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Novel Hierarchical Fault Diagnosis Approach for Smart Power Grid with Information Fusion of Multi-data Resources Based on Fuzzy Petri Net*

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***Abstract*—Considering the problem of the complicated structure of smart power grid, the varied topology after fault and multi-data resources of fault information, this paper presents a novel hierarchical fault diagnosis approach for smart power grid with information fusion of multi-data resources based on fuzzy petri net, which contains diagnosis layers of the switch and the information fusion of multi-data. In the diagnosis layer of switch, the network topology is established based on the information provided by the SCADA system. In the diagnosis layer of the information fusion of multi-data, a smart power grid fault-diagnosis method of directional weighted fuzzy petri nets using the diagnosis information from fault recorder and WAMS is presented, which considering the information of protection and circuit breaker. Then fault diagnosis is conducted information fusion with the improved D-S evidence theory. Finally, the diagnostic decision is obtained with C-means algorithm. The simulation shows that the method has good adaptability, and in the case of incomplete information, the method can still obtain correct diagnosis results, and has certain universality and fault tolerance ability.**

Keywords—fault diagnosis; multi-source information; hierarchical ; weighted fuzzy Petri net (WFPN);

I. INTRODUCTION

With the development of smart power grid, diagnosing the faults of the smart power grid timely and accurately to ensure the safe and stable operation of power grid is of great significance [1]. Currently, there are many fault diagnosis methods at home and abroad, such as genetic algorithm [2], expert system [3], artificial neural network [4], bayesian network [5], etc., but the existing methods are difficult to solve complex fault of the system reasonably. Considering the information of protection and circuit breaker of the switch from the SCADA system after the fault, the traditional fault diagnosis methods cannot effectively eliminate the negative impact on fault diagnosis under the uncertainty condition of protection and breaker mal operation, refusing action and lost information by transmission, so the fault diagnosis only relies on the switch and the single data resources is not satisfactory [6-7]. Reasonable use of fault recorder and PMU, combined with the information of switch is becoming a hot area of research of power fault diagnosis for smart power grid [7-11].

Based on the above consideration, this paper presents a novel hierarchical fault diagnosis approach for smart power grid with information fusion of multi-data resources [12] based on fuzzy petri net, which contains diagnosis layers of the switch and the information fusion of multi-data. When to realize the rapid diagnosis of the single power grid fault based on the information of switch form SCADA system, this method which integrates the information of switch, fault recorder and electrical form WAMS, utilizes directional weighted fuzzy Petri net (DWFPN) to model the bus and line in each spread fault direction to guarantee the universality and fault tolerance ability. Then fault diagnosis is conducted information fusion with the improved D-S evidence theory [13-14]. Finally, the diagnostic decision is obtained with C-means algorithm [15].

II. FRAMEWORK OF HIERARCHICAL FAULT DIAGNOSIS

As there are more single failures of smart power grid, the fault diagnosis method based on information of switch can accurately make judgments, if the meaning of combining electric parameters makes no sense, the delay of electric parameters wave record’s transmission will reduce the efficiency of fault diagnosis; When miss operation and mal operation of protection and switch causes multi-element power outage or accidental multiple faults, only based on the diagnosis of switch often cannot judge the fault components and the non-fault power outage components, so we must combine with information of electric parameters to make comprehensively identify. Therefore, this paper presents that it is necessary to adopt hierarchical model to make fault diagnosis of the smart power grid, the flowchart is shown in figure 1.

Firstly, according to the switch state and protecting action sequence information in time provided by SCADA system, use the method of connection analysis to make quick analysis on

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smart grid topology and narrow the searching fault area; If the fault element is not the unique, enter the multi-source information fusion diagnosis layer, then fuse the results of each direction using the improved D-S evidence theory; If the fault element is unique, the diagnosis ends; Finally, the diagnostic decision is obtained with C-means algorithm.

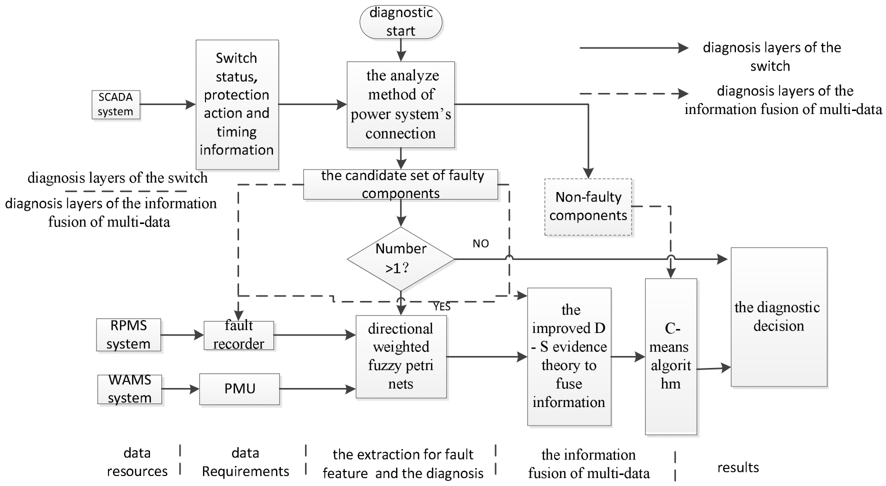


Fig.1 Flowchart of the novel hierarchical fault diagnosis approach for smart power grid with information fusion of multi-data resources based on fuzzy petri net

III. THE FAULT DIAGNOSIS LAYER OF SWITCH QUANTITY

According to the switch quantity information provided from SCADA system, the analyze method of power system's connection[16] is used to analyze the topology of smart power grid to search fault area and narrow the scope of diagnosis. The specific searching steps are as follows:

1) Build a collection M of all components in the line and use digital codes to get the set M *;

2) Establish subsets , put elements from the collection of M_i^* i(i = 1, 2, 3...) into the subsets ;

3) Search the closing circuit breaker connected with component i, CB_j (j = 1, 2, 3...) is searched;

4) Continue to search all the components connected with CB_j (j = 1, 2, 3...) and numbered for k (k = 1, 2, 3...). Then continue to search the closed circuit breaker connected with CB_j (j = 1, 2, 3...) until the closing ones are none. Put all the searched components into set N_1 ;

5) Remove the element belonged to set N_1 from set M^* ;

6) Establish subsets N_2 , put the remaining elements in the collection of M^* into subsets P ;

7) Repeat *3) - 5)*, make same searching as element i, put all the searched elements into N_2 , and remove them from M^* . Set M^* will be empty and searching is complete (if the set is not null, the search continues).

8) List all subsets, and the fault area are the sets not concluding active elements.

9) Reference numbers, get suspicious fault component sets Q .

IV. THE DIAGNOSTIC LAYER OF INFORMATION FUSION USING MULTI-DATA RESOURCES

Information fusion of multi-data resources diagnostic layer diagnoses whether multiple component failures of component fault candidate set further, comprehensives the amount of fault information of the switch, electrical characteristics. In this paper, the amount of information recorded in the electrical wave device and collected from PMU diagnosed by DWFPN, the credibility of each wire in the direction of the body as evidence participated in multi-source information fusion diagnosis.

A. The basic idea of fault diagnosis

Protection of power system protection generally installed main protection, the first backup protection and the second backup protection, and both sides of line have main protection and two backup protection. Protection of bus or transformer generally is composed only by the main protection. When they act, all of their associated circuit breakers will be opened, the specific protection principle refers to literature [11].

This layer is presents directional weighted fuzzy Petri net method, and use the improved D-S evidence theory to fuse information , the basic idea of fault diagnosis is that weighted fuzzy Petri net model taking each line ends (both S and R) as the object is established for lines; For bus, as each circuit breaker may lead to expand the range of failure for its refusing action when the main protection of the bus actions, it is need to jump all of the circuit breaker connected to remove the fault. And establish weighted fuzzy Petri net model respectively breakdown for each spread direction, establish the model of weighted fuzzy Petri net respectively for each extending direction of fault, then fuse the results of each direction using the improved D-S evidence theory. The chart of fault diagnosis in this layer is shown in figure 2.

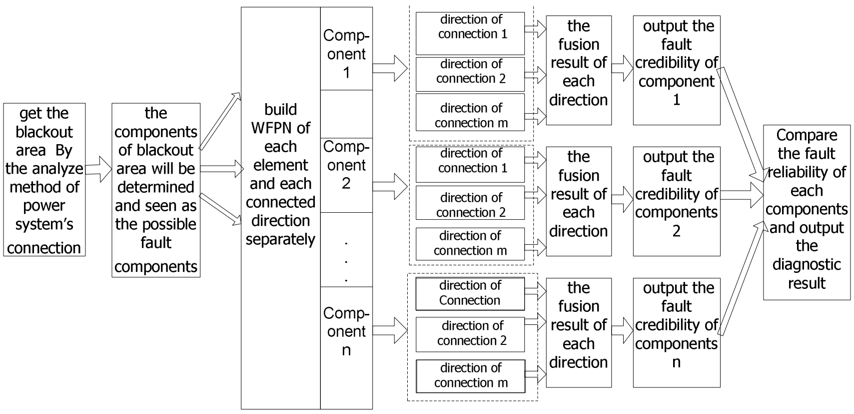


Fig.2 Flowchart of fault diagnosis in power system based on directional weighed fuzzy Petri net

B. *The model based on DWFPN*

To illustrate the modeling and reasoning process based on DWFPN, the paper takes the bus and lines in the model of local power system as an example shown in figure 3.

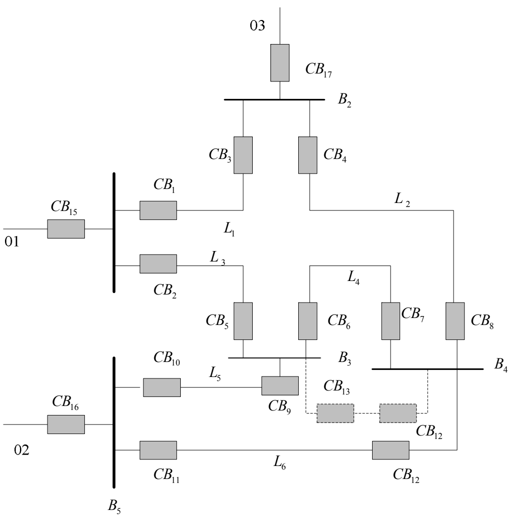
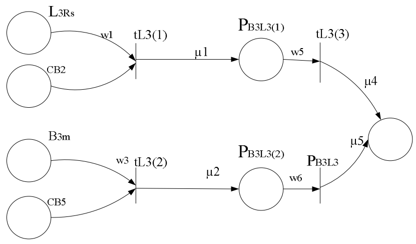


Fig.3 Partial power system model

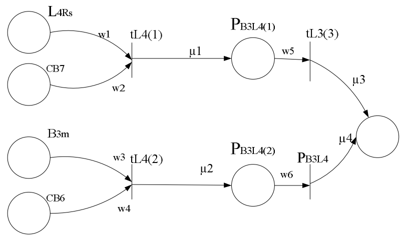
The system model includes 5 bus $B1-B5$, 6 lines $L1-L6$, 12 circuit breakers CB_1-CB_{12} and 41 protections, which includes 17 main protections, 24 backup protections $B_{1m},...B_{5m}$; $L_{1Sm},...L_{6Sm}$; $L_{1Rm},...L_{6Rm}$; $L_{1Sp},...L_{6Sp}$; $L_{1Rp},...L_{6Rp}$; $L_{1Ss},...L_{6Ss}$; $L_{1Rs},...L_{6Rs}$.

As shown in figure 3 (not containing L_7), the bus B_3 fails and the model of FPN shown in figure 4 (a),(b),(c) in three spread of fault direction (L_3, L_4, L_5) is established respectively; similarly, when line fails, the model of FPN shown in figure 5 (a),(b),(c) in two spread of fault direction (L_2, L_3) on both ends (S and R from left to right) of the line is established respectively;

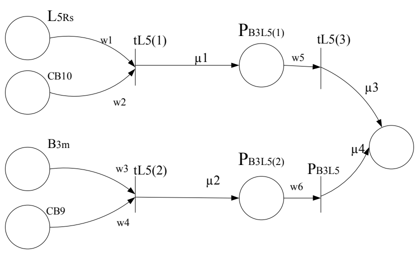
It should be pointed out that the correct protection and its circuit breaker are expressed in one library in this paper, if you have multiple remote back-up protections, you need to ride



(a) WFPN model of line L_3

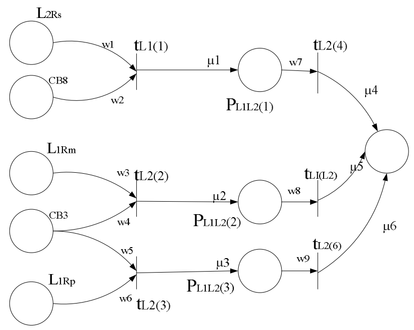


(b) WFPN model of line L_4

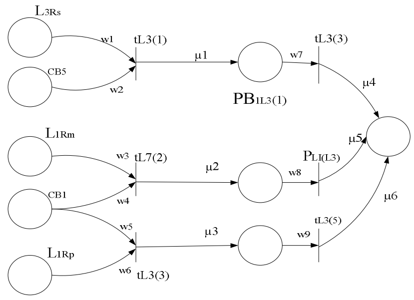


(c) WFPN model of line L_5

Fig.4 DWFPN model of bus B_3



(a)WFPN model of line L_2



(b) WFPN model of line L_3

Fig.5 DWFPN model of line L_1

factors(γ_1 and γ_2) in front of the library credibility.

$$\gamma_1 = \frac{S_1}{S_2} \tag{1}$$

$$\gamma_2 = \frac{R_1}{R_2} \tag{2}$$

Here S_1 is the number of protection or circuit breaker that has acted in side S , S_2 is the number of all the protection or the circuit breakers in side S , R_1 is the number of protection or circuit breaker that has acted in side R, R is the number of all the protection or the circuit breakers in side R .The paper organizes data based on the field data, and the action reliability value of protection and circuit breaker can be seen [12].

$$\theta_{CB} = \frac{\theta_1}{\theta_2} \tag{3}$$

Here θ_1 is the number of acted circuit breaker corresponding to the protection of components, θ_2 is the total number of acted circuit breaker corresponding to the protection of components.

C. Fusion with the improved D-S evidence theory

Make the reliability value of protection and circuit breaker get from the formula above as body of evidence, using the improved D-S evidence theory to fuse information and solve the conflict problem existed among the body of evidence, and then we can get more precise and comprehensive fault diagnosis.

The D-S evidence theory is an important means of uncertainty reasoning. To identify framework, the rules of evidence $m_1, m_2, ..., m_n$ are synthesis as type (4):

$$m(A) = \begin{cases} 0 & A = \varphi \\ (1-K)^{-1} \sum\limits_{\cap A_i = A} \prod\limits_{i \le j \le n} m_j(A_i) & A \ne \varphi \end{cases} \tag{4}$$

The basic probability assignment (BPA) shown in above formula expresses the degree of the conflict among evidence and satisfies the condition as below:

$$\sum_i m_j(A_i) = 1 \tag{5}$$

$$K = \sum_{\cap A_i = \varphi} \sum_{1 \le j \le n} m_j(A_i) \tag{6}$$

In application, most are from two aspects of modifying data-resources and synthetic rules to improve [13-17], and some problems such as robustness and fairness [14] will exist. In this article, the modification of evidence body based on credibility and the synthetic rules based on distribution of local conflicts [14] are adopted to fuse the evidence, and then the improved D-S evidence theory of information fusion will be formed.

1) Modification of evidence body based on the credibility. Credibility of evidence $\mu_i (\mu_i \le 1)$ reflects the relative reliability among the evidence, and we set the evidence credibility which has the highest reliability to 1 in forensics group. μ_i will be served as a correction coefficient, is to modify the original evidence body, the remaining probability will be assigned to the unknown situation $M^{'}(\Theta)$, and then the BPA values revised body of evidence M will be got and shown in type (7) :

$$M = [m(A_1)m(A_2)\cdots m(A_n)m(\Theta)] \tag{7}$$

Here

$$m(A_m) = \{\mu m^{'}(A_m) \big| m = 1, 2, \cdots, n\} \tag{8}$$

$$m(\Theta) = 1 - \sum_{m=1}^{n} m(A_m) \tag{9}$$

And $$m^{'}(A_m) \in M^{'} \tag{10}$$

2) Synthetic rules based on the distribution of local conflicts. The conflicts of local are distributed between two focal elements which cause conflicts:

$$\begin{cases} m_{jk}(A) = \sum\limits_{B \cap C = A} m_j(B) m_k(C) + f(A) \\ f(A) = \sum\limits_{A \cap D = \varphi} \left(\dfrac{m_j^2(A) m_k(D)}{m_j(A) + m_k(D)} + \dfrac{m_k^2(A) m_j(D)}{m_j(D) + m_k(A)} \right) \end{cases} \tag{11}$$

Here B、C、$D \subset \{A_1, A_1, \cdots, \Theta\}$, the value of the BPA, $m_j(\Theta) \subset M_j$, $m_k(\Theta) \subset M_k$, $m_{jk}(A)$ is BPA values of the new evidence body M_{jk} after fusion.

After two every evidence is composited, the new evidence obtained will be normalized, such as M_{jk} that is normalized:

$$m_{jk}^{'}(A) : m_{jk}^{'}(A) = \frac{m_{jk}(A)}{\sum m_{jk}(\Theta)} \tag{12}$$

D. The decision-making of the fault diagnosis based on the fuzzy C-means clustering method

Because the fusion results of evidence will change along with the change of fault lines, and not suitable for direct diagnostic decision, this paper uses the fuzzy C-means clustering method (FCM) [18] to make cluster analysis for the fusion results of D-S evidence theory.

The data set $X = \{x_1, x_2, \cdots, x_N\}$ is divided into class c using FCM, and the minimum of the function through the iterative approximation for optimum criterion is

$$J_m(U,V) = \sum_{j=1}^{N}\sum_{i=1}^{c} u_{ij}^m d_{ij}^2 \tag{13}$$

Among them, the matrix of membership degree $U = (u_{ij})_{c\times N}$,element u_{ij} indicates the degree of data point x_j belongs to the class w_i and satisfies

$$u_{ij} \in [0,1], \sum_{i=1}^{c} u_{ij} = 1 \tag{14}$$

The subordinate class of data points can be decided by comparing with the set threshold; $V = \{v_1, v_2, \cdots, v_c\}$, v_i is the center of classification w_i ,index $m \in [1,\infty)$;

$$d_{ij}^2 = (x_j - v_i)^T A(x_j - v_i) \tag{15}$$

d_{ij}^2 is the distance to the center of the class w_i from data points x_j ,the data's distance. The Euclidean distance is adopted when $A = I$ in this paper.

In this paper, the circuit is divided into two types of fault and non-fault, the membership threshold of FCM is set to 0.5, the class that the center values are bigger is seen as the fault line set, the line which membership is greater than its threshold in the fault line set is seen as the fault line, and then the decision-making of the fault diagnosis will be given.

V. SIMULATIONS

Through simulation of data information such as SCADA system, the wide-area measurement system and fault information system, it is proved that the fault diagnosis method combined with different network model is effective.

Example 1

Take the model shown in figure 4（B_{3m} acted ）and 5 as an example. Figure 5 is the known model that increases the line L7, and remain the calculation results of three directions in figure 4. According to the respective input and output matrix and the condition of known to calculate, we can get the result of the experiment shown in the table I below.

TABLE I
TEST RESULT OF EXAMPLE 1

No.	protection actions	operation of circuit breakers	fault components/ credibility
figure 4	CB_{3m}	CB_5、CB_6、CB_9	$B_3(a)/0.8302$ $B_3(b)/0.8302$ $B_3(c)/0.8302$
Figure 5	CB_{3m}、L_{7Rs}	CB_5、CB_6、CB_9、CB_{14}	$B_3(a)/0.8302$ $B_3(b)/0.8302$ $B_3(c)/0.8302$ $B_3(d)/0.6543$

From the table I we can know that when network topology change, we only need to model and calculate for the changed line to reduce the complexity of the diagnosis model.

Example 2

Using 14 node model of the smart power grid power to model, and its system structure of simulation is shown in figure 6. The topology consists of 34 components, 74 protections and 42 circuit breakers. The bus protection is $B_{01m},\ldots,B_{14m}$; the main protection of the line is $LXsm$ and $LXRm$; the nearly backup protection of the line is $LXsp$ and $LXRp$; the remote back-up protection of the line is $LXRs$ and $LXSs$.

Take the part of power system test results as shown in table Ⅱ.

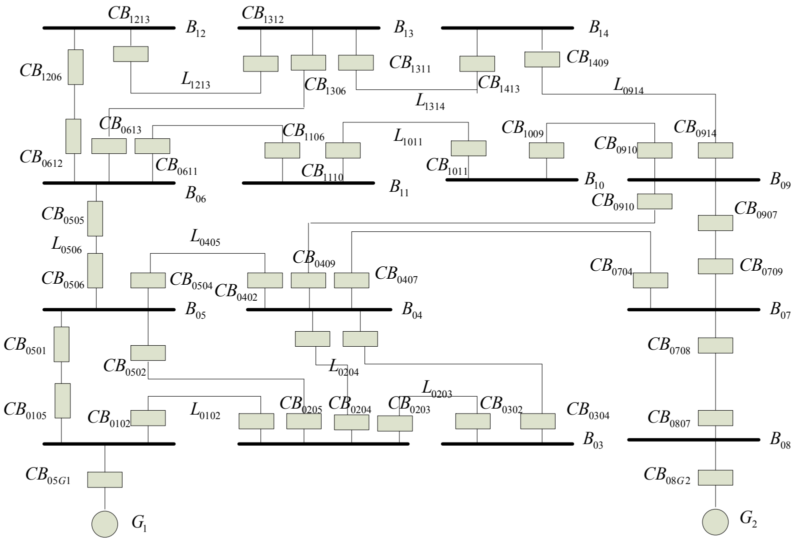


Fig.6 Fourteen-bus power system

TABLE II
Test result of 14 bus power system

No.	protection actions	operation of circuit breakers	fault components/ credibility	decision-making
1	B_{13m}	CB_{1312}、CB_{1306}、CB_{1314}	B_{13} / 0.8302	–
2	B_{13m}、L_{1314Rs}	CB_{1312}、CB_{1306}、CB_{1413}	B_{13} / 0.7716	CB_{1314} refuse act
3	B_{13m}、L_{1314Rp}	CB_{1312}、CB_{1306}、CB_{1314}	B_{13} / 0.8302, L_{1314} / 0.3723	L_{1314Rp} mal operation
4	B_{07m}、B_{10m}	CB_{0704}、CB_{0709}、CB_{0708}、CB_{1011}、CB_{1009}	B_{07} / 0.8302, B_{10} / 0.8302	–
5	B_{07m}、L_{1011Rs}、L_{0204Rm}、L_{0204Sm}	CB_{0704}、CB_{0709}、CB_{0708}、CB_{1110}、CB_{1009}	B_{07} / 0.8302, B_{10} / 0.8302, L_{1011} / 0.2670	CB_{1011} refuse act
6	B_{11m}、L_{1011Rs}、L_{0204Rm}、L_{0204Sm}	CB_{1106}、CB_{1011}、CB_{0204}、CB_{0402}	B_{11} / 0.7422, L_{0204} / 0.8910	CB_{1110} refuse act
7	B_{11m}、L_{1011Rs}、L_{0204Rm}、L_{0204Sm}	CB_{1106}、CB_{1011}、CB_{0402}	B_{11} / 0.7422, L_{0204} / 0.7143	CB_{1110} refuse act, CB_{0204} refuse act
8	L_{0204Rm}、L_{0204Sm}	CB_{1106}、CB_{1110}、CB_{0402}、CB_{0204}	B_{11} / 0.6242, L_{0204} / 0.8910	B_{11m} lost

Example 1 and 4 in table 5 are diagnosis of complete information, we can get the correct results by reasoning.

Example 2 and example 3 is on the basis of example 1 in the case of breaker's refusing action and protection's mal operation.

Example 5 and example 6 analyze the condition that further increases the uncertainty.

Results show that although the mal operation and refusing action lead to expansion of the fault area, this paper can also get correct diagnosis results by the improved algorithm. We can see that the algorithm has good universality and fault tolerance ability for the refusing and false action of circuit breaker and protection.

Example 7 and 8 are fault diagnosis removing some action information of protection and circuit breakers on the basis of example 6 and simulating the case of information loss.

Although the fault credibility of line L0204 dropped from 0.8910 to 0.7143 due to loss of information of the circuit breaker CB0204, we can get the right diagnosis results by comparing example 6 and example 7.

Example 8 simulated the condition of missing the key information of main protection. From the results we can see that the main protection B11 is lost, and the fault credibility of bus B11 dropped from 0.7422 to 0.6242. Though this information will make influence on the results of the analysis, the correct diagnosis basis can be provided for operators.

The diagnosis results of example 7 and 8 show that the improved algorithm proposed in this paper also has some fault tolerance under the condition of missing information. To sum up, the algorithm can accurately judge the fault components under the condition of information's loss or incomplete information. So the method presented in this paper has high fault tolerance and generality.

VI. CONCLUSION

In this paper, by analyzing the change of network topology In this paper, by analyzing the change of network topology and the fault information's influence on fault, a novel hierarchical fault diagnosis approach for smart power grid with information fusion of multi-data resources based on fuzzy petri net is presented. The method uses dual-data resources to analyze fault diagnosis based on the information of the switch and electricity by establishing the network topology and directional weighted fuzzy Petri nets. And quotes the improved D-S evidence theory to make information fusion. Finally, the fuzzy c-means clustering method is used to draw the final diagnosis decision. The simulation through examples shows that the algorithm can not only effectively solve the defects by using the single data resource for diagnosis, but can get the correct result in the case of incomplete information. Besides, the method has good universality and fault tolerance ability.

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