Fault Diagnosis Method of Circuit Breakers Based on Weighted Fuzzy Petri Nets

Xiaotong Zhang¹,a, Qing Chen¹, Mengxuan Sun¹, Wudi Huang¹ and Wangyuan Gao²

¹ Key Laboratory of Power System Intelligent Dispatch and Control (Shandong University), Ministry of Education Jinan, China
² State Grid Nanjing Power Supply Company, Nanjing, China

a mxtzhang@163.com

Abstract. The maintenance and self-healing of circuit breakers are very difficult when the fault diagnosis results of circuit breakers cannot cover all kinds of fault causes. This paper proposes a method for comprehensively diagnosing circuit breaker faults. The method simulates the action process of circuit breakers based on weighted fuzzy Petri nets and makes it feasible to infer circuit breaker fault causes from different aspects. The model shows the action sequence of the circuit breaker by associating the control mechanism, the operating mechanism, the transmission mechanism and the contact part of the circuit breaker, and each part of it is described with the corresponding abnormal signals of the circuit breaker stored in the substation end. Specific fault reasons of the circuit breaker can be inferred by considering the action sequence and the relationship between the abnormal information and fault causes. The results for some test cases show that this method can obtain the diagnosis results covering various possible fault causes.

1. Introduction

High-voltage circuit breaker is responsible for the load control and fault protection of the power system. The timely and accurate fault analysis of high-voltage circuit breaker is the basic task to ensure the safe operation of the power grid [1]. In recent years, most of the researches focus on mechanical fault diagnosis [2], such as a method based on fuzzy fusion and support vector machine [3], a research based on factor analysis and support vector machine [4], a study using improved wavelet packet-feature entropy method [5]. All of the above studies are concentrated on micro electrical quantities, but they haven’t analyzed fault causes from the macroscopic perspective. Currently, scholars have adopted a method on the basis of Petri nets and the rough set theory [6], and the diagnosis process encompasses a variety of fault reasons, but its model cannot describe the physical relationship within the circuit breaker.

At present, data mining technology can acquire a large number of abnormal information inside the circuit breaker at the station end [7]. These signals combining the logical reasoning method can realize more efficient and accurate fault diagnosis of circuit breaker.

Through the above analysis, this paper proposes a circuit breaker fault diagnosis method based on weighted fuzzy Petri nets. The model simulates the fault conditions of each stage in the whole action process of circuit breaker. The bottom layer of Petri nets reflects abnormal signals from the station end, and the higher layer represents fault causes, and the logical regulation of the model...
connects different layers and action periods. The method considers the physical relationship and uses the abnormal information of the station end, which makes the fault diagnosis reliable and comprehensive.

2. Analysis on SF6 circuit breaker action process
Since 1970s, SF6 circuit breaker has gradually become the most important type of circuit breaker in the high voltage power grid [8]. Therefore, the paper takes SF6 circuit breaker diagnosis process as an example. Firstly, the control circuit sends an opening/closing command to the operating mechanism, then the opening/closing coil of the operating mechanism is energized, and the armature is attracted to generate displacement, which drives the dice to trip. Under the condition of spring energy having been stored, the valve is actuated, and then the transmission mechanism is activated, and finally the contact part moves [9].

When the hydraulic pressure or barometric pressure of the operating mechanism is too low to allow its action, it will occur the opening latching or closing latching or reclosing latching [10].

3. Construction of Petri nets

3.1. Definitions of weighted fuzzy Petri nets
Definition 1: The weighted fuzzy Petri net is a ten-tuple:

\[ S_{\text{WFPN}} = \{P, T, O, U, T_{\text{thr}}, W, \alpha, M, Q\} \]  

\( P = \{p_1, p_2, \ldots, p_n\} \) is library set, the total number of elements is \( n \); \( T = \{t_1, t_2, \ldots, t_m\} \) is transition set, the total number of elements is \( m \); \( I = \{\delta_j\} \) belongs to matrix \( n \times m \), if \( p_i \) is the input of \( t_j \), \( \delta_{ij} = 1 \), otherwise \( \delta_{ij} = 0 \); \( O = \{\gamma_j\} \) belongs to matrix \( m \times n \), if \( p_j \) is the output of \( t_i \), \( \gamma_{ij} = 1 \), otherwise \( \gamma_{ij} = 0 \); \( U = [\mu_1, \mu_2, \ldots, \mu_m] \) is the transition confidence vector; \( T_{\text{thr}} = [\lambda_1, \lambda_2, \ldots, \lambda_m] \) is the threshold vector of transition ignition; \( W = (w_{ij}) \) is the weight matrix of the input arc, \( \forall j \in \{1, 2, \ldots, m\}, \sum_{i=1}^{n} w_{ij} = 1 \); \( \alpha = [\alpha_1, \alpha_2, \ldots, \alpha_n] \) represents the confidence of the library when token is not considered; \( M = [\alpha_1, \alpha_2, \ldots, \alpha_m] \) is the confidence vector of the library after synthesizing token; \( Q = [q_1, q_2, \ldots, q_n] \) is the initial library identification matrix, if token exists in library \( p_i, q_i = 1 \), otherwise \( q_i = 0 \).

Definition 2: If token in the current library reaches the next library through transition, its input arc weight and transition threshold is 1, and threshold is 0, then the current library is called virtual library.

In this paper, the rule containing negative proposition is defined as follows:
Definition 3: When proposition \( p_1 \) is true, proposition \( p_2 \) is not true, and the rule is realized by rectifying the input arc weight and the transition threshold.

3.2. Reasoning mechanism of Petri nets
In Petri nets, fault conditions and connections between each stage of circuit breaker can be graphically represented. And the dynamic change of the fault process can also be described by matrix analysis method [11]. In order to make the representation more convenient, it is assumed that \( A, B, C, D, E \) are matrices and their orders accord with the matrix operation law, and the operators are defined as follows:

1) Taking the big operator \( \odot : C = A \odot B \), then \( c_{ij} = \max\left(a_{ij}, b_{ij}\right) \).
2) Comparison operator \( \odot : C = A \odot B \), if \( a_{ij} \geq b_{ij} \), \( c_{ij} = 1 \); otherwise \( c_{ij} = 0 \).
3) Multiplication operator \( \odot : C = A \odot B \), then \( c_{ij} = a_{ij} b_{ij} \).
4) Multiplication operator \( \otimes : \mathbf{C} = \mathbf{D} \otimes \mathbf{E} \), then \( c_{ij} = \max_{1 \leq k \leq q} (d_{ik} \cdot e_{kj}) \).

5) Matrix multiplication \( \bullet : \mathbf{C} = \mathbf{D} \bullet \mathbf{E} \), then \( c_{ij} = \sum_{k=1}^{q} d_{ik} \cdot e_{kj} \).

In this paper, the reasoning process of weighted fuzzy Petri nets obtained by improving the reasoning method in literature [12] is as follows:

Step 1: Given initial variables, including the input function matrix \( \mathbf{I} \), the output function matrix \( \mathbf{O} \), initial library identification matrix \( \mathbf{Q} \), transition confidence matrix \( \mathbf{U} \), transition threshold matrix \( \mathbf{T}_{\text{thre}} \), library confidence matrix \( \mathbf{\alpha} = [\alpha_1, \alpha_2, \ldots, \alpha_n] \), and the weight matrix of the input arc \( \mathbf{W} = (w_{ij})_k = 0 \).

Step 2: Calculate the library confidence after considering the token \( \mathbf{M}^0 = [\alpha_1, \alpha_2, \ldots, \alpha_n] \).

\[
\mathbf{M}^0 = \mathbf{a} \odot \mathbf{Q}
\]  

(2)

Step 3: Calculate the synthetic input credibility of the transition.

\[
\mathbf{E}^k = \mathbf{M}^k \bullet \mathbf{W}
\]  

(3)

Step 4: Compare the synthetic input credibility of the transition with the threshold.

\[
\mathbf{G}^k = \mathbf{E}^k \odot \mathbf{T}_{\text{thre}}
\]  

(4)

Step 5: Calculate the synthetic input credibility of the ignitable transition.

\[
\mathbf{H}^k = \mathbf{E}^k \odot \mathbf{G}^k
\]  

(5)

Step 6: Calculate the confidence matrix of the library considering token.

\[
\mathbf{M}^{k+1} = \left[ (\mathbf{H}^k \odot \mathbf{U}) \odot \mathbf{O} \right] \oplus \mathbf{M}^k
\]  

(6)

Step 7: If \( \mathbf{M}^{k+1} = \mathbf{M}^k \), the Petri net is stable, otherwise, \( k = k + 1 \), the calculation returns to step 3.

4. Construction of circuit breaker fault diagnosis model

4.1. Construction of weighted fuzzy Petri Nets

According to the action process of the circuit breaker and the abnormal information available at the station end, the Petri net model is as Figure 1 and Table 1:

![Figure 1. The weighted fuzzy Petri net of SF6 circuit breaker](image-url)
| Name          | Information                                      | Name          | Information                                      |
|--------------|--------------------------------------------------|--------------|--------------------------------------------------|
| f1           | Control loop fault                               | d6           | The coil core is jammed or deformed              |
| f2           | Opening/closing coil circuit fault               | d7           | Opening/closing coil circuit block               |
| f3           | opening/closing valve action fault               | d8           | Failure of energy storage motor                  |
| f4           | Transmission failure                             | d9           | The circuit is not tightly sealed                |
| f5           | Contact part failure                             | d10          | Oil pump/air pump failure                        |
| f6           | Circuit breaker acts successfully                | d11          | Spring mechanism failure                         |
| e1           | Control loop failure                             | d12          | Transmission mechanism blockage                  |
| e2           | Coil loop part failure                           | d13          | Dynamic and static contacts not aligned          |
| e3           | Opening/closing valve action fault               | d14          | The ability of arc extinction drops              |
| e4           | Transmission mechanism failure                   | m1           | The first control circuit is off                 |
| e5           | Contact and arc chute fault                      | m2           | The second control circuit is off                |
| d1           | control circuit is off                           | m3           | The first control power supply lost              |
| d2           | control power supply lost                        | m4           | The second control power supply lost             |
| d3           | coil loop resistance burned                      | m5           | the voltage of the coil is abnormal              |
| d4           | Bad contact of secondary wiring                  | m6           | effective value of current is too small          |
| d5           | Opening/closing coil short circuit               | m7           | the current time of coil is too short            |
| m8           | effective value of current is too large          | m9           | the current time of coil is too long             |
| m10          | opening/closing circuit is locked                | m11          | Total trip is abnormal                           |
| m12          | Storage motor starts frequently                  | m13          | Energy storage motor suppression timeout         |
| m14          | the oil/barometric pressure abnormal             | m15          | system cannot build pressure                     |
| m16          | spring does not store energy;                    | m17          | time for contact moving is too long              |
| m18          | contact action is not the same time              | m19          | Temperature of shell is too high                 |
| m20          | micro water exceeds the standard                | m21          | SF6 gas leaks                                   |

In the Petri net model shown in Figure 1, circuit breaker operation process is divided into five stages: the control circuit→the opening/closing coil circuit→the kinetic energy part of the operating mechanism→the transition mechanism→the contact part. If token stays in f1, it is the control loop fault; if token stays in f4, it is the transmission mechanism fault; if the fault signals comprise two or more portions at the same time, the former portion is generally the main fault reason, according to physical relationships of circuit breaker where the latter part can’t activate correctly in the case of the former part failure.

4.2. Parameter determination method
After building a fault diagnosis model, the next step is the inference based on matrix operation. The main calculation method is referred to section 3.2. The parameter determination method is as follows:

- Transition input arc weights: after referring to literature [13], every step of weight adjustment is related to back-propagation error value. η is learning efficiency, $E = \frac{e^2}{2}$ is back-propagation.
quantity, \( e \) is the difference between the library confidence expectation \( \alpha_i \) and synthetic library confidence value \( y_i \), and \( y_i = \mu x_i, x_i = \sum_{j=1}^{n} \alpha_j \cdot \omega_j \).

The weight modification gradient is

\[
\frac{\partial E}{\partial \omega_j} = \frac{\partial E}{\partial e_i} \cdot \frac{\partial e_i}{\partial y_i} \cdot \frac{\partial y_i}{\partial x_i} \cdot \frac{\partial x_i}{\partial \omega_j} = -e_i \mu \alpha_i \tag{7}
\]

The weight correction is \( \Delta \omega = -\eta \frac{\partial E}{\partial \omega_j} \). The new weight is \( \omega_j^{(1)} = \omega_j + \Delta \omega_j \), and it is substituted into equation (7). Then repeated iterative calculation is made until the value of back-propagation error is within the allowable error.

- From the perspective of fault tolerance, the transition confidence is set as 0.95, and the transition threshold is 0.4. According to the historical data and expert experience, the confidence of the initial library (not including token) is set as 0.9; the confidence of the virtual library is 1; the threshold of transition after the virtual library is 0; the confidence of the transition is 1; when there is a negative proposition, the weight of the library is -0.5. And all transition delays are 0.

4.3. Process of circuit breaker failure diagnosis

In Figure 1, the second stage is taken as an example. When there are abnormal signal \( m7 \) and \( m8 \), the initial token is placed in library \( m7, m8 \) and \( f1 \). According to the weighted fuzzy calculation, the synthetic confidence is greater than the transition threshold, and the transition is ignited, which means the token is transferred to library \( d5 \) and \( f1 \). Repeating the above process, token is transferred to library \( e2 \) and virtual library \( f1' \). The next calculation results still meet the transition rules, and then token moves to \( e2' \) and \( f2 \). At this time, the synthetic confidence is less than the threshold, and then the token does not remove when Petri nets reach steady state. It can be drawn that the failure is caused by “the part of opening/closing coil circuit” and “opening/closing coil short circuit”.

5. Reasoning verification

An example of SF6 circuit breaker fault mentioned in [13] is taken to verify the effectiveness of the method described in this paper.

When the failure of opening/closing circuit of the SF6 circuit breaker occurs, abnormal signals are detected at the substation end: ①“the on-off current time of the coil is too short”, ②“the effective value of the opening/closing current is too large”, ③“the energy storage motor starts frequently”, ④“the energy storage motor has a long suppression time”.

Since the abnormal signals contain only the second stage and the third stage, the simplified Petri net model has been shown in Figure 2.
Figure 2. The initial weighted fuzzy Petri net model

As previously described, when the fault information covers two stages at the same time, generally the previous stage is thought as the main reason. For the convenience of display, the following shows the calculation process of the efficient part. And its parameters are determined according to the method introduced in 4.2. Initial identification matrix $Q = \begin{bmatrix} 0.9000, 0, 0, 0.9000, 0.9000, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 \end{bmatrix}$. The input arc weight matrix is:

$$W = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.3 & 0.6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.4 & 0.32 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.4 & 0.68 & 0.18 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.82 & 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 & 1 & 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 & 1 & 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 & 1 & 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 & 1 & 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 & 1 & 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 & 1 & 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 & 1 & 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 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

According to section 3.2 reasoning process is as follows:

$M1 = \begin{bmatrix} 0.9000, 0, 0, 0.9000, 0.9000, 0, 0.9000, 0, 0.8550, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 \end{bmatrix}$

$M2 = \begin{bmatrix} 0.9000, 0, 0, 0.9000, 0.9000, 0, 0.9000, 0, 0.8550, 0, 0.9000, 0.8123, 0, 0, 0 \end{bmatrix}$

$M3 = \begin{bmatrix} 0.9000, 0, 0, 0.9000, 0.9000, 0, 0.9000, 0, 0.8550, 0, 0.9000, 0.8123, 0.8550, 0.8123 \end{bmatrix}$

$M4 = \begin{bmatrix} 0.9000, 0, 0, 0.9000, 0.9000, 0, 0.9000, 0, 0.8550, 0, 0.9000, 0.8123, 0.8550, 0.8123 \end{bmatrix}$
At this time $M_3 = M_4$, the cycle ends. And the Petri net state is shown in Figure 3.

Figure 3. The stable Petri net model

The failure reason is $f_2$: “the failure of the opening/closing coil circuit”. The diagnosis result is consistent with the actual failure cause while the calculation process and result are clear and comprehensive. It can be seen from the example that the fault diagnosis method of the high-voltage circuit breaker proposed in this paper can quickly and accurately judge the cause of the fault by comprehensively utilizing the station information and considering the action process of the circuit breaker. The method in this paper has a good performance in calculation accuracy and grid universality.

6. conclusion

How to comprehensively analyze the fault cause is one of the problems in the fault diagnosis of circuit breaker. In order to make the fault diagnosis process consider all aspects of fault information as much as possible and improve the reliability of diagnosis, this paper takes the abnormal information at the substation as the analysis object for diagnosis and analysis. At the same time, the sequence of the circuit breaker action process is integrated into the fault diagnosis to avoid the redundancy of the diagnosis result. In addition, on the basis of traditional weighted fuzzy Petri nets, virtual library and negative proposition are added. And the negative proposition is expressed by taking negative value of weight, so as to completely simulate a clear fault reasoning process of circuit breaker.

Acknowledgments

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

References

[1] Wang L, Chen Q and Gao H et al 2018 Intelligent substation fault tracing architecture based on big data mining technology Automation of Electric Power System 42(03) 84-91
[2] Guan Y, Yang Y and Zhong J et al 2018 Summary of mechanical fault diagnosis method of the high voltage circuit breakers High Voltage Apparatus 54(07) 10-19
[3] Mei F, Mei J and Zheng J et al 2013 Application of particle swarm optimization KFCM and SVM diagnostic model in fault diagnosis of circuit breakers Proceedings of the CSEE 33(36) 134-141
[4] Cheng X, Guan Y and Zhang W et al 2014 Mechanical fault diagnosis method for high voltage circuit breaker based on factor analysis and support vector machine algorithm Transactions of China Electrotechnical Society 29(07) 209-215

[5] Sun L, Hu X and Ji Y et al 2007 Application of improved wavelet package-characteristic entropy in fault diagnosis of high voltage circuit breakers Proceedings of the CSEE 27(12) 103-108

[6] Sun N and Zhao J 2011 Circuit breaker failure diagnosis based on rough set theory and Petri nets Electric Power 44 (8) 9-13

[7] Wang L, Chen Q and Li T et al 2013 Grid fault diagnosis architecture based on grid platform Automation of Electric Power System 37(03) 70-76

[8] Li X, Qin H and Xiong Z et al 2009 Repair technology of AC high voltage SF6 circuit breaker (Beijing: China Electric Power Press) pp 343-358

[9] Duan C, Zhai Z and Qi Z et al 2014 Fault detection and diagnosis technology for high voltage circuit breakers (Beijing: China Electric Power Press) p 6

[10] Lin W 2011 Modern High Voltage Electrical Technology (Beijing: China Machine Press) p 257

[11] Sun J, Qin S and Song Y 2014 Fault diagnosis of electric power systems based on fuzzy Petri nets IEEE Transactions on Power Systems 19(4) 2053-59

[12] Wu W, Wen F and Xue Y et al 2013 Delay-constrained weighted fuzzy Petri net fault diagnosis model based on multi-source information Automation of Electric Power Systems 37(24) 43-53

[13] Cheng X, Zhu X and Du Y et al 2018 Fault diagnosis of high voltage circuit breaker based on neural fuzzy Petri nets Transactions of China Electrotechnical Society 33(11) 2535-44