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Development and evaluation of virtual refrigerant mass flow sensors for fault detection and diagnostics

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ABSTRACT

Refrigerant mass flow rate is an important measurement for monitoring equipment performance and enabling fault detection and diagnostics. This paper presents and evaluates three different virtual refrigerant mass flow (VRMF) sensors that use mathematical models to estimate flow rate using low cost measurements. The first model uses a compressor map that relates refrigerant flow rate to measurements of condensing and evaporating saturation temperature, and to compressor inlet temperature measurements. The second model uses an energy-balance method on the compressor that uses the compressor power consumption. The third model is developed using an empirical correlation for an electronic expansion valve (EEV) based on an orifice equation. The three VRMFs are shown to work well in estimating refrigerant mass flow rate for various systems under fault-free conditions with less than 5% RMS error. The combination of the three VRMFs can be utilized to detect and diagnose when the compressor and/or expansion device is not providing the expected flow.

Développement et évaluation de capteurs virtuels de débit massique de frigorigène pour la détection de défaut et les diagnostics

Mots clés : Capteur virtuel ; Débit massique de frigorigène ; Détection de défaut et diagnostic ; Compresseur ; Dispositif de détente ; Contrôle de performance

1. Introduction

Space heating, ventilation and air conditioning (HVAC) account for 40% of residential primary energy use, and for 30% of primary energy use in commercial buildings (Energy Efficiency and Renewable Energy, 2008). Over half of all conditioned floor space in the U.S. incorporates packaged HVAC equipment in their system design (Brodrick, 2000). The study conducted by Messenger (2008) indicates unitary air conditioners typically

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Nomenclature

A	area [m^2]
C	empirical coefficient for expansion valve
a, *b*, *c*	empirical constants
$C_{d,eev}$	correction coefficient for EEV model
D	diameter
d	current needle diameter [m]
EER	energy efficiency ratio
EEV	electronic expansion valve
EEVSTEP	opening of EEV [step]
E(x)	expected value of x
F	force [N]
f	compressor speed [Hz]
FDD	fault detection and diagnostics
H	maximum needle position [m]
h	certain needle position [m]
h	enthalpy [kJ kg^{-1}]
h(*x*)	discriminant function
K_{flow}	ratio of refrigerant volumetric flow rate at operating speed to value at rated speed
k_{sp}	spring constant [N m^{-1}]
l(*x*)	likelihood ratio
M_N	mean vector matrix without fault
M_C	mean vector matrix with fault
M	mean vector matrix describing the distribution of residuals
$\dot{m}_{map}$	refrigerant mass flow rate based on compressor map [kg s^{-1}]
$\dot{m}_{energy}$	refrigerant mass flow rate based on compressor energy balance [kg s^{-1}]
$\dot{m}_{TXV}$	refrigerant mass flow rate based on TXV model [kg s^{-1}]
$\dot{m}_{EEV}$	refrigerant mass flow rate based on EEV model [kg s^{-1}]
P	pressure [Pa]
P(*x*)	mixture density function
$P(w_i/x)$	conditional probability of ω_i given that *x*
$P(w_i)$	prior density function
R	region
S	weighted average
SC	subcooling [K]
TXV	thermostatic expansion valve
T	temperature [K]
t	frequency parameter of the Fourier transform
$\dot{W}$	compressor input power [W]
V^t	optimum coefficient
$\dot{V}$	volume flow rate [m^3 s^{-1}]
VRMF	virtual refrigerant mass flow sensor
x_0	threshold partitioned into two regions, R_1 and R_2
Y	vector of current residuals

Subscripts

actual	actual
b	bulb
C	current
c	condenser
cri	critical
current	current
diaph	diaphragm
dis	discharge
e	evaporator
f	liquid
g	gas
max	maximum
measured	measurement
min	minimum
N	normal
orifice	orifice
pin	needle
pred	estimation
rated	rated condition
sat	saturation
sp	spring
sp,cl	closed spring
suc	suction
TXV	thermostatic expansion valve

Greek

ρ	density [kg m^{-3}]
α_{loss}	compressor heat loss ratio
δ	spring deflection [m]
μ_i	mean of residual
Σ_1	covariance matrix without fault conditions
Σ_2	covariance matrix with fault conditions
ε	Bayesian classification error
η	Mahalanobis distance
σ	standard deviations
ω_i	class *i*
v_o	threshold for given distribution
ξ	standard normal random variable

do not achieve rated efficiency because of improper installation or lack of servicing in the field. This paper suggested that service and replacement programs can yield energy savings on the order of 30–50%. The other study from ADM (2009) evaluated 109 units in the field and found that 89 had fault conditions, with 31 having two or more faults. The average energy efficient ratio (EER) for the units increased from 6.6 before servicing to 7.0 after servicing, an average increase of 6.1%. Another investigation (Katipamula and Brambley, 2005) suggested that faults or non-optimal control can cause the malfunction of equipment or performance degradation from 15 to 50%. Automated diagnostics has the potential to address these field performance problems and produce significant energy savings.

Even though various fault detection and diagnostic (FDD) studies (Kim et al., 2009; Li and Braun, 2007; Rossi and Braun, 1997) have been carried out for air conditioner and heat pump systems with fixed speed compressors and fixed orifice expansion (FXO) valves, FDD research for systems with variable speed compressors and electronic expansion valves (EEV) has been limited. The use of variable speed compressors is common