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Deep learning-based fault diagnosis of variable refrigerant flow air-conditioning system for building energy saving

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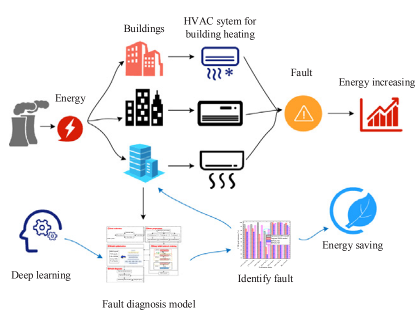
HIGHLIGHTS

- Deep learning-based models are developed for fault diagnosis of variable flow refrigerant system.
- The parameter optimized selection strategy of deep belief network model is proposed for fault diagnosis.
- Feature extracted by the unsupervised layer can improve the fault diagnosis performance of models.
- The model based DBN method does not need very deep for fault diagnosis of variable flow refrigerant system.

GRAPHICAL ABSTRACT

Building energy consumption increased year by year with the development of society. While air conditioning and heating systems account for approximately half of the total energy consumption of the building. Air conditioning and heating equipment will inevitably occur some faults after the long run period, and faults will cause energy consumption of these equipment increased. Fault diagnosis of air conditioning system is of great significance to energy saving of the building. Therefore, a novel fault diagnosis approach for building energy saving is proposed through the deep learning method which is deep belief network.



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ABSTRACT

The fault diagnosis of air-conditioning systems is of great significance to the energy saving of buildings. This study proposes a novel fault diagnosis approach for building energy saving based on the deep learning method which is deep belief network, and its application potential in the air conditioning fault diagnosis field is investigated. Then, a parameter optimization selection strategy is developed for model optimization. Four kinds of faults of the variable flow refrigerant system under heating mode are used to evaluate the performance of the models. The fault diagnosis results show that the deep belief network model with initial parameters can be used to diagnose the faults of the variable flow refrigerant system. Through the parameter optimization selection strategy, the fault diagnosis correct rate of the optimized model is 97.7%, which is improved by 5.05% compared with the model with initial parameters. The number of hidden layers of the deep belief network model is selected to be 2 layers. This result indicates that the fault diagnosis for variable flow refrigerant systems may not require a very deep model. Additionally, the performance of the optimized deep belief network model is compared with that of the traditional back propagation neural network, and the former is better. This finding also shows that the

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unsupervised restricted Boltzmann machine layer for data feature reconstruction can improve the fault diagnosis performance.

Nomenclature

a_i	the bias of visible layer
b_j	the bias of hidden layer
DBN	deep belief network
CD	contrastive divergence
$EXV_{heating}$	heating electronic expansion valve opening
EXV_{subc}	electronic expansion valve opening corresponding to the subcooler
f_{com}	compressor operational frequency, Hz
$f_{com,T}$	compressor operational target frequency, Hz
$f_{od,fan}$	outdoor fan operational frequency, Hz
h	the hidden layer unit
I_{com}	compressor operational electric current, A
$I_{od,fan}$	outdoor fan operational electric current, A
NN	the neural network
N_h	number of hidden layer nodes
N_{RBM}	maximum number of RBM epochs
N_{NN}	maximum number of neural network epochs
N_{layers}	the depth of hidden layer
P_{cond}	condensing saturation pressure, MPa
P_{evap}	evaporating saturation pressure, MPa
RBM	restricted Boltzmann machines
$T_{com,dis}$	compressor discharge temperature, °C
$T_{com,sh}$	compressor shell temperature, °C
T_{df}	deforest temperature at the bottom side of condenser, °C
$T_{subc,out,L}$	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}	compressor module temperature, °C
$T_{od,fan}$	outdoor fan module temperature, °C
v	the visible layer units
w_{ij}	the weight between the visible and hidden layers
Z	the normalized constant
ε_{RBM}	the learning rate of RBM
ε_{NN}	the learning rate of NN

Greeks

ω	connection weights
ε	the learning rate

1. Introduction

Building energy consumption has increased year by year with the development of the society. This accounts for approximately 40% of the global primary energy demand [1]. Meanwhile, air-conditioning and heating systems account for approximately half of the total energy consumption of buildings [2,3]. Especially when the Chinese government advocates a coal-to-electricity policy, the energy consumption of building heating will continue to increase [4]. Fault leads to decrease in efficiency in the field of induction motor [5], stator current [6], submersible induction motor [7], maintenance decision [8] and air-conditioning system [9]. Running a fault system leads to increase in its energy consumption and carbon emission which causes economical and environmental losses [10]. Therefore, diagnosing fault prior to system failure saves energy, reduces downtime cost, carbon emission and also time required for planning spares and inventory. Air-conditioning and heating equipment will inevitably experience faults after their long running operation, and these faults will cause the increase in energy consumption of the equipment. Nearly 42% of chiller service resources and 26% of chiller repair costs were wasted because of eight typical component faults, including condenser fouling, refrigerant leakage, etc. [11]. A survey on buildings in the UK found that 25–50% of energy wastage were due to faults in building heating, ventilation, and air conditioning (HVAC) systems. If those faults were detected and diagnosed early, then the range could be reduced below 15% [12]. Energy wastage was reported to be 5.45% for 40% cooling coil leakage of the variable air volume (VAV) systems when faults occurred on all floors [13]. Liang [14] analyzed the fault diagnosis and energy consumption of an air-conditioning system and the results demonstrated that faults could affect energy consumption; hence an effective fault diagnosis strategy is relevant to energy saving. In recent years, China has continued to implement energy-saving emission reduction initiatives, green buildings and building energy efficiency policies [15]. Therefore, the fault diagnosis study of HVAC systems has great potential for building energy saving and environment protection.

1.1. Studies on the application of data-driven methods

The fault diagnosis of HVAC systems can be divided into three categories: quantitative model-based methods [16], qualitative model-based methods [17] and data-driven methods. Data-driven methods which currently dominates air-conditioning fault diagnosis research, include principal component analysis (PCA), neural network (NN), support vector machine (SVM) and other machine learning methods. (1) PCA: Wang [18] introduced the data-driven method into the sensor fault detection and diagnosis (FDD) of HVAC systems in 2005. The following year, Xiao [19] developed a diagnostic tool for online sensor health monitoring and fault diagnosis of air-handling units (AHU) of in building automation systems. To reduce the impact of data noise on sensor FDD performance, Xu [20] proposed the sensor FDD strategy based on wavelet analysis and PCA methods. Xiao [21] proposed an expert-based multivariate decoupling method to enhance the capability of the PCA-based method in fault diagnosis. A sensor FDD strategy was also developed by exploiting model-based sensor redundancy with a state observer design [22]. Hadi [23] proposed an integrated framework for FDD using PCA, joint angle analysis and linear causal methods. Du [24] proposed a data-driven based evaluation logic to assess the measurement reliability by using subtractive clustering and PCA methods. Guo [25] proposed an enhanced sensor FDD method based on the Satizky-Golay and PCA methods. Modularized PCA method combined with expert-based multivariate decoupling for FDD was developed for the variable refrigerant flow (VRF) system faults [26]. (2) Neural network: Wang proposed a model to monitor the performance degradation of valves by using the recurrent CMAC NN [27]. Du and Bo [28,29] combined wavelet analysis with the NN to diagnose faults in VAV and AHU systems. Zhu [30] introduced the fault diagnosis of sensors in an AHU based on the NN that was pre-processed by wavelet and fractal. The combined strategy of using dual NNs was also proposed to detect the faults of sensors in the supply air temperature control loop of AHU [31]. Moreover, a FDD strategy based on NNs and subtractive clustering analysis was used to diagnose the fault source through the