High Voltage Circuit Breaker Fault Diagnosis Based on Reasoning chain and Bayes

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Abstract. In order to find the reason of the high voltage circuit breaker rejection quickly, an fault diagnosis method based on reasoning chain and Bayesian network (BN) is presented in the paper. Firstly, the concept of event set is introduced. A fault symptom set is constructed based on the measured circuit breaker characteristic parameters and warning signals. And the direct cause of circuit breaker failure, such as a part of the circuit breaker components or mechanism failure constitute the fault cause set. After that, when the high voltage circuit breaker fails, a subset of fault symptoms and fault causes is obtained according to the information. Then an reasoning chain is constructed according to the causal relationship between the two. Finally, a corresponding Bayesian network model for reasoning chain is built. The probability of fault causes is obtained by Bayesian backward reasoning, so as to realize the rapid analysis of circuit breaker faults. And the effectiveness of the method is verified by the result of practical fault diagnosis examples.

1. Introduction
High voltage circuit breaker is the most important control and protection equipment in the power system. The reliable operation of high voltage circuit breaker is very important to the safety and stability of power system. However, during the operation of the power grid, the circuit breaker often fails to operate. This is not only not conducive to power transmission or the removal of system failures, but also may lead to further expansion of power outages or even the consequences of power system disconnection. Therefore, it is of great significance for the stable operation of the power system to detect various parameters of the circuit breaker and diagnose the fault reason of the circuit breaker as soon as possible according to the logical relationship between characteristic parameters and faults.

The purpose of fault diagnosis of high voltage circuit breaker is to determine the nature, category, position and cause of the fault, so as to check and repair as soon as possible according to the diagnosis result. Currently, the method of support vector machine (SVM) [1], fuzzy theory [2], D-S evidence theory [3], neural network [4,5], Petri net [6] and others were applied to fault diagnosis of high voltage circuit breakers. In addition, as a kind of uncertain knowledge representation and reasoning model based on probability analysis and graph theory, Bayesian network is also widely used in the field of fault diagnosis. A Bayesian network model for fault diagnosis of circuit breakers was constructed in [7]. Although it improves the diagnosis efficiency, only the current characteristics of opening and closing coils were considered in that paper. Rough set theory and Bayesian network were combined to
diagnostic faults for circuit breakers [8,9]. The method is effective, but the analysis of fault causes and characteristics is still not comprehensive enough.

On the basis of the above research, this paper proposes a fault diagnosis method based on causal reasoning chain and Bayesian network. In addition to the characteristic parameters such as voltage and current obtained through measurement, the abnormal and warning signals that can be received are added as the judgment basis, which makes fault diagnosis more comprehensive and reliable. Furthermore, the Bayesian network is further simplified with the help of the reasoning chain, which is more concise than the network used in other papers. In the end, taking SF6 high voltage circuit breaker as an example, the fault diagnosis model was constructed and the effective of the method was proved.

2. Brief introduction of high voltage circuit breaker

High voltage circuit breaker is an important control and protection equipment in high voltage power system. At present, SF6 circuit breakers account for a large proportion in China's high-voltage and ultra-high-voltage power grids. The structure of high voltage circuit breaker mainly includes breaking element, operation mechanism, insulating support and base. The breaking element is the actuator used to load and break the normal operating current and fault current, which includes contact, conductive part and interrupter. And the operation of the contact is driven by the operating mechanism. In brief, the simple structure diagram of circuit breaker action process is shown in figure1:

![Figure 1. Simple structure diagram of circuit breaker operation process](image)

Table 1. Fault causes set C and prior probability

| number | fault cause                                              | prior probability(%) |
|--------|----------------------------------------------------------|----------------------|
| c1     | Control source or loop failure                           | 2.13                 |
| c2     | Operating power supply failure                           | 3.21                 |
| c3     | Poor contact of auxiliary switch or secondary wiring      | 9.84                 |
| c4     | Opening/closing coil shorted                             | 4.57                 |
| c5     | Opening/closing coil、circuit resistance burn out         | 12.63                |
| c6     | Coil core jamming or push rod deformation                | 21.23                |
| c7     | Moving contact insulated connecting rod fault or drive mechanism element jamming | 22.15 |
| c8     | Moving、static contact are not centered                   | 5.61                 |
| c9     | The electrical endurance of motor is too short           | 3.20                 |
| c10    | Stored energy motor fault                                | 3.25                 |
| c11    | Circuit、sealing ring、valves not seal or leakage          | 14.31                |
| c12    | Pressure switch contacts failed or pressure gauge and circuit misoperation | 2.04 |
| c13    | Closing spring pull rod detachment or transmission gear badly worn | 7.66 |
| c14    | SF6 circuit breaker arc extinguishing failure            | 4.08                 |

At the same time, some information can be received when the failure occurs. These information...
include the warning signal before and during the circuit breaker's failure as well as the measured voltage, current and other characteristic quantity information. It is through this data and information, the specific fault conditions and causes can be determined. After filtering and sorting, the useful information is formed into a set of fault symptoms and listed in table 2.

Table 2. Fault symptoms set D

| number | fault symptom |
|--------|---------------|
| d1     | Two control circuit breaking |
| d2     | Two control power disappearing |
| d3     | The first control circuit breaking, the second control power disappearing |
| d4     | The second control circuit breaking, the first control power disappearing |
| d5     | The voltage of opening/closing coil is abnormal |
| d6     | The circuit value of opening/closing coil is too low |
| d7     | The circuit value of opening/closing coil is too high |
| d8     | The time of opening/closing coil circuit is too short |
| d9     | The time of opening/closing coil circuit is too long |
| d10    | The time of moving contact opening/closing is too long |
| d11    | Opening/closing asynchronous |
| d12    | Total trip abnormal |
| d13    | The temperature of operation mechanism housing is too high |
| d14    | The time of hydraulic/air operating mechanism pressing is too long |
| d15    | Hydraulic/air operating mechanism cannot be pressed |
| d16    | Hydraulic/air operating mechanism restart frequently |
| d17    | Oil/air pressure reduce abnormally |
| d18    | Oil/air pressure rise abnormally |
| d19    | The spring stores no energy |
| d20    | The content of micro-water in SF6 more than the standard |
| d21    | Low SF6 pressure |

3. Reasoning chain

The reasoning chain is a data structure composed of interconnected nodes, each of which points to other nodes or is pointed to by other nodes. There is a causal logic between the connected nodes, which can be divided into event nodes and cause nodes. The cause node provides an explanation for the occurrence of the event node, and the existing event may cause the occurrence of subsequent events [12]. The simplest and most intuitive type of the reasoning chain writes to P→Q, means "if P then Q".

For circuit breaker failure, the fault causes are the cause nodes, and the fault symptoms are the event nodes. All of the fault causes in table 1 constitute a set called fault causes set C, C={c1, c2, ..., c14}. A fault symptoms set D is constituted by all of the fault symptoms in table 2 as well, and D={d1, d2, ..., d21}. Therefore, the reasoning chain from fault causes C to fault symptoms D can be constructed based on the causal relationship between the two. For example, we can know the message that the voltage of opening/closing coil is abnormal if there’s an operating power supply failure. That is, if c2 then d5.

4. Bayes

Bayesian network is an uncertain knowledge representation and reasoning model based on probability analysis and graph theory, and an information representation framework that combines causal knowledge with probabilistic knowledge. The mathematical basis of Bayesian network is Bayes theorem, which contains two key factors: prior probability and posterior probability. The prior probability is obtained mainly through expert knowledge and historical experience. And the posterior probability is calculated by prior information and sample data according to Bayes theorem.

If H represents hypothesis and E represents arguments supporting hypothesis, Bayesian formula
[13] is shown in (1):

$$p(H_i | E_1, E_2, \ldots, E_n) = \frac{p(E_1, E_2, \ldots, E_n | H_i) \cdot p(H_i)}{\sum_{k=1}^{m} p(E_1, E_2, \ldots, E_n | H_k) \cdot p(H_k)} \quad (1)$$

In the formula (1):
- $p(H_i)$: The prior probability of hypothesis $H_i$ is true;
- $p(E_1, E_2, \ldots, E_n | H_i)$: The probability of leading to argument $E_1, E_2, \ldots, E_n$ when $H_i$ is true;
- $p(E_j | E_i, E_2, \ldots, E_n)$: The probability of hypothesis $H_i$ can be deduced when argument $E_1, E_2, \ldots, E_n$ is true.

Since the application of formula (1) requires arguments and assumptions of all possible combinations of conditional probabilities, which is a very difficult work. Therefore, the small arguments can be ignored in applying sometimes, and assume that the conditions between the arguments are independent. After that, the formula (2) is obtained.

$$p(H_i | E_1, E_2, \ldots, E_n) = \frac{p(E_1 | H_i) \cdot p(E_2 | H_i) \cdot \ldots \cdot p(E_n | H_i) \cdot p(H_i)}{\sum_{k=1}^{m} p(E_1 | H_k) \cdot p(E_2 | H_k) \cdot \ldots \cdot p(E_n | H_k) \cdot p(H_k)} \quad (2)$$

In the process of circuit breaker fault diagnosis, hypothesis H is the fault causes of the circuit breaker; and the symptoms of fault are the arguments E in favor of the hypothesis. Furthermore, the prior probability represents the empirical probability of deriving the result from the cause, which represents the probability of obtaining the corresponding fault symptom information under the condition that some kind of fault occurs in the circuit breaker. In this paper, the fault diagnosis of circuit breaker is a process of probing the cause from the results. That is to say, the posterior probability is needed. By using the obtained fault symptom information, the probability of the corresponding cause of the circuit breaker's failure can be calculated. Then the most likely cause can be inferred.

The numerical value of the prior probability of circuit breaker failure are given in table 1. And the connection relationship and between fault cause and fault symptom are shown in table 3. The numerical value in that are the probability of leading to $d_j$ when $c_i$ is true ($i=1, 2, \ldots, 14; j=1, 2, \ldots, 21$).

**Table 3. Fault symptom connection**

| number | $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $d_6$ | $d_7$ | $d_8$ | $d_9$ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $c_1$  | 1     | 1     | 1     | 1     | —     | —     | —     | —     | —     |
| $c_2$  | —     | —     | —     | —     | 0.45  | 0.1   | —     | —     | —     |
| $c_3$  | —     | —     | —     | —     | —     | 0.1   | 0.2   | —     | —     |
| $c_4$  | —     | —     | —     | —     | —     | —     | 0.5   | 0.5   | —     |
| $c_5$  | —     | —     | —     | —     | —     | —     | 0.55  | 0.8   | —     |
| $c_6$  | —     | —     | —     | —     | —     | —     | —     | 0.3   | 0.95  |

| number | $d_{10}$ | $d_{11}$ | $d_{12}$ | $d_{13}$ | $d_{14}$ | $d_{15}$ | $d_{16}$ | $d_{17}$ | $d_{18}$ | $d_{19}$ | $d_{20}$ | $d_{21}$ |
|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $c_7$  | 0.75      | 0.5      | 0.7       | —         | —         | —         | —         | —         | —         | —         | —         | —         |
| $c_8$  | 0.2       | 0.5      | 0.15      | 0.55      | —         | —         | —         | —         | —         | —         | —         | —         |
| $c_9$  | 0.05      | —        | 0.15      | 0.45      | —         | —         | —         | —         | —         | —         | —         | —         |
| $c_{10}$ | —     | —        | —         | —         | 0.2      | 0.35     | 0.7       | —         | —         | —         | —         | —         |
| $c_{11}$ | —     | —        | —         | —         | 0.8      | 0.65     | 0.3       | 0.95      | —         | —         | —         | —         |
| $c_{12}$ | —     | —        | —         | —         | —        | —        | —         | 0.05      | 1         | —         | —         | —         |
| $c_{13}$ | —     | —        | —         | —         | —        | —        | —         | —         | —         | —         | —         | —         |
| $c_{14}$ | —     | —        | —         | —         | —        | —        | —         | —         | —         | —         | —         | 1        | 1        |
5. Construction of fault diagnosis model

5.1. Construction of reasoning chain based on causality

Take the rejection of circuit breaker caused by electrical reasons of control and auxiliary secondary circuit as an example. It is assumed that the circuit breaker fault is caused by a short circuit in the opening/closing coil. Then according to the causal relationship, the symptoms of fault are that the circuit of opening/closing coil value is too high and the time of opening/closing coil circuit is too short. Therefore, the fault cause is $c_4$, and the fault symptoms are $d_7$ and $d_8$. The reasoning chain is drawn in figure 2(a).

In addition, it can be seen from table 3 that different causes of fault may show the same symptoms. So all the fault symptom information is classified into a subset of fault symptom named $D_x$ in this paper. All fault causes associated with elements in this subset are suspected fault causes, which composite a subset of fault cause named $C_x$. After that, on the basis of the fault symptom information we obtained, a larger reasoning chain can be constructed. Set the subset $D_x = \{d_7, d_8\}$ of fault symptoms, then the subset of fault causes associated with it is $C_x = \{c_3, c_4, c_5, c_6\}$. The reasoning chain is drawn in figure 2(b).

![Figure 2](image1.png)

**Figure 2.** Schematic diagram of reasoning chain for circuit breaker fault diagnosis

5.2. Construction of Bayesian networks

![Figure 3](image2.png)

**Figure 3.** Bayesian network diagram for circuit breaker fault diagnosis

For the reasoning chain shown in figure 2(b), the Bayesian network is established and shown in figure 3. Compared with other Bayesian models, the Bayesian network model based on reasoning chain in the figure simplifies the complexity of the network. In case the data is not lost, it also completely
covers the possible causes of fault, and achieves a fast and accurate judgment of the fault causes of the high voltage circuit breaker.

5.3. Fault diagnosis process
The fault diagnosis process of high voltage circuit breaker based on reasoning chain and Bayesian network is as follows:
1) Through collecting and analyzing the fault data of circuit breaker, a subset of fault symptoms is obtained. After that, the corresponding fault causes subset is constructed.
2) The reasoning chain is constructed according to table 3.
3) The corresponding Bayesian network model is constructed according to the reasoning chain. And the fault probability of each suspected fault cause is obtained by Bayesian backward inference. Finally, output the calculated results by size.

6. Case study
A case study is made of a fault of SF6 circuit breaker refusing opening. The model number of the circuit breaker is LW6B-126, and the actual cause of the failure is that the drive mechanism element is jammed. Table 4 shows the abnormal data obtained after circuit breaker failure and its normal range for comparison.

| project                        | Abnormal data | normal range |
|--------------------------------|---------------|--------------|
| The time of moving contact opening (ms) | 56            | 32~40        |
| Total trip (mm)                | 121           | 144~156      |

According to the measured parameters, it can be obtained that the time of moving contact opening is too long and the total trip is abnormal. It means that the fault symptoms subset \( D_x = \{d_{10}, d_{12}\} \), and the related fault causes subset \( C_x = \{c_7, c_8, c_9\} \). The Bayesian network is shown in figure 4.

Figure 4. Bayesian network diagram for case study
Combining the conditional probability in table 3 and applying the Bayesian formula (2), we can get the probability results of each fault cause as follows: \( c_7 = 0.984 \), \( c_8 = 0.014 \), \( c_9 = 0.002 \). Therefore, it can be inferred that the fault is caused by \( c_7 \) (moving contact insulated connecting rod fault or drive mechanism element jamming), which is consistent with the reality.

7. Conclusion
In this paper, the reasoning chain is applied to fault diagnosis of high voltage circuit breaker. It takes high voltage SF6 circuit breaker as an example to study a fault diagnosis method combined reasoning chain and Bayes. On the basis of the obtained fault symptom information, the corresponding reasoning chain is constructed. Then the probability of circuit breaker fault is obtained by using Bayesian network to infer backward. The functions of reasoning chain and Bayesian network can complement
each other. For one thing, the reasoning chain is used to simplify the data of fault features to obtain the minimum event set, which reduces the complexity of network structure and facilitates the construction of an optimized Bayesian network model. For another, the Bayesian network can be used to analyze the fault causes of the circuit breakers and realize the efficient and rapid fault diagnosis of the high voltage circuit breakers. Compared with other fault diagnosis methods of circuit breakers, this method uses more fault parameters and information, and diagnoses more comprehensive fault types. Moreover, the addition of reasoning chain reduces the complexity of Bayesian network, which is conducive to infer results more rapidly. Finally, effectiveness of the method is verified by the result of practical fault diagnosis case study.

Acknowledgments
The authors gratefully acknowledge the financial support from the National Science Foundation of China (5187070349).

References
[1] Mei F, Mei J and Zheng J et al 2013 Application of Particle Swarm Fused KFCM and Classification Model of SVM for Fault Diagnosis of Circuit Breaker Proceedings of the CSEE 33(36):134-141
[2] Huang L, Wang W and Wu Z et al 2008 Diagnosis Model of HV SF6 Circuit Breaker Based on Fuzzy Theory High Voltage Apparatus 44(3):246-249
[3] Zhang C, Wang W and Xu L et al 2007 Diagnostic Technique of Mechanical Failure of Circuit Breaker Based on D-S Algorithm Electric Switchgear 2007(2):1-4
[4] Yang L and Zhu Y 2015 High voltage circuit breaker fault diagnosis of probabilistic neural network Power System Protection and Control 43(10):62-67
[5] Xie W, Li P and Li H et al 2013 High Voltage Circuit Breaker Fault Diagnosis Model Based on Probabilistic Neural Networks Journal of Jiangnan University(Natural Science Edition) 12(5): 559-564
[6] Cheng X, Zhu X and Du Y et al 2018 High Voltage Circuit Breaker Fault Diagnosis Based on Neural Fuzzy Petri Nets Transactions of China Electrotechnical Society 33(11): 2535-2544
[7] Wang S and Li X 2018 Circuit Breaker Fault Detection Method Based on Bayesian Approach Industrial Control Computer 31(4):147-148,151
[8] Rong Y, Ge B and Zhao J et al 2009 Fault Diagnosis of SF6 Circuit Breaker Using Rough Set Theory and Bayesian Network High Voltage Apparatus 35(12):2995-2999
[9] Ma X, Han F and Li H 2008 Synthetic Fault Diagnosis Method of Vacuum Circuit Breaker Based on Rough Set Theory and Bayesian Network Modern Electric Power 25(3):42-46
[10] Zhu J and Li C 1985 High Voltage Circuit Breaker (Beijing: Water Resources and Electric Power Press) pp 103-111
[11] Li X, Qin H and Xiong Z 2009 Maintenance Process of AC High Voltage SF6 Circuit Breaker (Beijing: China Electric Power Press) pp 330-341
[12] Zhang N, Feng L and Yang J et al 2014 Transmission Grid Fault Diagnosis Based on Reasoning Chain Automation of Electric Power Systems 38(22):78-84
[13] Negnevitsk M 2012 Artificial Intelligence: A Guide to Intelligent Systems, Third Edition (Beijing: Machinery industry press) p 39