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Multi-source information fusion based fault diagnosis of ground-source heat pump using Bayesian network

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HIGHLIGHTS

- A multi-source information fusion based fault diagnosis methodology is proposed.
- The diagnosis model is obtained by combining two proposed Bayesian networks.
- The proposed model can increase the fault diagnostic accuracy for single fault.
- The model can correct the wrong results for multiple-simultaneous faults.

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ABSTRACT

In order to increase the diagnostic accuracy of ground-source heat pump (GSHP) system, especially for multiple-simultaneous faults, the paper proposes a multi-source information fusion based fault diagnosis methodology by using Bayesian network, due to the fact that it is considered to be one of the most useful models in the filed of probabilistic knowledge representation and reasoning, and can deal with the uncertainty problem of fault diagnosis well. The Bayesian networks based on sensor data and observed information of human being are established, respectively. Each Bayesian network consists of two layers: fault layer and fault symptom layer. The Bayesian network structure is established according to the cause and effect sequence of faults and symptoms, and the parameters are studied by using Noisy-OR and Noisy-MAX model. The entire fault diagnosis model is established by combining the two proposed Bayesian networks. Six fault diagnosis cases of GSHP system are studied, and the results show that the fault diagnosis model using evidences from only sensor data is accurate for single fault, while it is not accurate enough for multiple-simultaneous faults. By adding the observed information as evidences, the probability of fault present for single fault of "Refrigerant overcharge" increases to 100% from 99.69%, and the probabilities of fault present for multiple-simultaneous faults of "Non-condensable gas" and "Expansion valve port largen" increases to almost 100% from 61.1% and 52.3%, respectively. In addition, the observed information can correct the wrong fault diagnostic results, such as "Evaporator fouling". Therefore, the multi-source information fusion based fault diagnosis model using Bayesian network can increase the fault diagnostic accuracy greatly.

1. Introduction

Ground-source heat pumps (GSHP) recovering heat from ground, have been widely utilized all over the world, which result in primary energy consumption reduction up to 60% compared to conventional heating systems, are of great significance in energy saving and environment protection [1–4]. Failure of the heat pump will cause reduction of energy efficiency and increment of environmental pollution. The relevant faults occurred in GSHP are divided into hard faults and soft faults. Generally, hard faults are easy to be detected and estimated, and soft faults are more difficult to be discovered [5]. The common hard faults include (a) compressor hard shutdown; (b) valve choke completely; (c) fan stop running, and so on. And the common soft faults include: (a) refrigerant overcharge; (b) Refrigerant leakage; (c) evaporator fouling, and so on. Various fault diagnosis techniques are developed and used, to locate the soft faults exactly in heat pump systems.

Using fault diagnosis techniques, the degradation performance of heat pump systems can be detected early, and the exact reasons for degradation can be diagnosed [6]. Xiao et al. [7] presented a fault diagnosis strategy based on a simple regression model and a set of generic rules for centrifugal chillers. Lee et al. [8] described a scheme for on-line fault detection and diagnosis at the subsystem level in an air-handling unit using general regression neural networks, which consisted of process estimation, residual generation,

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and fault detection and diagnosis. Wang and Cui [9] developed an online strategy to detect, diagnose and validate sensor faults in centrifugal using principal-component analysis method. Mohanraj et al. [10,11] review the applications of artificial neural networks for refrigeration, air conditioning and heat pumps, and presented the suitability of artificial neural network to predict the performance of a direct expansion solar assisted heat pump, and the experiments were performed. Li and Braun [12] extended the decoupling-based fault detection and diagnosis method to heat pumps, and developed diagnostic features for leakage within check valves and reversing valves. Sun et al. [13] developed an online sensor fault detection and diagnosis strategy based on data fusion technology to detect faults in the building cooling load direct measurement. Najafi et al. [14] developed diagnostic algorithms for air handling units that can address such constraints more effectively, such as modeling limitations, measurement constraints, and the complexity of concurrent faults, by systematically employing machine-learning techniques. Gang and Wang [15] developed artificial neural network models for predicting the temperature of the water exiting the ground heat exchanger. A numerical simulation package of a Hybrid ground source heat pump system is adopted for training and testing the model.

Bayesian network (BN) is considered to be one of the most useful models in the filed of probabilistic knowledge representation and reasoning, which has been widely used in reliability evaluation and fault diagnosis. Cai et al. [16–18] studied the reliability of subsea blowout preventer control system, subsea blowout preventer operations and human factors on offshore blowouts by using Bayesian network or dynamic Bayesian network. Langseth and Portinale [19] and Weber et al. [20] presented a bibliographical review over the last decade on the application of Bayesian network to reliability, dependability, risk analysis and maintenance. Recently, the application of Bayesian network on fault diagnosis has been investigated deeply. Dey and Stori [21] developed and presented a process monitoring and diagnosis approach based on a Bayesian belief network for incorporating multiple process metrics from multiple sensor sources in sequential machining operations to identify the root cause of process variations and provide a probabilistic confidence level of the diagnosis. Sahin et al. [22] presented a fault diagnosis system for airplane engines using Bayesian networks and distributed particle swarm optimization. Gonzalez et al. [23] developed a methodology for the real-time detection and quantification of instrument gross error. Zhu et al. [24] proposed an active and dynamic method of diagnosis of crop diseases to achieve rapid and precise diagnosis of crop diseases, using Bayesian networks to represent the relationships among the symptoms and crop diseases. However, there are few application of Bayesian network in the heating, ventilation, and air conditioning system. Zhao et al. [25] proposed a generic intelligent fault detection and diagnosis strategy to simulate the actual diagnostic thinking of chiller experts, and developed a three-layer diagnostic Bayesian network to diagnose chiller faults based on the Bayesian network theory.

In order to increase the diagnostic accuracy, especially for multiple-simultaneous faults, this work presented a multi-source information fusion based fault diagnosis methodology for GSHP system by using Bayesian network method. The proposed Bayesian network consists of two layers: fault layer and fault symptom layer. The fault symptom layer includes not only sensor data but also observed information, which can increase the fault diagnostic accuracy greatly. The paper is structured as follows: Section 2 presents the faults and fault symptoms of GSHP system. In Section 3, the fault diagnosis methodology is developed using Bayesian network. In Section 4, the fault diagnosis results using evidences from sensor data and observed information is researched. Section 5 summarizes the paper.

2. Faults and fault symptoms

The schematic diagram of a GSHP system in the heating mode is depicted in Fig. 1 [26–28]. The system mainly consists of three major circuits: (a) the ground heat exchanger circuit, (b) the heat pump unit circuit, and (c) the indoor fan coil circuit [29–32]. The ground heat exchanger circuit composes of a ground heat exchanger and a water pump; the heat pump unit circuit composes of a compressor, an evaporator, a condenser, an electronic expansion valve and a 4-way valve; and the indoor fan coil circuit composes of several indoor fan coils and a water pump. The Coefficient of Performance (COP) of the GSHP system is 3.5, and the noise can be controlled less than 65 decibels.

As mentioned above, the soft faults of GSHP system are difficult to detect, which are diagnosed by monitoring the system status. According to references review and practical experience, eight soft faults are imposed in this work: (a) refrigerant overcharge (ReOv); (b) refrigerant leakage (ReLe); (c) evaporator fouling (EvFo); (d) condenser fouling (CoFo); (e) non-condensable gas (NcGa); (f) compressor suction or discharge valve leakage (CoVL); (g) expansion valve port largen (ExPL); and (h) high pressure pipe line blockage (HPLB) [33–36]. Each fault has two states, which are present and absent.

The status of GSHP is monitored by using temperature sensors and pressure sensors. The fault symptoms therefore include: (a) evaporating pressure (EvaPr, Pe); (b) condensing pressure (ConPr, Pc); (c) evaporating temperature (EvaTe, Te); (d) condensing temperature (ConTe, Tc); (e) compressor suction temperature (ComST, Ts); (f) compressor discharge temperature (ComDT, Td); (g) evaporator water temperature difference (EvaTD, ΔTe); and (h) condenser water temperature difference (ConTD, ΔTc). Each fault symptom obtained from sensor data has three states, which are higher, lower and normal.

The relationship between faults and symptoms obtained from sensor data are given in Table 1. Taking ReLe for example, the refrigerant in the heat pump unit circuit decreases because of refrigerant leakage, making both of evaporating pressure and condensing pressure decrease. The refrigerant discharge superheat temperature therefore increases, making the compressor suction temperature and discharge temperature increase. Due to the fact that the heat pump work in a state of ill health with insufficient refrigerant, the heat absorption capacity and heating capacity decrease, therefore, all of the evaporating temperature, condensing temperature, evaporator water temperature difference and condenser water temperature difference decrease.

In addition, several fault symptoms can be observed directly by human being, such as (a) compressor can not stop; (b) compressor surface frost; and (c) compressor vibration. These symptoms can help to diagnose the faults of GSHP system more accurately. The relationship between faults and symptoms obtained from observed information is given in Table 2. Similarly, taking ReLe for example, four observed fault symptoms including (a) too much foam (ToMuF), (b) compressor surface frost (CoSuF), (c) pungent odor (PunOd), and (d) grease stains in wiped joint (GrSWJ) can be caused by refrigerant leakage. Each fault symptom obtained from observed information has two states, which are present and absent.

3. Fault diagnosis methodology

3.1. Fault diagnosis based on sensor data

The fault diagnosis model of GSHP system is established by using Bayesian network method. Specifically, each Bayesian net-