Applied Thermal Engineering 142 (2018) 303–310

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Systematic design of membership functions for fuzzy logic control of variable speed refrigeration system

Seok Kwon Jeong[a,*], Chang Ho Han[b], Li Hua[c], Wahyu Kunto Wibowo[d]

[a] Department of Refrigeration and Air-conditioning Engineering, Pukyong National University, San 100, Yongdang-dong, Nam-gu, Busan, South Korea
[b] Graduate School of Refrigeration and Air-conditioning Engineering, Pukyong National University, San 100, Yongdang-dong, Nam-gu, Busan, South Korea
[c] School of EMU Application and Maintenance Engineering, Dalian Jiaotong University, No. 794 Huanghe Road, Dalian Shahekou, China
[d] Department of Electrical Engineering, Pertamina University, Jalan Teuku Nyak Arief, Simprug, Kebayoran Lama, Jakarta, Indonesia

ARTICLE INFO

Keywords:
Variable speed refrigeration system
Fuzzy logic control
Membership function range
Systematic design
Control accuracy

ABSTRACT

The systematic design of membership functions (MFs) for the fuzzy logic control (FLC) of a variable speed refrigeration system (VSRS) is presented in this paper to reduce trial and error as well as dependence on expert knowledge. In particular, the influence of MFs on the error and error change rate of controlled variables is investigated in detail to verify the validity of the designed MFs. To this end, the range of MFs obtained based on the control accuracy and experimental data for the static and dynamic states of the VSRS were used as the criterion values. Two different values from the criterion were then used to compare the control performance through simulations and experiments. Some simulations and real experiments for the VSRS were conducted to verify the validity of the designed MFs. The experimental results showed good agreement with the simulation results. The error change rate and sampling time strongly affected the control performance of the VSRS in the transient state. Moreover, the desired control accuracy at steady-state, an essential element in the design specifications, was successfully achieved using the proposed approach. The suggested method can be applied using the control accuracy and simple experimental results from the static and dynamic states of the target system without depending on iterative work when designing MFs, which will be helpful for beginners.

1. Introduction

Recently, capacity control for a variable speed refrigeration system (VSRS) with a variable speed drive has been attracting considerable attention because of the ability to save energy and the quick reaction capability over a wide range of load variations [1–4]. VSRS is composed of a variable speed compressor, an electronic expansion valve (EEV), and heat exchangers (condenser and evaporator). All of the components in the refrigeration cycle are connected to one another with long pipes and valves. For this reason, the entire system has strong inherent nonlinear characteristics such as time delay in the operational ranges. Moreover, accurately identifying the dynamic characteristics of VSRS by modeling is very difficult and cumbersome. Even a sophisticated mathematical model for VSRS has many drawbacks when designing a control system because of high-order differential terms in the model. Therefore, a robust control method that is less dependent on a mathematical model is strongly required for VSRS.

So far, many control methods have been applied to VSRS to obtain robust control performance [3–14]. They are largely divided into two groups: model-based control and artificial intelligence (AI) techniques without a mathematical model. Proportional-integral-derivative (PID) logic, linear quadratic regulator (LQR), linear quadratic Gaussian (LQG), H-infinity, and sliding mode control are representative model-based controls [3–9]. On the other hand, fuzzy logic control (FLC) is a typical AI technique approach [10–23]. With VSRS, it is not easy to construct a linear model because of high-order terms and difficulty parameter identification. Even if a model is constructed, it will inevitably include uncertainties. Therefore, it is not enough merely for the PID control to have robust control performance on the VSRS. Other control methods such as LQR and LQG are suitable for multi-input multi-output system control. These two methods can obtain the optimum control performance between input energy and control accuracy [5–7]. However, not only is it difficult to maintain the robustness of the control system due to the modeling errors inherent in linearized state equations, but also these methods are not practical because of the high order of the state space model. H-infinity and sliding mode control are popular as robust controls that prevent model uncertainties and disturbances [8,9]. In spite of their excellent robustness in theory, they still need a mathematical model and complicated calculations during the design process. In contrast, FLC has been widely applied in various

* Corresponding author.
E-mail addresses: skjeong@pknu.ac.kr (S.K. Jeong), chhan@pukyong.ac.kr (C.H. Han), wahyu.kw@universitaspertamina.ac.id (W.K. Wibowo).

https://doi.org/10.1016/j.applthermaleng.2018.06.082
Received 6 March 2018; Received in revised form 19 June 2018; Accepted 27 June 2018
Available online 28 June 2018
1359-4311/

Nomenclature

T_a	chamber temperature	b_i	the center of area of membership functions
T_s	superheat	$\mu(i)$	output membership value
T_o	outlet temperature of evaporator	n	the number of fuzzy linguistic variables
T_i	inlet temperature of evaporator	e	control error
f_c	frequency of inverter	ee	error change rate
V_e	opening angle of EEV	Δe	error variation
U^c	defuzzified crisp value	t_s	sampling time
		e_{lim}	the allowable maximum error (control accuracy)
		e_{max}	the maximum error range of input variable

industrial fields as a robust control method for nonlinear systems with time delay and model uncertainties [10–14].

FLC for systems with nonlinear characteristics including VSRS has been studied as a robust control method to promote stability and control performance [11–21]. However, most of the previous studies mainly focused on improving the total control performance including transient characteristics [12,20] or reducing steady-state errors [11] based on the knowledge of system experts. Some papers focused on analyzing the energy saving ability when FLC was applied to VSRS [13,14]. Previous studies adopted a systematic design approach for the rule base and membership functions (MFs) based on the knowledge of an expert, which are vital design factors in FLC [16–21]. Unfortunately, however, none of the studies directly examined the VSRS control, but focused on the general system control, such as using tuned PI gain for a rule base and MFs [16–18], using histograms from a laser tracking system [19,20], or developing MFs for a waste water treatment system [21]. Furthermore, some of them did not verify the validity of the suggested method by performing experiments or simulations [16–19]. Some papers demonstrated their ideas only with simulations [20,21]. In fact, the design of MFs and a rule base has been heavily reliant on the knowledge of experts in the related field of application. Thus, it is difficult to analyze how MFs affect the response of the system when the criteria for the MFs change [16–21]. Consequently, systematic FLC design for VSRS still remains largely uninvestigated with a lack of supporting experimental data, which motivated the present study.

In this paper, a systematic MF design methodology for FLC of VSRS is proposed based on the allowable maximum error (control accuracy) and experimental data in static and dynamic states. Specifically, the influence of MFs on the error and error change rate of the controlled variables is investigated in detail. At first, the range of MFs obtained from the control accuracy and experimental results in the static and dynamic states of VSRS were set up as the criteria values [4,11] Secondly, two different values from the criteria were prepared to compare the control performance through simulations and experiments. Next, simulations were conducted to analyze the effects of MF ranges on the control performance using the transfer functions of VSRS, which were obtained from experiments [4]. Finally, real experiments for VSRS were performed and the results were compared with the simulation results. The proposed method is expected to be very helpful for designing MFs for FLC of VSRS for beginners because it can reduce tremendous iteration work and the dependence on the experiences of experts.

2. Fuzzy logic controller design for variable speed refrigeration system

2.1. Fuzzy logic control of the variable speed refrigeration system

Fig. 1 shows the schematic FLC diagram for VSRS. VSRS consists of a variable speed compressor, heat exchangers, and an EEV. In this system, the main controlled variable is chamber temperature T_a. The superheat T_s is also auxiliary controlled to maintain maximum coefficient of performance (COP) and prevent damage to the compressor due to the liquid back phenomenon. The subscripts 'a' and 's' in the temperature T describe the air temperature in the chamber and superheat, respectively. The superheat T_s was calculated from the temperature difference between the output and input of the evaporator, $T_s = T_o - T_i$. The chamber temperature T_a was precisely controlled by an inverter that regulates the motor rotational speed of the compressor. Meanwhile, the superheat was controlled by a step motor drive that adjusts the opening angle of the EEV. The manipulated variables, i.e. the control signals, were the frequency f_c (Hz) of the inverter and the opening angle V_e(%) of the EEV.

The fuzzy controller consisted of fuzzification, knowledge base, fuzzy inference, and defuzzification units as shown in Fig. 2. The knowledge base was composed of a database and a rule base, which is described in "IF-THEN" form. The MFs were used for the fuzzification to compute a membership value from a crisp value, and to calculate a crisp value from a membership value for defuzzification. Mamdani's min-max arithmetic was applied for the inference. Thus, the minimum value was selected for the input fuzzification and the maximum value was chosen for the output fuzzification.

Fig. 3 shows the inputs and outputs for FLC of VSRS. Two FLCs were independently employed for controlling the chamber temperature T_a and the superheat T_s. The FLCs had two inputs (e, ee) and a single

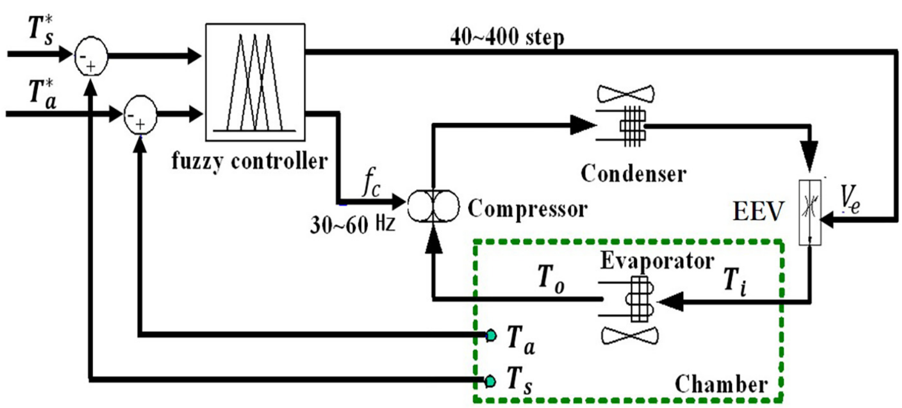

Fig. 1. Schematic diagram of FLC for VSRS.