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Fault diagnosis for temperature, flow rate and pressure sensors in VAV systems using wavelet neural network

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ABSTRACT

Wavelet neural network, the integration of wavelet analysis and neural network, is presented to diagnose the faults of sensors including temperature, flow rate and pressure in variable air volume (VAV) systems to ensure well capacity of energy conservation. Wavelet analysis is used to process the original data collected from the building automation first. With three-level wavelet decomposition, the series of characteristic information representing various operation conditions of the system are obtained. In addition, neural network is developed to diagnose the source of the fault. To improve the diagnosis efficiency, three data groups based on several physical models or balances are classified and constructed. Using the data decomposed by three-level wavelet, the neural network can be well trained and series of convergent networks are obtained. Finally, the new measurements to diagnose are similarly processed by wavelet. And the well-trained convergent neural networks are used to identify the operation condition and isolate the source of the fault.

1. Introduction

Variable air volume (VAV) systems are widely used in actual buildings to save energy through employing some optimal control strategies. Obviously, energy conservation capacity of a real VAV system deeply depends on the executing efficiency of various control loops including outdoor air flow rate, supply air temperature, supply air static pressure and zone temperature controllers. These controllers modulate related components after comparing the measurements of the control variables with the optimal setpoints. With the effective control, energy conservation and better indoor air quality can be achieved. During the control process, however, one premise can never be ignored: the measurements are accurate. If the sensors are biased, the controller may be misled and give incorrect commands. The related components may be incorrectly modulated. Finally the energy consumption of the system may be unreasonably increased greatly. In summer conditions, for example, the positive biases (the measurements are larger than the true values) of supply air temperature mislead the controller to open the water valve at a larger position. The quantity of chilled water is increased incorrectly, which wastes more energy of the pumps. Similarly, the biases of outdoor air flow rate sensors may increase the chilled water flow rate or decrease the chilled water temperature that may increase energy consumption of the pumps or chillers. The faults of supply air static pressure sensor may require higher rotational speed of the supply fan, which means more energy consumption of the fan. Consequently, the waste of energy is always inevitable under those various faulty conditions although optimal control strategies are applied in the system. Finding a suitable method to detect and diagnose the faults occurred in the VAV system, to avoid the waste of energy, is a significant target.

Recently, the study of fault detection and diagnosis (FDD) for sensors in heating, ventilation and air conditioning field are more active than ever after the popularity of research on faults of facilities including chillers [1–4] and air-handling units [5–10]. Two typical diagnosis methods for sensor faults have been developed. One is the model-based, and the other is the data-driven.

The model-based method [11–14] is to obtain predicted values of the parameters calculated by the mathematical models first. Then the differences between the outputs of real process and those of predicted ones, so-called residuals, are calculated and used as the fault indexes to diagnose. Stylianou and Nikanour [1] used a first-order model to detect faults of temperature sensors by comparing the actual temperature decay with the model output using the hypothesis testing. Wang and Wang [15] developed model-based strategies to diagnose the faults of commonly used temperature and flow rate sensors in chilling plant. The premise of model-based method is that accurate mathematical models must be built. And this premise is also the difficult point for the application. The model-based method is efficient to discover the abrupt faults of sensors such as the complete failure through analyzing the great change of operation conditions caused by the abrupt faults. Limited by the precision of the prediction models, however, it is insensitive

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Nomenclature

S	original signal
S_{ij}	the jth wavelet decomposition coefficient on the ith level
E	energy of the wavelet node
I	input of neural network
O	output of neural network
X	variable
X'	decomposition variable using wavelet
X''	predicted variable using neural network
T	temperature (K)
M	flow rate (kg/s)
P	pressure (Pa)
n	rotational speed (r/min)
G	data group
Q	heat exchange quantity (kJ)
c_p	specific heat at constant pressure (kJ/kg/K)
$\bar{x}$	true value of variable x
f_x	measuring bias
υ_x	measuring noises
α	drifting speed of fault

Greek symbols

Π	eigenvectors matrix
σ	statistic variance for diagnosis

Subscripts and superscripts

SA	supply air
OA	outdoor air
RA	return air
EA	exhaust air
SW	supply water
RW	return water
SF	supply fan
RF	return fan
A	air
W	water

to detect the small fixed or drifting biases since not abrupt change but slow degradation of the operation or control efficiency happens.

The data-driven approaches [16–18], on the other hand, never construct physical models but just learn the intrinsic relations among variables or parameters through employing the process data including normal and faulty conditions. Recently, principal component analysis [19,20] and Fisher discriminant analysis [21] were presented to diagnose the sensor faults in heating, ventilation and air conditioning systems. Besides the statistic method, neural network and wavelet analysis also began to apply in this field. Lee [22] presented general regression neural network models to diagnose the abrupt and performance degradation faults in an air-handling unit. Wang and Chen [23] developed a neural network trained by lots of running data to diagnose the faults of outdoor, supply and return air flow rate sensors. Later, Chen et al. [18] employed wavelet analysis to diagnose the faults of flow rate sensors in central chilling systems. Obviously, the data-driven method highly relies on the quantity and quality of the data obtained. Fortunately, with the popularity of building automation and energy management and control systems, the various historical operation data including normality and fault can be collected and obtained easily.

A data-driven diagnosis method combining wavelet analysis with neural network is presented in this paper that can be used to diagnose the faults in the VAV systems. Wavelet decomposition is used to process the original data and then the characteristic data representing the main operation information of the system are obtained. Employing these data decomposed, the neural networks are well trained and then they can identify various faults of commonly used sensors including temperature, flow rate and pressure in the VAV systems.

2. Wavelet neural network

Neural network technique is a valuable pattern recognition method in theory and application. It is widely used in engineering application [24–26] especially to deal those issues concerned in non-linear or complicated systems. It is efficient to learn the certain status or operation condition of the objective systems. And then the well-trained network can recognize these various conditions. Actually, the process of fault diagnosis is essentially a kind of recognition classification or recognition. Therefore, the neural network can be used as a diagnosis method. In fact, it has been well applied to detect and diagnose faults in many fields [27–30].

2.1. Application opportunity in VAV systems

As a complicated non-linear system, the VAV system includes many control components and measuring sensors. According to the different control strategies, the variables have changeable control relations. Also, the variables have implicit physical relations because of the physical principles. For this complex system, it is difficult to construct not only general but also precise models for so many variables. As a data-driven method, however, neural network never construct detailed models but continually learn the operation data. Through lots of training, the neural network can capture the important physical and control relations among the different variables in the VAV system. Once the networks obtain the main information of different operation conditions, they can be used for fault diagnosis.

Though neural network is capable of learning and judging various operation conditions, its capacity of data processing or analyzing is not satisfied. Especially for the VAV system, there are large quantities of samples for many measuring and control points. Since the noises are always included in the measurements and some uncertainty factors usually disturb the control actions, the pure neural network method may be affected or disturbed. As a result, its diagnosis efficiency is limited. The mistaken-warnings or missing-warnings may happen inevitably. To solve this problem, the data selected for training must be preprocessed to remove those disturbing information.

Wavelet analysis, originally developed from the Fourier transform at the end of 1980s [31,32], is widely used in various engineering [33–35] systems. The wavelet analysis, also called wavelet transform, employs two opposite time intervals: shorter and longer. The shorter time interval can be used by wavelet analysis to analyze the high frequency characteristics of the signals. While the longer one is used to analyze the low frequency characteristics of the signals. Since it is capable of data processing, it can be used as the complement for neural network.

Through analyzing the time-varying signals of variables in the VAV system, the wavelet can capture the local time-frequency domain information. The main important information of the system can be seized. Simultaneously, the disturbing factors can be removed. Indeed, the data after processing are much better than