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A fault diagnosis method based on signed directed graph and matrix for nuclear power plants

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HIGHLIGHTS

- "Rules matrix" is proposed for FDD.
- "State matrix" is proposed to solve SDG online inference.
- SDG inference and search method are combined for FDD.

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ABSTRACT

In order to solve SDG online fault diagnosis and inference, matrix diagnosis and inference methods are proposed for fault detection and diagnosis (FDD). Firstly, "rules matrix" based on SDG model is used for FDD. Secondly, "status matrix" is proposed to achieve SDG online inference. According to different diagnosis results, "status matrix" is applied for the depth-first search and the breadth-first search respectively to find the propagation paths of each fault. Finally, the SDG model of the secondary-loop system in pressurized water reactor (PWR) is built to verify the effectiveness of the proposed method. The simulation experiment results indicate that the "status matrix" used for online inference can be used to find the fault propagation paths and to explain the causes for fault. Therefore, it can be concluded that the proposed method is one of the fault diagnosis for nuclear power plants (NPPs), which can be used to facilitate the development of fault diagnostic system.

1. Introduction

When the fault occurs, the deviation of one of the system parameters exceeds the acceptable range and the system performance is lower than normal, which increases the risk of a nuclear power plants (NPPs). Fault detection and diagnosis (FDD) provides alarming and diagnostic functions for NPPs (Liu et al., 2013). Online FDD in NPPs helps the operator to know the state of system in a timely manner and to take appropriate measures in case of accident deterioration. Signed directed graph (SDG) shows the complex relationship between system parameters and makes modeling and inference easy. So SDG is adopted for FDD in this paper.

SDG was first proposed to express complex relationships between the parameters in chemical industry (Iri et al., 1979). The conception of SDG was then put forward by Shiozaki et al. (1985). Rules obtained using SDG model were used for FDD in chemical industry (Kramer and Palowitch, 1987). SDG combined with fuzzy logic was used for FDD. Compared with the traditional expert system, the method had the advantage of calculating the possible coefficient of fault on the basis of fuzzy logic (Tarifa and Scenna, 2003). Conversion rules obtained using SDG model were put forward (Shiozakij et al., 1985). SDG diagnosis algorithm was proposed for multiple faults diagnosis by Venkatasubramanian (1997). Matrix algorithm was proposed for FDD and diagnostic system was developed using SDG (Kokawa et al., 1983). The model matrix was utilized to improve the efficiency of diagnosis (Gang et al., 2012). The residuals of principal component analysis (PCA) were used as the SDG threshold to avoid the unpredictable thresholds (Vedam and Venkatasubramanian, 1999). PCA was combined with SDG to search for all possible faults in FDD (Ma et al., 2006). SDG-PCA method was aimed to improve the ability of fault isolation (Yang and Xiao, 2007).

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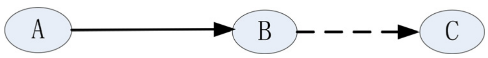

Fig. 1. Sketch map of SDG model

It can be seen from the presentation above that most studies of SDG combined with others method were for FDD, but few studies on SDG itself. If SDG is a complex model, then SDG model is easy to appear the "information explosion". So it is hard to achieve SDG online inference. Based on these properties of SDG method, "rules matrix" and "status matrix" are proposed in this paper to overcome the shortcoming.

2. Signed directed graphs

2.1. Concept of signed directed graphs

SDG consists of nodes and direction branches. Nodes are divided into parameter nodes and fault nodes. $N=(n_1, n_2, ..., n_\alpha, n_{\alpha+1}, ...n_m)$ represent the node status, there are ¨α p̈arameter nodes and "m − α"fault nodes in a SDG model. Parameter nodes status are in three status: "0″, "1", and "−1" (He et al., 2014). The method can be shown as:

$$\psi_i = \begin{cases} -1, & \text{if} \quad n_i < n_{il} \\ 0, & \text{if} \quad n_{il} < n_i < n_{ih} (1 \le i \le \alpha) \\ 1, & \text{if} \quad n_i > n_{ih} \end{cases} \tag{1}$$

where n_i stands for the value of ith parameter, n_{il} represents the lower limit of ith parameter, and n_{ih} represents the upper limit of ith parameter.

The parameters status of $N_1=(n_1, n_2, ..., n_\alpha)$ can be expressed as "parameter matrix" $P = \left[\psi_1 ... \psi_i ... \psi_\alpha\right]$ in this paper. The fault nodes status is determined by formula (2).

$$\psi_i = \begin{cases} 1, & \text{if fault node } i \text{ occurres} \\ 0, & \text{if fault node } i \text{ does not occur} \end{cases} \quad (\alpha + 1 \le i \le m) \tag{2}$$

The node status is achieved using formula (1) and (2). S is the "node matrix". Matrix S includes the status of fault and parameter nodes, namely: $S = \left[\psi_1 ... \psi_i ... \psi_m\right]$.

The relationships of nodes can be expressed as branches, which include positive impact shown by solid lines and negative impact shown by dashed lines in SDG model. A SDG model is shown as an example in Fig. 1.

2.2. Establishment of SDG model

There are main three kinds of methods for establishment SDG model: mathematical model, experience knowledge and flow chart (Umeda and Kuriyama, 1980; Oyeleye and Kramer, 1988; Maurya et al., 2004). Due to lack of sensing information, inaccuracy of measurement, unknown status of systems, and lack of knowledge on degradation, and so on, the mathematical model is difficult to apply in NPPs. Experience knowledge is mainly based on the experience of development in NPPs. Flow chart is in accordance with the relationships by observing the flow chart of NPPs. Flow chart and experience knowledge can be easily established in NPPs. Therefore, the main establishment SDG methods are formulated by combining flow chart with the experience knowledge.

In this paper, key parameters are based on experience and flow chart. But different person may choose different parameters. So following the principles are to be observed for selecting key parameters:

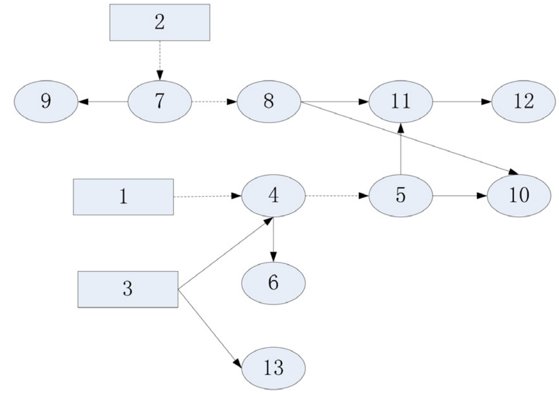

Fig. 2. Sample of SDG model.

(1) Faults must be rapidly and accurately identified before any protection measures are taken in NPPs.
(2) Parameters must be used to distinguish similar faults in the FDD process.
(3) The parameters choose by following principle (1) and (2) must be affirmed through experts groups discuss on.

SDG model is easy to appear an infinite loop graph model, but it cannot be used to achieve SDG inference. So, SDG model should be acyclic graph. If it appears a loop graph, SDG model can be transformed into an acyclic graph (Liu et al., 2014).

2.3. Model matrix

According to SDG model, "model matrix" $C=(C_{ij})$ can be defined as shown below.

$$C_{ij} = \begin{cases} 1, & \text{edge between nodes } i \text{ to } j, \text{ and positive influence} \\ 0, & \text{no edge between nodes } i \text{ to node } j \\ -1, & \text{edge between nodes } i \text{ to } j, \text{ and negative influence} \end{cases} \tag{3}$$

SDG model can be expressed as "model matrix" C and C is a m-dimensional determinant. Each value of C_{ij} indicates the effect of the relationships between parameters (Wang et al., 1995; Sehagl et al., 2000). Thus, SDG model can be stored in the matrix. For sample, SDG model can be established as show in Fig. 2.

It can be seen from Fig. 2 that when $3 \to 4$ is positive influence, $C_{3*4}=1$. When $4 \to 5$ is negative influence, $C_{4*5}=-1$. When $3 \to 5$ is no direct influence, $C_{3*5}=0$. According to formula (3), "model matrix" C can be obtained as shown below:

$$C = \begin{bmatrix} 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$