wo}. PID controller presented reasonable control solution for more stable SH and T_{wo} values in the steady state. ANN controller pair was selected to achieve minimum power consumption and more stable SH and T_{wo} values in the transient behavior and better rising time performance (reach to the desired value rapidly). In the second case, ANN controller showed 8.1 percent and 6.6 percent lower power consumption than both PID and Fuzzy controllers, respectively. In addition, Fuzzy controller showed 1.4 percent lower power consumption than PID controller. While a chiller system is being operated at a lower water flow rate, which means less cooling load, compressor speed decreases. Hence, power consumption of the compressor decreases. It can be seen from Figs. 12-14 that ANN control algorithm gave more robust response to the disturbance effect in the system. On the other hand, other control algorithms needed longer response time to eliminate the disturbance effect. Since most consumer electronics products are under the influence of disturbance effects, control algorithms whose transient response is robust against to the disturbance effect should be used to provide consumer comfort. Although controller design based on ANN is an expensive method in the manner of hardware and software, using such a controller seems necessary if the system has much disturbance.

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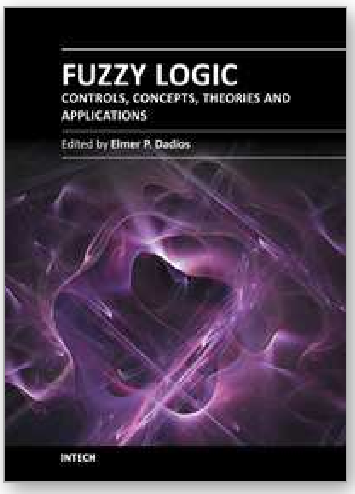

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Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821