Expert Systems with Applications 36 (2009) 8631–8638

Contents lists available at ScienceDirect

Expert Systems with Applications

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

Predicting of fan speed for energy saving in HVAC system based on adaptive network based fuzzy inference system

Servet Soyguder *, Hasan Alli

Firat University, Department of Mechanical Engineering, 23279 Elaziğ, Turkey

A R T I C L E   I N F O

Keywords:
HVAC system
Fan motor speed predicting
Air flow control
Energy saving
Temperature control
PID control
ANFIS

A B S T R A C T

In this paper, a HVAC (heating, ventilating and air-conditioning) system has two different zones was designed and fan motor speed to minimize energy consumption of the HVAC system was controlled by a conventional (proportional–integral-derivative) PID controller. The desired temperatures were realized by variable flow-rate by considering the ambient temperature for each zone. The control algorithm was transformed for a programmable logic controller (PLC). The realized system has been controlled by PLC used PID control algorithm. The input–output data set of the HVAC system were first stored and than these data sets were used to predict the fan motor speed based on adaptive network based fuzzy inference system (ANFIS). In simulations, root-mean-square (RMS) and the coefficient of multiple determinations (R^2) as two performance measures were obtained to compare the predicted and actual values for model validation. All simulations have shown that the proposed method is more effective and controls the systems quite well.

1. Introduction

The comfort of the people in their living environment is partially dependent on the quality and temperature of air in their building. Three interrelated systems are used to provide the desired air temperature and quality. These are the ventilating system, the heating system and the air conditioning system. The purpose of HVAC system of a building is to provide complete thermal comfort for its occupants. On the other hand, energy saving in this system is one of the most important issue because of its cost. Hence, it is necessary to understand the aspects of minimum energy consumption in order to design an effective HVAC system.

Teitel, Levi, Zhao, Barak, Bar-lev and Shmuel have employed for variable frequency drives method which is routinely used to vary pump and fan motor speed in heating, ventilating and air conditioning of buildings (Teitel et al., 2008). In these applications, speed control is used to regulate the flow of water or air because speed adjustment is an energy efficient method of flow control. The aim of this study is to present a thermodynamic model for an air-cooled centrifugal chiller which is developed specifically to analyze how the speed control of the condenser fans influences the chiller's COP under various operating conditions (Yu & Chan, 2006, 2007). Moreover, the other study of the same authors is made to investigate how the use of variable speed condenser fans enables air-cooled chillers to operate more efficiently (Yu & Chan, 2006, 2007). Besides, variable fan speed control is increasingly used for chiller compressors to save power when chillers are operating at part load. The power saving comes from the improved efficiency of the motors when operating at a lower speed under part-load conditions (Aprea, Mastrullo, Renno, & Vanoli, 2004; Tassou & Quereshi, 1998).

HVAC systems require control of environmental variables such as pressure, temperature, humidity. Furthermore, HVAC system is necessary to implement a realistic thermal environment in terms of temperature and air flow rate in the space of virtual reality (Shin, Chang, & Kim, 2002; Kaynakli, Pulat, and Kilic, 2005). As in other industrial applications, most of the controllers commissioned in HVAC systems are of the proportional–integral-derivative (PID) type (Bi et al., 2000; Seem, 1998). This is mainly because PID is simple yet sufficient for most HVAC application specifications. However, tuning a PID controller requires an accurate model of a process and an effective controller design rule. In addition to that, the tuning procedure can be a time-consuming, expensive and difficult task (Bi et al., 2000; Krakow & Lin, 1995; Pinnella, Wechselberger, Hittle, & Pederson, 1986; Riverol & Pilipovik, 2005).

The developments in intelligent methods make them possible to use in nonlinear analysis and control. Intelligent methods were first used to increase the robustness of existing models however they have been used to obtain new models in recent years. In addition to PID control of HVAC systems, the various studies using intelligent methods were presented. A neural network (NN) model was developed to predict air pressure coefficients across the openings in a light weight, single sided, naturally ventilated test room

* Corresponding author. Tel.: +90 424 2370000x5330; fax: +90 424 2415526.
E-mail addresses: ssoyguder@firat.edu.tr (S. Soyguder), halli@firat.edu.tr (H. Alli).

0957-4174/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2008.10.033

Nomenclature

A	area (m^2)
$\dot{m}_{ca}$	the mass flow-rate in fan channel (kg/h)
$\dot{m}_{z1a,in}$	the mass flow-rate entered to Zone-1 (kg/h)
$\dot{m}_{z2a,in}$	the mass flow-rate entered to Zone-2 (kg/h)
$\dot{m}_{sva,out}$	the mass flow-rate exist from safety valve (kg/h)
$\dot{m}_{exha,out}$	the mass flow-rate exist from exhaust (kg/h)
Q	convection and transmission heat (J)
W	Work (J)
$\dot{m}_{z1a,in} = \dot{m}_{Za}$	the mass flow-rate entered to Zone-1 (kg/h)
h_{in}	specific enthalpy(J/kg)
h_{out}	specific enthalpy (J/kg)
U	the internal energy (J)
C_v	constant heat (kJ/kg K)
C_p	constant pressure (kJ/kg K)
T	inner temperature (°C)
T_n	instant temperature (°C)
T_{n-1}	vicious circle temperature (°C)
$T_{sh,gir}$	cool air temperature (°C)
T_{out}	outside temperature (°C)
T_{eva}	evaporator temperature (°C)
h_{out}	convection coefficient for outside-surface (J/m^2 K)
h_{in}	convection coefficient for inner-surface (J/m^2 K)
K	transmission coefficient (J/m K)
L_1	thickness for Zone-1 (m)
L_2	thickness for Zone-2 (m)
M_n	calculated value of the loop output at sample time n
K_p	the loop gain
K_i	proportional constant of the integral term
K_d	proportional constant of the differential term
c_f	flow discharge coefficient
$\Delta\rho$	relatively constant
M_{in}	initial value of the loop output
e_n	value of the loop error at sample time n
e_{n-1}	previous value of the loop error
e_x	value of the loop error at sample time x
O_i	output of ANFIS layer
A_i	linguistic label
w_i	firing strength of rules
RMS	root-mean square error
R^2	fraction of variance
$y_{pre,m}$	predicted value
$t_{mea,m}$	measured value

(Kalogirou, Eftekhari, & Marjanovic, 2003). The applicability of natural ventilation as a passive cooling system was investigated in modern buildings in Kayseri using model simulations of indoor air velocity by the fluent. Using the simulated data, an ANFIS model was employed to predict the indoor average and maximum air velocities (Ayata, Çam, & Yıldız, 2007). A systematic approach for optimal set point control for in-building section was presented (Lu, Wenjian, Lihua, Shujiang, & Chai, 2005). The major components of in-building section were analyzed to identify the energy conservation potential. In order to save energy for delivery of supply air and chilled water, a variable pressure set point method was analyzed by a simple example and an intelligent neural network model-ANFIS was proposed to compute the variable pressure set points influenced by variation of cooling loads of end users. In addition, fuzzy logic control (FLC) of HVAC systems was studied by many authors (Huang & Nelson, 1994). The obtained results were compared with those of PID control and these studies indicated that FLC had better results. FLC is extensively used in processes where systems dynamics is either very complex or exhibit highly nonlinear characters. Besides, FLC is one of useful control schemes for plants having difficulties in deriving mathematical models or having performance limitations with conventional linear control methods. FLC is designed on the basis of human experience that means a mathematical model is not required for controlling a system. Because of this advantage, fuzzy logic-based control schemes were implemented for many industrial applications (Hung, Lin & Chung; 2007; Tang & Mulholland, 1987). FLCs were successfully applied to many complex industrial processes and domestic appliances in recent years (Tsang, 2001). The first FLC algorithm implemented by Mamdani was designed to synthesize the linguistic control protocol of an experienced operator (Mamdani, 1974). Consequently, different control tuning methodologies have been proposed in the literature such as auto-tuning, self-tuning, artificial intelligence, and optimization methods.

In this study, based on considering the above literatures, the required fan motor speed to minimize energy consumption and the required damper gap rates for obtaining the desired temperatures of two different zones for each time step were found by using PID control algorithm. The damper gap rate is also proportional with air flow rate. Besides, in this study, an expert system for fan motor speed and air flow control of HVAC system based on ANFIS is presented. In simulations, root-mean-square (RMS) and the coefficient of multiple determinations (R^2) as two performance measures are given to compare the predicted and actual values for model validation. All simulations have shown that the proposed method is more effective and controls the systems quite well.

The outline of the paper is as follows. In Section 2, the model of the HVAC system is presented. The design of the considered real-time HVAC system is given Section 3. Section 4 briefly describes the adaptive network based fuzzy inference system (ANFIS). Then, in Section 5, the experimental results are presented. In the experiment, the fan motor speed and the damper gap rate being proportional with air flow rate has been controlled using PID controllers and ANFIS. Finally, conclusions are given in Section 6.

2. The model of the HVAC system

Fig. 1 shows the schematic diagram of the modeled system in this study. The main elements of the system: The cooling zone-areas, evaporator, cooling unit, fan, damper motors, channels, thermocouples. Obtaining of the mathematical model of the cooled zone by considering all parameters is quite difficult. Fort this reason, we consider the following assumptions:

(1) The effect of the instantaneous variations of air speed in the zones on the pressure is neglected.
(2) There is no air leakage except the exhaust valves of the zones.
(3) The air flow in the zones is homogeneous.

The mass flow-rate ($\dot{m}_{ca}$) absorbed from the cooling unit does not change because the supply fun has constant the number of revolution. However, the mass flow-rate of the air entering to the zones changes depending on the temperatures of the zones. The continuously variations of the input mass flow-rate ($\dot{m}_{z1a,in}$) Zone-1 and ($\dot{m}_{z2a,in}$) Zone-2 are realized by regulating the gap rates of dampers into the entrances of zone-channels, depending on the control output signals.