Applied Thermal Engineering 115 (2017) 744–755

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Modularized PCA method combined with expert-based multivariate decoupling for FDD in VRF systems including indoor unit faults

Yabin Guo [a], Guannan Li [a], Huanxin Chen [a,*], Yunpeng Hu [b], Haorong Li [c], Jiangyan Liu [a], Min Hu [a], Wenju Hu [d]

[a] Department of Refrigeration & Cryogenics, Huazhong University of Science and Technology, Wuhan, China
[b] Department of Building Environment and Energy Application Engineering, Wuhan Business University, 816 Dongfeng Avenue, Wuhan, Hubei 430056, China
[c] Durham School of Architectural Engineering and Construction, College of Engineering, University of Nebraska-Lincoln, Omaha, NE, USA
[d] Beijing Key Lab of Heating, Gas Supply, Ventilating and Air Conditioning Engineering, Beijing University of Civil Engineering and Architecture, Beijing, China

HIGHLIGHTS

- A fault detection strategy for VRF system using modularized PCA method is proposed.
- The expert-based multivariate decoupling strategy using six variables is developed to isolate faults.
- The FDD method can detect IDU faults and identify which is faulty.
- The FDD method also can recognize ODU fault and system level fault.

ARTICLE INFO

Article history:
Received 1 November 2016
Revised 12 December 2016
Accepted 4 January 2017
Available online 5 January 2017

Keywords:
Modularized principle component analysis
Fault detection and diagnosis
Indoor unit fault
Multivariable decoupling
Variable refrigerant flow air-conditioning system

ABSTRACT

Developing fault detection and diagnosis (FDD) for the variable refrigerant flow (VRF) system is very important for saving energy and improving reliability of the equipment. For indoor unit (IDU) faults of VRF system, it is especially necessary to detect faults and identify which IDU is faulty. Therefore, this paper has proposed a fault detection strategy based on modularized PCA method, which cannot only detect faults but also specify the faulty IDU. Fault detection models are established respectively for outdoor unit (ODU) and IDUs of VRF system using the modularized PCA method. Then, the expert-based multivariate decoupling strategy with six variables for VRF system is developed to isolate faults. Four common faults are taken into account for VRF system, which include two IDUs faults (electronic expansion valve fault and IDU air-side fouling), one ODU fault (reversing valve stick) and one system fault (refrigerant undercharge). The proposed FDD strategy is evaluated by experimental data of four faults. The test results have shown that modularized PCA-based fault detection method and rule-based diagnosis method are effective for the four typical faults in VRF system. Therefore, it is quite suitable for FDD of VRF system.

1. Introduction

Fouling of heat exchanger, inappropriate refrigerant charge amount, valve fault, improper installation and poor maintenance may cause much trouble to many heating, ventilation and air conditioning (HVAC) systems. These problems may decrease operational efficiency and indoor room comfort, and increase energy consumption and risk of component damage. Previous literature shows that 15% energy efficiency loss and 20% capacity degradation on average are due to 25% refrigerant charge amount reduction of the split air-conditioning systems [1]. 10–40% of HVAC energy consumption can be saved using a successful fault detection and diagnosis (FDD) strategy [2–4]. As a consequence, it is necessary to develop an effective FDD systems that can maintain the HVAC system in normal operating conditions with the minimum cost.

In the last few decades, a lot of researches on FDD about HVAC system have been carried out. Yang et al. [5,6] evaluated the impact of evaporator air side fouling and different filter types on the performance of packaged air conditioners. The results illustrated that cooling capacity of equipment was reduced and energy efficiency ratio (EER) was reduced with fouling because of increasing fan power in most cases. Zhao et al. [7] proposed a decoupling-based FDD methodology with some decoupling features, which could handle multiple faults of centrifugal chillers. Li and Braun

* Corresponding author.
E-mail address: chenhuanxin@tsinghua.org.cn (H. Chen).

http://dx.doi.org/10.1016/j.applthermaleng.2017.01.008
1359-4311/

Nomenclature

Cov	the covariance matrix
C_x	the corresponding projection matrix
c_α	the confidence limit of the standard normal distribution
E	residual subspace
e	the projection of the measurement vector in the residual subspace
EXV	electronic expansion valve
f_{com}	the compressor operating frequency, Hz
FDD	fault detection and diagnosis
I_{com}	the compressor electric current, A
IDU	indoor unit
k	the number of principal components
n_{fan}	fan speed of indoor unit
ODU	outdoor unit
P	load matrix
P_{cond}	condensing saturation pressure, MPa
P_{evap}	evaporating saturation pressure, MPa
Q_α	threshold of the Q-statistic
Q	statistic squared prediction error
$T_{subc,out,L}$	liquid refrigerant temperature at the subcooler outlet pipe, °C
$T_{subc,out,V}$	vapor refrigerant temperature at the subcooler outlet pipe, °C
$T_{SPR,in}$	vapor–liquid separator inlet pipe temperature, °C
$T_{SPR,out}$	vapor–liquid separator outlet pipe temperature, °C
$T_{com,shell}$	compressor shell temperature, °C
T_{dis}	compressor discharge temperature, °C
T_{indoor}	indoor temperature, °C
T_{in}	inlet temperature of IDU, °C
T_{out}	outlet temperature of IDU, °C
$T_{air,in}$	return air temperature of IDU, °C
T_{ob}	remote controller temperature of IDU, °C
VRF	variable refrigerant flow
$\hat{X}$	principle subspace
$\hat{x}_{new}$	the projection of the measurement vector in the principal component subspace

Greeks

λ_j	eigenvalues of covariance matrix

Subscripts

com	the compressor
cond	condenser
evap	evaporator
fan	indoor fan
in	inlet
out	outlet
subc	subcooler
SPR	vapor–liquid separator

[8] formulated model-based FDD in a generic way, which is developed using a physical decoupling methodology. There are some additional faults in the heat pump system, such as reversing valve leakage and check valve leakage faults. Therefore, Li and Braun [9] developed decoupling features for these additional faults. Zhao et al. [10–16] used data driven methods to detect and diagnose faults of chillers, variable-air-volume system and air handing units. However, there are rather few studies regarding the fault detection and diagnosis of variable refrigerant flow (VRF) system in the open literatures.

The VRF system allows one outdoor unit to connect to two or more indoor units by pipes. They are popular because of small space requirement, flexible form and high efficiency, which can use common pipework for cooling and heating. As the VRF system is becoming one of the essential components in HVAC systems of buildings, it is necessary to develop a FDD method of the VRF system. Virtual refrigerant charge sensor of the VRF system was proposed by Li et al. [17], which was enhanced using data-based analysis methods. Kim et al. [18] proposed a fault detection algorithm for plural heat exchanger faults of VRF system under heating mode using regression method. Shin et al. [19] developed two fault detection techniques (state observer and temperature variance) of indoor unit (IDU) to detect heat exchanger air-side fouling and valve sticking faults in heating mode. But there are few researches on the detection and diagnosis of IDU faults and most of them are developed under in heating mode.

Therefore, this study develops an approach to detect and diagnose four faults including two IDUs faults (EXV fault and IDU air-side fouling), one ODU fault (reversing valve stick) and one system level fault (refrigerant undercharge) of VRF system in cooling and heating modes. Principal component analysis (PCA) method has good ability to detect chiller faults [20–22], air handing unit faults [23,24], variable air volume (VAV) system faults [25,26], VRF system [27] and other air-conditioning systems faults. Therefore, this paper employs the PCA method to detect faults of VRF system. On one hand, because the number of the IDU isn't fixed, it is difficult to establish the unitary PCA model for VRF system. Therefore, the modularized PCA method is proposed to detect faults of VRF system with different numbers of IDUs and identify which IDU is faulty. On the other hand, faults need to be diagnosed when they are successfully detected. The Q-contribution plot is widely used to diagnose sensor faults of air conditioning system, but the fault diagnosis ability of PCA for other faults (except sensor fault) of air conditioning system is weakness. The reason that PCA is a pure data driven method and less knowledge of process [28]. As a result, this study develops a reliable fault isolation approach using expert-based multivariate decoupling. Four fault experiments are implemented to test the performance of the FDD method in this study.

The paper is organized as follows: Section 2 outlines the fault detection process using modularized PCA method; Section 3 introduces related details of the proposed fault diagnosis method using expert-based multivariate decoupling; Section 4 describes experiments and fault implementation method; Finally, four fault FDD results of the VRF system are discussed in Section 5 and Section 6 provides a conclusive summary.

2. Fault detection using modularized PCA method

This section briefly describes the principles of PCA and how the modularized PCA models are used to detect VRF system faults including indoor unit faults.

2.1. A brief review on the PCA method in fault detection applications

PCA model projects data vector into two orthogonal subspaces (principle component subspace and residual subspace). As for VRF system, the corresponding statistics are established to test the operation condition. Firstly, a data set $X^0_{n\times m}$ of normal working condition is obtained, and n denotes the number of samples and m