Research on Fault Diagnosis of Complex System Based on Bayesian Network

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ABSTRACT: The Fault tree analysis has large limitations in the application of complex fault diagnosis system, which is difficult to solve complex system fault diagnosis polymorphism exhibited events, uncertainty of information, failure logical relationship and other issues, this paper presents a novel Bayesian network method, which can solve these problems better. This paper is taking an example of faulting diagnosis of the fan system to verify the effectiveness of this new method.

KEYWORDS: Fault tree; Bayesian networks; Fault diagnosis.

1 INTRODUCTION

Fault Tree Analysis method referred to as FTA. In the field of fault diagnosis, this method can help the maintenance workers to locate the fault accurately and analyze it. FTA method is very suitable for simple systems. In view of the complex mechanical system fault diagnosis, exists the correctness of fault logic relation and the dimorphism problem of fault status, also, because of the limitations of modeling capabilities, it does not meet the requirements of complex mechanical system fault diagnosis. With the continuous development of modern machinery and equipment, and a more complex internal structure, the problem of fault becomes more complex and diversification, However, because the work environment and the level of other operations personnel differences, thus, causing uncertainty of failure information. Formation process of maintenance expert’s experience also contains a lot of uncertainties. Therefore, in the field of fault diagnosis, the problem is how to set up the fault diagnosis model of uncertainty fault information. In recent years, with the research in the field of uncertainty theory, Bayesian network enters everyone's perspective. Today, the Bayesian network has become a hot spot in the field uncertain theory. It has a strong ability to adapt to complex mechanical system for fault diagnosis. The advantages of FTA are simple and intuitive. The advantages of Bayesian networks are the strong modeling and analysis capabilities. In this paper, the advantages of FTA and Bayesian networks are fused, and the mapping of fault tree to Bayesian network is proposed, and then the fault diagnosis of complex mechanical system is carried out.

2 FAULT BAYESIAN NETWORK

The definition of Fault Bayesian Network (FBN): 

\[ FBN=(G_F, P_F) \]

where \( G_F \) is a topological structure, \( P_F \) is probability distributions, \( FBN \) is a two-tuples, \( G_F \) is directed acyclic graph, and \( G_F=(E_V, E) \) wherein \( E_i \) is fault set, which corresponding to the units, parts and small systems etc. of complex mechanical system. The formula \( E_V=[E_{v1}, E_{v2},...E_{vn}] \) means n-ary fault events of mechanical system, where \( E_{vi} \) is any event and \( E_{W}=(e_{v1}, e_{v2} ... e_{vm}) \) means the event \( E_{vi} \) can take m-ary numerical values corresponding to \( e_{v1}. e_{v2}. ... e_{vm} \), thus the value of different events are not the same. Direction between nodes A and B arcs represent a causal relationship between them. The \( P_F \) represents the strength of the causal effect between nodes. Any node has its own conditional probability table, expressed the interaction effect quantitatively with its parent node. Setting a node \( x \), of which parent node set is \( P_o(x) \). Under certain circumstances of \( P_o(x) \), the conditional probability of node \( x \) is 

\[ P(x \mid P_o(x)) \]

Joint probability:
$$P(E_v) = P(E_{v1}, \cdots, E_{vn}) = \prod_{i=1}^{n} P(E_v | P_a(E_v))$$  \hspace{1cm} (1)$$

Marginal probability: \( P(a) = \sum_{\beta} P(a|\beta) \)  \hspace{1cm} (2)

Conditional probability: \( P(\beta | a) = \frac{P(a|\beta)}{P(a)} \)  \hspace{1cm} (3)

3 \ RELATIONSHIP \ BETWEEN \ FAULT \ TREE
AND \ FAULT \ BAYESIAN \ NETWORK

The node of the Bayesian network is closely related to the Fault tree. Fault tree (FT) referred to as a triple, \( FT=(E_v, O, D) \), where \( E_v \) represents event set, \( O \) represents logical operation set and the formula is \( O=(AND, OR, NOT, XOR, INHIBIT, NAND, NOR, VOTE) \) of which \( AND, OR, NOT, XOR, INHIBIT, NAND, NOR, VOTE \) respectively represent AND gate, OR gate, NOT gate, Exclusive-OR gate, Inhibit gate, NAND gate, NOR gate and Vote gate. \( D \) represents the domain of discourse. Because the domain of discourse of each event is binary, the value is normal or fault, the fault is 1 and the normal is 0.

Each event of Fault tree has only two states, normal or fault.

The state of the bottom event is:

\[
x_i = \begin{cases} 0 & \text{when the bottom event i does not occur (normal)} \\ 1 & \text{when the bottom event i occur (fault)} \\ \end{cases}
\]

\( i=1,2,3,\cdots,n \) \( (n \ is \ the \ number \ of \ the \ bottom \ events) \)

The state of the top event is:

\[
\phi(\cdot) = \begin{cases} 1 & \text{when the i-th event occur} \\ 0 & \text{when the i-th does not occur} \\ \end{cases}
\]  \hspace{1cm} (5)

\( FT \) only describes the dimorphism of events, but \( FBN \) can describe the polymorphism of events. The node status of \( FBN \) is described as:

\[
x_i = \begin{cases} 0 & \text{when the event i is in state 0} \\ 1 & \text{when the event i is in state 1} \\ \vdots \\ m & \text{when the event i is in state m} \\ \end{cases}
\]  \hspace{1cm} (6)

The structure function of top event \( T \) is \( \Phi(x) = \Phi(x_1, x_2, \cdots, x_n) \)

\[
\Phi(\cdot) = \begin{cases} 0 & \text{when the event T is in state 0} \\ 1 & \text{when the event T is in state 1} \\ \vdots \\ m & \text{when the event T is in state m} \\ \end{cases}
\]  \hspace{1cm} (7)

The event set of \( FT \) are corresponding to the node set of \( FBN \). The input values are \( E_{v1}, E_{v2}, \cdots, E_{vn} \) and \( T \) is the output logic gate. Every logic gate is different from the probability distribution of Bayesian network. In this paper, the probability distribution is calculated as follows:

AND gate:

\[
P(T = 1 | E_{v1} = 1, E_{v2} = 1) = 1, P(T = 1 | \text{else}) = 0 \]  \hspace{1cm} (8)

OR gate:

\[
P(T = 1 | E_{v1} = 0, E_{v2} = 0) = 0, P(T = 1 | \text{else}) = 1 \]  \hspace{1cm} (9)

NOT gate:

\[
P(T = 1 | E_v = 0) = 0, P(T = 1 | \text{else}) = 0 \]  \hspace{1cm} (10)

Exclusive-OR gate:

\[
P(T = 1 | E_{v1} = 1, E_{v2} = 0) = 1, P(T = 1 | \text{else}) = 0 \]  \hspace{1cm} (11)

\[
P(T = 1 | E_{v1} = 0, E_{v2} = 1) = 1, P(T = 1 | \text{else}) = 0 \]  \hspace{1cm} (12)

NAND gate:

\[
P(T = 1 | E_{v1} = 1, E_{v2} = 1) = 1, P(T = 1 | \text{else}) = 0 \]  \hspace{1cm} (13)

NOR gate:

\[
P(T = 1 | E_{v1} = 0, E_{v2} = 0) = 1, P(T = 1 | \text{else}) = 0 \]  \hspace{1cm} (14)

Vote gate:

\[
P(T = 1 | \sum_{i=1}^{n} E_{vi} \geq k) = 1, P(T = 1 | \text{else}) = 0 \]  \hspace{1cm} (15)

From the above properties, we can know that there is the determined relationship between the fault tree and Bayesian network. Thus, we can transform fault tree into fault Bayesian network.

4 \ FAULT \ DIAGNOSIS \ OF \ BAYESIAN
NETWORK

Equipment fault diagnosis technology is based on the working process of the equipment of all kinds of signals to determine equipment working status. If the device has a warning signal of abnormal operation, it is possible to accurately infer the cause of the fault. Bayesian network take the cause of the fault and the fault symptom as a node. When the abnormal signs, network according to the causal relationship between individual nodes and probability distribution can infer the probability of any failure cause size, and diagnosis results are obtained. In this paper, the fault tree and Bayesian network are combined to study the fault diagnosis. In this paper, we take a type of fan system, for example, to analyze. The system consists of the pickling electrical air unit, fog rolling row outlet air unit, entrance filter unit, underground depot delivery air unit, etc. This paper proposes the transform from fault tree to Bayesian network and take fault Bayesian network for example to analyze. Fault tree of fan system shown below, where \( A \) is top event, \( N, \(
O, Q, R, S are bottom events, B, C, D, E, F, G, H, J, K are middle events and a, b, c, d, f, h are logic OR gate. Event A represents fan system, B represents entrance filter unit, C represents fog rolling row outlet air unit, D represents underground depot delivery air unit, E is bearing’s temperature, F is couplings, G is bearing’s temperature, H is filtration system, J is bearing’s temperature, K is the wear of impeller, N is Abnormal sound operation, O is clearance check, Q is filtration capacity, R is Filter cleaning degree, S is Nozzle capability.

Fault tree specific relationship with the Bayesian network are: the nodes of the Bayesian network and the events of fault tree is relevant, and the bonding strength of Bayesian network and the logic OR gate are relevant. You can use a line with arrow of the Bayesian network to represent this relationship. Arrow pointing to the node is called the input of logic gates, and the arrow pointing to the other node is called output of logic gates. The probability and conditional probability distribution of the relative nodes on Bayesian network are as follows Table 1.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Prior probability distribution</th>
<th>Nodes</th>
<th>Prior probability distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>P(A</td>
<td>BCD)</td>
<td>H</td>
</tr>
<tr>
<td>B</td>
<td>P(B</td>
<td>EF)</td>
<td>K</td>
</tr>
<tr>
<td>C</td>
<td>P(C</td>
<td>GHI)</td>
<td>N</td>
</tr>
<tr>
<td>D</td>
<td>P(D</td>
<td>JK)</td>
<td>O</td>
</tr>
<tr>
<td>E</td>
<td>P(E</td>
<td>NO)</td>
<td>Q</td>
</tr>
<tr>
<td>F</td>
<td>P(F</td>
<td>NO)</td>
<td>R</td>
</tr>
<tr>
<td>G</td>
<td>P(G)</td>
<td>J</td>
<td>P(J)</td>
</tr>
<tr>
<td>K</td>
<td>P(K)</td>
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</tr>
</tbody>
</table>

In this paper, for Bayesian networks, we infer fault reason according to fault omen. We transform the Bayesian network (Figure 2) into a Join tree JT (Figure 3), thus, we can speculate the probability on the Bayesian network. In order to satisfy the constraints, JT must be initialized belief, it is mainly assign the prior probability of FBN to JT. The process is: order the belief potential of circle and edges are $\Phi_x = 1$, the parent node of every variable $V$ is $P_a(V)$, and let it corresponding to the appropriate circle, thus, we can know the conditional probability is $P(V | P_a(V))$, let $P(V | P_a(V))$ multiplier $\Phi_x$, and redefine $\Phi_x$. Initialization of belief potential even though it can satisfy the constraints, consistency condition is not satisfied, and therefore need JT to transfer belief (Collect Belief and Distribute Belief). Let ABCD be root nodes, and apply Distribute Belief and Collect belief on this nodes.

The transfer and absorption of belief under the node evidence undetermined state. The result using Collect Belief to transfer of JT structure is shown in Figure 4, which corresponds to the belief: $\Phi_1 \Phi_2 \Phi_3 \Phi_4 \Phi_5$. The result using Distribute Belief to transfer of JT structure is shown in Figure 5, which corresponds to the belief: $\Psi_1 \Psi_2 \Psi_3 \Psi_4 \Psi_5$. The formula for each belief is as follows:

$$\Phi = \Phi_1 = \sum_{J,K} P(J)P(K)P(D | J, K)$$  \hspace{1cm} (16)$$

$$\Phi_2 = \Phi_2 = \sum_{Q,R,S} P(Q)P(R)P(S)P(H | Q, R, S)$$  \hspace{1cm} (17)$$
\[ \phi_1 = \phi_{[\emptyset,O,F]} = \sum_{N,O} P(N)P(O)P(F|N,O) \] (18)

\[ \phi_2 = \phi_{[\emptyset,E,F]} = \sum_{E,F} P(E)P(F)P(B|E,F) \] (19)

\[ \phi_3 = \phi_{[\emptyset,C.G.H.D]} = \sum_{G,H,D} P(C|G,H)\phi_2\phi_4 \] (20)

\[ \psi_1 = \phi_{[A,B,C,D]} = \sum_{A,B,C} P(A|B,C,D)\phi_5 \] (21)

\[ \psi_2 = \phi_{[B,C,G,H,D]} = \sum_{B,C,G,H,D} P(C|G,H)\phi_2\phi_5 \] (22)

\[ \psi_3 = \phi_{[A,B,E,F]} = \sum_{B,E} P(B|E,F)\phi_4 \] (23)

\[ \psi_4 = \phi_{[B,C,G,H,D]} = \sum_{C,G,H,D} P(C|G,H)\phi_2\phi_5 \] (24)

\[ \psi_5 = \phi_{[A,B,C,D]} = \sum_{H,D} P(A|B,C,D)\phi_1 \] (25)

Under known the node evidence A=a, event A has been instantiated into a, thus, we can know the probability of ABCD nodes is \( P(al|B,C,D) \). At this node, we call the Collect belief to carry on a downward belief transfer that corresponding belief is \( \phi'_1, \phi'_2, \phi'_3, \phi'_4, \phi'_5 \) and this moment, the belief is equal to the belief under the state that the nodes evidence is uncertain, that is \( \phi'_1 = \phi_1, \phi'_2 = \phi_2, \phi'_3 = \phi_3, \phi'_4 = \phi_4, \phi'_5 = \phi_5 \). At this node, we call the Distributes belief to carry on a downward belief transfer that corresponding belief is \( \psi'_1, \psi'_2, \psi'_3, \psi'_4, \psi'_5 \), and the formula for each belief is as follows:

\[ \psi'_1 = \phi_{[A,B,C,D]} = \sum_{A,B,C} P(a|B,C,D)\phi_5 \] (26)

\[ \psi'_2 = \phi_{[B,C,G,H,D]} = \sum_{B,C,G,H,D} P(C|G,H)\phi'_2\phi'_3 \] (27)

\[ \psi'_3 = \phi_{[A,B,E,F]} = \sum_{B,E} P(B|E,F)\phi'_4 \] (28)

\[ \psi'_4 = \phi_{[B,C,G,H,D]} = \sum_{C,G,H,D} P(C|G,H)\phi'_2\phi'_5 \] (29)

\[ \psi'_5 = \phi_{[A,B,C,D]} = \sum_{H,D} P(a|B,C,D)\phi'_1 \] (30)

By the above processing method, the belief potential of JT meets the constraints and consistency, thus, we can carry out the local calculation of fault probability. Under the node evidence is uncertain, using theorem1, we can obtain the belief of the circle or the edge of a node or a node set. Theorem 1: For fault event node \( V \), distinguish a circle or edge \( X \), which includes the node \( V \), and marginalize its deliver potential as \( \phi_x \) which is calculated: \( P(V) = \phi_x^{-1} = \sum_{x \in V} \phi_x \). Under the node evidence \( A=a \), using theorem 2 we can calculate the beliefs potential of circle or edge of node or node set. Theorem 2: For the calculation of conditional probability ( \( P(V|e_v) \) ), that is calculate the probability of the fault reason node \( V \) when the fault symptom \( ev \) occur. We can obtain the partial computation model of \( P(V|e_v) \) is

\[ P(V|e_v) = \sum_{X \subseteq V} \sum_{\phi_x} \phi_x \] (31)

5 CONCLUSION

There exist limitation of traditional fault tree method. This paper presents a transform fault tree into fault Bayesian networks, and application failure Bayesian network fault diagnosis method. This method greatly reduces the complexity of FBN fault probability reasoning, and simplifies the operation. It is a new method to study the fault diagnosis. This method can overcome the problems of the complex system, such as the polymorphism, the uncertainty of information, the uncertainty of the fault logic relationship.

REFERENCES


70