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A novel proportional-derivative (PD) law based fuzzy logic principles assisted controller for simultaneously controlling indoor temperature and humidity using a direct expansion (DX) air conditioning (A/C) system

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ABSTRACT

A novel Proportional-Derivative (PD)law based Fuzzy Logic Controller (PFC) for a variable speed (VS) direct expansion (DX) air conditioning (A/C) system has been developed. There were two coupled control loops in this controller, i.e., varying supply fan speed to control indoor dry-bulb temperature (T_{db}), and compressor speed indoor wet-bulb temperature (T_{wb}). To weaken the coupling effect between the two loops, fuzzy logic principles were deployed. Furthermore, a PD law was used instead of a Proportional-Integral-Derivative (PID) law, in the PFC, which helped simplify not only calculation but also the structure of the PFC. The controller developed was validated by carrying out the controllability tests with the experimental conditions covering the normal operational range of a VS DX A/C system. The experimental results of the controllability tests suggested that the novel PFC developed is capable of realizing the simultaneous control of indoor temperature and humidity satisfactorily, in terms of control accuracy and sensitivity.

Régulateur assisté par les principes de la logique floue basés sur une nouvelle loi proportionnelle-dérivée (PD) pour contrôler simultanément la température et l'humidité intérieure à l'aide d'un système de conditionnement d'air (C/A) à détente directe

Mots clés : Vitesse variable ; Détente directe ; Conditionnement d'air ; Régulation simultanée ; Régulateur à logique floue ; Controle PD

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Nomenclatures

C	percentage of the maximum compressor speed (Maximum compressor speed is 6746 rpm) %
d	derivative error –
F	percentage of the maximum supply air fan speed (Maximum supply fan speed is 3680 rpm) %
p	proportional error –
Q_l	latent part of indoor cooling load kW
Q_s	sensible part of indoor cooling load kW
T_{db}	indoor air dry-bulb temperature °C
T_{wb}	indoor air wet-bulb temperature °C
t	sampling time step –
W	weight assigned to each linguistic variable –

Abbreviations

A/C	air conditioning
ANN	artificial neural network
DX	direct expansion
EEV	electronic expansion valve
E SHR	equipment sensible heat ratio
IAQ	indoor air quality
LGU	load generating unit
PFC	PD law based fuzzy logic controller
RH	relative humidity
SHR	sensible heat ratio
TCC	total cooling capacity

1. Introduction

In buildings, maintaining indoor humidity at an appropriate level is critically important since it directly affects the occupants' thermal comfort, indoor air quality (IAQ) and the operating efficiency of building A/C installations (Arren and Baughman, 1996; Berglund, 1998; Sterling et al., 1985; Toftum and Fanger, 1999). Various humidity control strategies developed for large-scale central A/C systems, such as heat pipe technology and pre-conditioning outdoor air (Hill and Jeter, 1994; Lstiburek, 2002; McGahey, 1998; Shirey, 1993; Westphalen, 2004; Westphalen et al., 2004), are not applicable to direct expansion air conditioning (DX A/C) systems given their discrete nature. However, DX A/C systems are simpler in configuration, more energy efficient and generally cost less to own and maintain than chilled water-based large-scale central A/C systems. Therefore, they have found wider applications in buildings, particularly in small to medium-scale buildings (Xu et al., 2012; Zhang, 2002). However, currently most DX A/C systems are equipped with single-speed compressors and fans, relying on ON/OFF cycling compressor to maintain indoor air dry-bulb temperature only. This results in an uncontrolled equilibrium indoor humidity, leading to a degraded level of thermal comfort for occupants, poor IAQ and low energy efficiency.

The introduction of variable-frequency inverters has made the speed control of compressor and supply fan in a DX A/C system possible, paving ways for simultaneously controlling both indoor air temperature and relative humidity (RH) using the DX A/C system. Since the variation of compressor and supply fan speeds will lead to the changes in the output sensible and latent cooling capacities of the DX A/C system, indoor air temperature and RH will be influenced. This was reflected in a previous experimental study by Krakow et al. (1995) who demonstrated that using a conventional PID control strategy, it was feasible to maintain indoor air temperature by varying compressor speed and indoor RH level supply fan speed. However, it was shown that the complex heat and mass transfer taking place in a variable speed (VS) DX A/C system made it extremely difficult to develop a control method for the intended simultaneous control of indoor air temperature and humidity. Due to the strong cross-coupling between two feedback loops (i.e., one for temperature by varying compressor speed and the other for humidity by varying supply fan speed), the transient performances of this conventional PID control strategy were inherently poor (Krakow et al., 1995). Following this study, a number of advanced controllers to simultaneously control indoor air temperature and humidity using DX A/C systems have been developed. Li and Deng (2007a, 2007b) developed a direct digital controller (DDC) for an experimental VS DX A/C system and concluded that the DDC for the simultaneous control of indoor temperature and humidity was operational, with acceptable control accuracy and sensitivity. Qi and Deng (2008, 2009) developed a multivariable dynamic model of the same VS DX A/C system. The model written in state-space representation was linearized at a specific operational state, to facilitate developing a multi-input multi-output (MIMO) controller. The results of controllability tests suggested that the MIMO controller could effectively control indoor air temperature and humidity. However, due to the linearization of the model at a fixed operational state, the MIMO controller was only functional over a small range around the specified operational state. Furthermore, Li et al. (2012) developed a dynamic artificial neural network (ANN) model based controller for the VS DX A/C system. Similar to Qi and Deng's MIMO controller, the dynamic ANN model was trained at a fixed operational state, so that the controller cannot function well when the DX system was operated away from the training point. To enable the controller to be functional over a wider operational range, an on-line adaptive ANN based controller was further developed. Through the continuous real-time updating of the ANN model, the adaptive controller can achieve the required control accuracy and sensitivity over a wider operational range, with, however, a much more complicated configuration (Li et al., 2013).

From the experience of previous controller developments, two obstacles to the successful development of a control method for the simultaneous indoor air temperature and humidity control using a VS DX A/C system can be observed, as follows:

- The heat and mass transfer between air side and refrigerant inside of the evaporator in a DX A/C system is extremely complex, making it a challenging task to develop a physical model based multi-variable controller;
- The control loops for controlling indoor air temperature and humidity are strongly coupled, which would fail a