

Electronic Circuit Fault Diagnosis Problem Using Fuzzy Petrinets

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ABSTRACT: In this paper, Fuzzy Petri Nets (FPN) is a tool to build fault diagnosis models aimed to accurately diagnose faults when some incomplete and uncertain alarm information of protective relays and circuit breakers is detected. Then, models of fault diagnosis based on FPN are built, and their corresponding logical testifications are carried out. Finally, the validity and feasibility of this method is illustrated by simulation examples. It is shown from seven cases that the faulted system elements can be diagnosed correctly by use of these models, and a satisfying result can also be achieved even in the situation with large amount of incomplete and uncertain alarm information.

KEYWORDS: Electric power system (EPS), fault diagnosis, fuzzy Petri nets (FPN).

I. INTRODUCTION

THE FAULT diagnosis of Electric Power System (EPS) is a process of discriminating faulted system elements by tripping of protective relays and circuit breakers. Up to now, there are many methods, such as ANN, GAs, Tabu, expert system and logic reasoning, etc. [1]–[6], which have been applied to fault diagnosis of EPS. Their purposes are focused to diagnose faults timely on-line so as to provide an accurate judging rule for dis-patch operators. Specially, as soon as some serious faults occur in a power system, a lot of alarm information is transmitted to the control center. Under such situation, the operators are re-quired to judge the cause, location and system elements with faults rapidly and accurately. Thus good fault diagnosis methods can provide accurate and effective diagnostic information to dis-patch operators and help them take necessary measures in fault situations so as to guarantee the secure and stable operation of EPS.

At present, what researchers are interested in is how to deal with uncertainty and incompleteness of tripping information. In practical applications, a lot of transmission data and detective information that energy management system (EMS) receives are incomplete, and the tripping of protective relays and circuit breakers are somehow uncertain with the increasing of the distance from protective relays to remote terminal units (RTU). The key problem is how to make good use of detected alarm information that is incomplete and uncertain. Thus some relevant re-search efforts are engaged in order to seek an effective approach to the fault diagnosis of EPS in the face of the situation with incomplete and uncertain information [6]–[8], in which the fuzzy logic shows its special ability in dealing with such uncertainty and incompleteness.

Normally, when some serious faults occur in an EPS, it is inevitable that a great lot of data are transmitted to the control center, which always characterize serious incompleteness and repetition. In order to meet the requirement of rapidity, Petri nets, which has the characteristics of parallel information processing and concurrent operating function, is a very suitable and useful modeling tool. Hence some methodologies of modeling and analysis for the fault diagnosis of EPS by Petri nets are presented, [9]–[11] because of its ability of clearly describing the relation of protective relays and circuit breakers and concurrent operating mechanism.

The analysis above induces an idea to apply hybrid methods to the fault diagnosis of EPS. A new type of fault diagnosis method is presented in this paper by combining Petri nets and fuzzy logic. The feature of this model is that

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the initial tokens of Fuzzy Petri Nets (FPN) may be set according to the data of truth value given by users, but the diagnosing process is really dominated by the fuzzy reasoning mechanism based on certainty factors and concurrent calculation mechanism of Petri nets.

II. FUZZY PETRI NETS

A. Basic Concepts of FPNs

Definition 1: A generalized FPN can be defined by an 8-tuple set as follows [15]:

$$FPN = (P, T, D, I, O, f, \alpha, \beta) \tag{1}$$

where

- $P = \{p_1, p_2, \dots, p_n\}$ is a finite set of places;
- $T = \{t_1, t_2, \dots, t_m\}$ is a finite set of transitions;
- $D = \{d_1, d_2, \dots, d_n\}$ is a finite set of propositions, and
- $P \cap T \cap D = \Phi, P \cap D;$

$I: T \rightarrow P_\infty$ is the input function, a mapping from transitions to bags of places which determines the input

places to a transition, and P_∞ denotes bags of places; $O: T \rightarrow P_\infty$ is the output function, a mapping from transitions to bags of places, which determines the output places from a transition;

$f: T \rightarrow [0,1]$ is an association function, a mapping from transitions to real values between 0 and 1;

$\alpha: P \rightarrow [0,1]$ is an association function, a mapping from places to real values between 0 and 1;

$\beta: D \rightarrow [0,1]$ is an association function, a mapping from propositions to real values between 0 and 1;

Let A is a set of directional arcs, β is an association function, a bijective mapping from places to propositions.

If p_i is a place, t_j is a transition, then there exists a directional arc A_{ij} from the place p_i to the transition t_j . If t_j is a transition, p_i is a place, then there exists a directional arc A_{ji} from the transition t_j to the place p_i . If t_j is a transition, then the transition t_j is said to be associated with a real value α_j which denotes the certainty factor (CF) of t_j . If p_i is a place, then the place p_i is said to be associated with the proposition d_i . The tokens of a place p_i is denoted by τ_i , where τ_i is a real value. If d_i is a proposition, then it indicates that the truth value of proposition d_i is β_i . The token in a place p_i is represented by a labeled dot τ_i . In addition, the following may be stipulated.

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$$\alpha : P \rightarrow [0,1]$$

$$\beta : P \rightarrow D$$

$$\begin{aligned}
 & A \subseteq P \times T \cup T \times P \\
 & p_j \in I(t_i) \quad a_{ji} \in A \\
 & p_k \in O(t_i) \quad t_i \\
 & f(t_i) = \mu_i, \mu_i \in [0,1] \quad t_i \\
 & \beta(p_i) = d_i \quad d_i \in D \quad p_i \\
 & \alpha(p_i) = y_i, y_i \in [0,1] \quad \alpha(p_i) \in [0,1] \\
 & \beta(p_i) = d_i \quad d_i \\
 & \alpha(p_i) = \frac{d_i \cdot y_i}{\alpha(p_i)} \quad p_i
 \end{aligned}$$

- 1) If p_i is a starting place, and then $\beta(p_i) = d_i, \alpha(p_i) = y_i (y_i \in [0,1])$ is a truth value of the proposition .
- 2) If y_i is a middle place, $\alpha(p_i) = \frac{d_i \cdot y_i}{\alpha(p_i)}$ may be selected according to some special requirement, and thus $\alpha(p_i) = \frac{f_\alpha(x)}{\alpha(p_i)}$. In this paper, a kind of Gauss function $f_\alpha(x) = e^{-1.5(x-1)^2}$ is employed.
- 3) For a transition t_k , if $p_i \in O(t_k)$, and the number of $p_i \in I(t_k)$ is more than 1, then the input value α_{in} of $f(x)$ is the product of all $\alpha(p_j)$, and $\alpha(p_i) = \prod_{j \in I(t_k)} \alpha(p_j)$.
- 4) If p_i is a terminal place, and $p_i \in O(t_k)$, then $y_i = \alpha(p_i) = \max(\alpha_{tk \cdot p_i} \cdot \mu_k)$, where $t' \in I(p_i)$, and $\alpha_{tk \cdot prod} = \prod_{i=1}^N \alpha(p_{ji}), \forall p_{ji} \in I(t_k), N \in \mathbb{Z}$.

B. Graphical Model of Petri Nets

The graphical model of Petri nets consists of nodes and arcs which represent different physical concepts. The node set is composed of two independent subsets, place set $P = \{p_1, p_2, \dots, p_n\}$, and transition set $T = \{t_1, t_2, \dots, t_m\}$. Each node corresponds with only one place element p_i or transition element t_j , and the place node is represented by a circle "O"; the transition node is represented by a bar "I" or "—". Two different kinds of weighted directional arcs are included in arc set, which are named as the subset of input arcs and the one of output arcs. The input arc is the directional one from place node to transition node and the output arc is the one from transition to place. The token number of each place is marked by a figure or the number of dots in each place icon (a circle), which may not only represent a certain material resource but also denote some corresponding information resource [12]–[14]. The arc weight is marked with a figure and its default value is one.

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Here a simple FPN model is shown in Fig. 1, which models the tripping process of protective relays and circuit breakers when some faults occur in a system element. It may be assumed that $\alpha(N) = y_N$ is initially given, and the threshold of each

place is λ , and μ_1, μ_2 is the CF value of transition t_1, t_2 , respectively. And each place (N, R, CB) associates with its corresponding proposition, d_N, d_R , and d_{CB} separately. The reasoning rules are as follows.

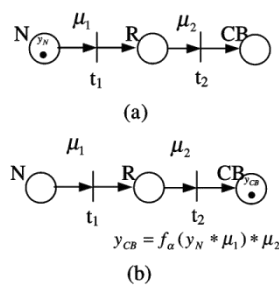


Fig. 1. FPN model of protective relay operation.

- 1) If d_N , then $d_R(CF = \mu_1)$.
- 2) If d_R , then $d_{CB}(CF = \mu_2)$.

It is obvious that the reasoning procedure based on the above rules is consistent with the tripping reasoning process of protec-

tive relays and circuit breakers. As is shown in Fig. 1, if $y_N \geq \lambda$,

then t_1 is fired, and the truth value of R is $\alpha(R) = f(y_N, \mu_1)$;
if $\alpha(R) \geq \lambda$, then t_2 is fired, and $y_{CB} = f(y_N, \mu_1) * \mu_2$.

C. Fuzzy Reasoning

Generally speaking, the fuzzy reasoning depends on the fuzzy rule set

$$R = \{R_1, R_2, \dots, R_n\} \quad (2)$$

and

$$R_i : \text{If } d_j \text{ Then } d_k (CF = \mu_i), \quad (i = 1, 2, \dots, n) \quad (3)$$

where, 1) d_j and d_k are propositions that include fuzzy variables, such as: "high", "low" and "hot", etc., the truth value of each proposition is a real value between 0 and 1. 2) $\mu_i \in [0, 1]$ is the certainty factor (CF) of R_i , which indicates the reliability of R_i .

As a matter of fact, the fuzzy reasoning with FPN is carried out based on the certainty factor of fuzzy rules. Let $\lambda \in [0, 1]$ be the threshold, and if the truth value of proposition d_j is $y_j \in [0, 1]$, then:

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Case 1) if $y_j \geq \lambda$ then R_i can be fired, and the truth value of proposition $d_k = y_j \cdot \mu_i$.

Case 2) if $y_j \leq \lambda$ then R_i cannot be fired.

In this paper, the value of λ is assumed to be 0.05.

In practical applications, a lots of rules are of composite ones in which some predicates, such as “and” or/and “or”, are in-cluded. Here several typical examples are shown as follows.

- 1) If d_{j1} and d_{j2} and ... and d_{jn} , then d_k (CF = μ_i).
- 2) If d_j , then d_{k1} and d_{k2} and ... and d_{kn} (CF = μ_i).
- 3) If d_{j1} or d_{j2} or ... or d_{jn} , then d_k (CF = μ_i).
- 4) If d_j , then d_{k1} or d_{k2} or ... or d_{kn} (CF = μ_i).

The effective reasoning strategies and the corresponding al-gorithms based on FPN are addressed in [15]. Fig. 2 shows a

model of fault diagnosis of L_1 with FPN, which is the sub-model of the global model illustrated in Fig. 4(a). It is assumed

that $\mu(_) = 0.95$ and the initial truth value of propositions on

L_{1Sm} , L_{1Rm} , CB_7 , and CB_{11} is 0.9, 0.9, 0.95, and 0.95, respec-

tively. According to the initial marks shown in Fig. 2, the propo-sitions corresponding to four places, protective relays (L_{1Sm}

and L_{1Rm}) and circuit breakers (CB_7 and CB_{11}), are tenable

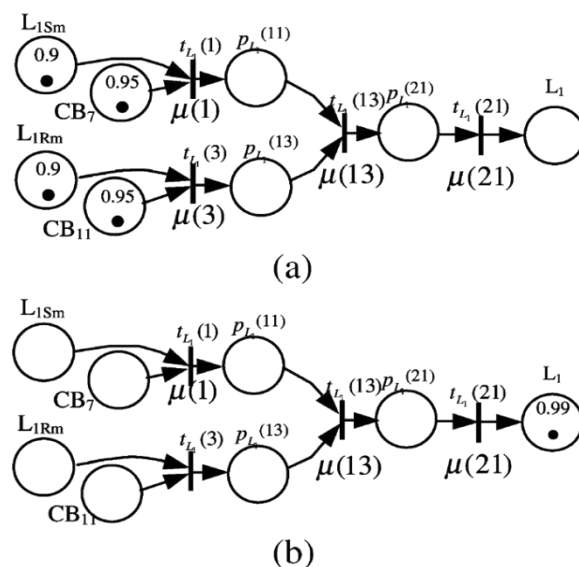


Fig. 2. Fault diagnosis submodel of line L_1 based on FPN.

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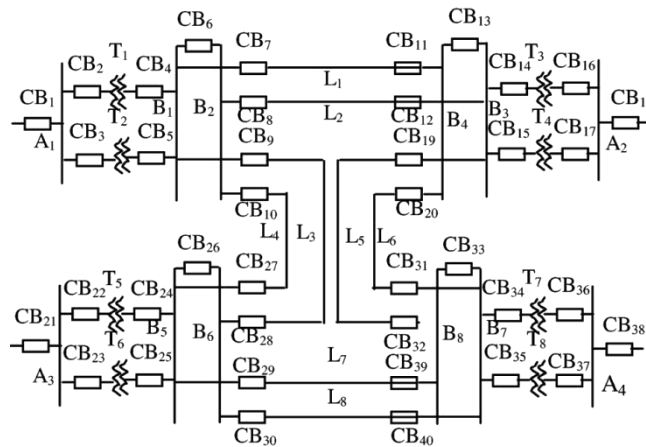


Fig. 3. Diagram of protection in part of an EPS.

and the truth values of these propositions are fuzzy values of corresponding system elements actions.

$$\begin{aligned} \text{Let } \beta(L_{1Sm}) &= d_{L_{1S}}, \beta(L_{1Rm}) = d_{L_{1R}}, \beta(L_{CB7}) = \\ d_{CB7}, \beta(L_{CB11}) &= d_{CB11}, \beta(p_{L1}(11)) = d_{p11}, \beta(p_{L1}(13)) = \\ d_{p13}, \beta(p_{L1}(21)) &= d_{p21}, \beta(L_1) = d_{L_1}. \end{aligned}$$

Thus, four fuzzy rules relevant to Fig. 2 may be given as follows.

- Case 1) If $d_{L_{1S}}$ and d_{CB7} , then d_{p11} .
- Case 2) If $d_{L_{1R}}$ and d_{CB11} , then d_{p13} .
- Case 3) If d_{p11} and d_{p13} , then d_{p21} .
- Case 4) If d_{p21} , then d_{L_1} .

As to the first three rules, considering the function of the

predicate “and”, and let $f(x) = e^{-1.5(x-1)}$ thus the final reasoning result is shown in Fig. 2(b). The whole calculation process is as follows. First, let the initial truth value of propositions, L_{1Sm} , L_{1Rm} , $CB7$, and $CB11$, be 0.9, 0.9, 0.95, and 0.95, respectively, then $\alpha(p_{L1}(11))$ and $\alpha(p_{L1}(13))$ have the same

$$\begin{aligned} \text{value as } f(0.9 \cdot 0.95 \cdot 0.95) &= 0.948, \text{ therefore, } \alpha(p_{L1}(21)) = \\ f_{\alpha}(0.948 \cdot 0.948 \cdot 0.95) &= f_{\alpha}(0.968 \cdot 0.95) \\ &= 0.968, \text{ finally, } \alpha(L_1) = 0.99 \text{ may be obtained.} \end{aligned}$$

It is obvious that the firing process of Petri nets is consistent with the mechanism of actions of relays. Thus, the fault diagnosis model of EPS based on FPN is feasible through detecting the tripping information of protective relays and circuit breakers.

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III. THE FAULT DIAGNOSIS MODEL BASED ON FPN

As is shown in Fig. 3 from [2], a local sketch map of operational principle and protection configuration of protective relay system of an EPS is given, in which 28 system elements, 84 protective relays, and 40 circuit breakers are included.

In Fig. 3, 28 system elements ($S_1 - S_{28}$) may be listed as: $A_1, \dots, A_4; T_1, \dots, T_8; B_1, \dots, B_8; L_1, \dots, L_8$; and 40 circuit breakers (C_1, \dots, C_{40}) are in turn as: $CB_1, CB_2, \dots, CB_{40}$; for the 84 protective relays, in which 36 main protective relays (r_1, \dots, r_{36}) may be enumerated as $A_{1m}, \dots, A_{4m}; T_{1m}, \dots, T_{8m}; B_{1m}, \dots, B_{8m}; L_{1Sm}, L_{1Rm}, \dots, L_{8Sm}, L_{8Rm}$; and 48 backup protections ($R_{37} - R_{84}$) are in turn as: $T_{1p}, \dots, T_{8p}; T_{1s}, \dots, T_{8s}; L_{1Sp}, L_{1Rp}, \dots, L_{8Sp}, L_{8Rp}; L_{1Ss}, L_{1Rs}, \dots, L_{8Ss}, L_{8Rs}$. It should be

indicated that in the above, A, B, T, and L represent single bus, double bus, transformer and line, respectively; as to line L , its subscript, S or R, represent the sending and receiving terminals; and another type of subscript m, p, and s represents main, primary backup, and second backup protective relays separately.

Normally, the protective relay system consists of main protective relays (MPRs) and some backup protective relays (BPRs) in power systems. The detailed operational rules can be seen in [2], [4]. But in practice, the tripping of protective relays is affected by various uncertain factors, and the alarm information from system is also incomplete. Therefore, it is difficult to diagnose faults effectively by ordinary reasoning tools, so that some new methods and tools should be employed to overcome difficulties and improve the diagnosis accuracy. In this paper, FPN are introduced as a type of modeling tool and reasoning mechanism to carry out the fault diagnosis of EPS, which is provided with the strongpoint of synthetic integration of Petri nets with fuzzy logic in both the modeling and reasoning of fault diagnosis. Thus the fault diagnosis model based on Petri nets with FPN is studied in depth as follows.

A. The Fault Diagnosis Model

The FPN may be expressed by a bijective graph, in which there are two kinds of nodes: places and transitions. Some places may contain a token marked with a truth value between 0 and 1, and some places may not, which are the same as the ones in ordinary Petri nets. Each transition associates with a certainty factor between 0 and 1. The relationship either from a place to

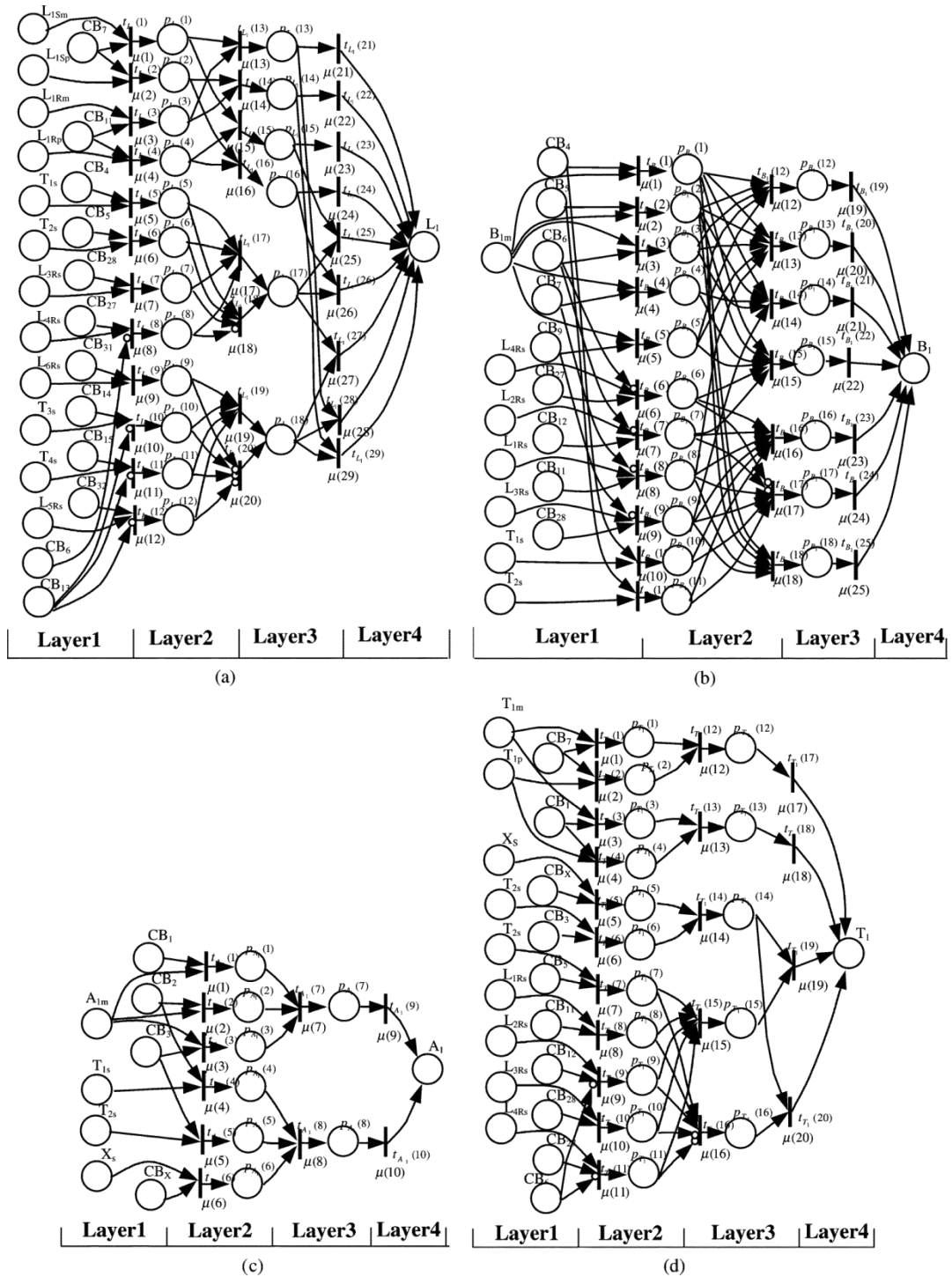


Fig. 4. Fault diagnosis models based on FPN. (a) Line L₁. (b) Bus B₁. (c) Bus A₁. (d) Transformer T₁.

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a transition or from a transition to a place is represented by a directional arc. Combined with the practical background of EPS, the P elements, viz. places, of FPN model consist of transmission lines, transformers, buses, protective relays, circuit breakers, and the corresponding transitional places. The T elements, viz. transitions, are composed of fault transition and action marks.

In this section, a FPN model of fault diagnosis is given as Fig. 4, which corresponds to line L₁, bus B₁, bus A₁ and transformer T₁ in Fig. 3. Models for other 24 system elements shown in Fig. 3 can be built in the same way. The outstanding characteristics of such FPN models lies in the organic integration of the concurrent structure of Petri nets and fuzzy reasoning knowledge from expertise experiences.

There are three subsets of nodes in this model: in the first one, S₁, transmission lines, transformers and buses are included; and protective relays in the second one, S₂; and circuit breakers are in the third one, S₃. As is shown in Fig. 4 that arrowed lines represent the causality of mutual operation among relays and circuit breakers when some faults occur. The truth value of each place describes uncertainty of operation of protective relays and circuit breakers, and the setting of initial truth value of starting places is given by users. The rules are explained as follows. The uncertainty of operation of protective relays and circuit breakers is represented by means of the truth value in places, and the magnitude of initial tokens in starting places are set according to the priority of the tripping of protective relays and corresponding circuit breakers when some faults occur. In normal situation, the possibility of tripping main protective relays is higher than that of backup protective relays, and the possibility of tripping the primary backup protective relays is higher than that of the second backup protective relays. Considering the reliability of protective relays let the initial truth value of main protective relays be 0.9 because they are the most prominent and immediate protections. And let the initial truth value of the primary backup protective relays and the second backup protective relays be 0.8 and 0.7, respectively. The initial truth value of circuit breakers is assumed to be higher 0.05 than that of the corresponding protective relays because circuit breakers are generally behave with higher reliability than protective relays. In Fig. 4, the initial truth value of places in Layer 1 are set according to above rules, and the initial truth values of places in Layer 2, Layer 3, and Layer 4 are assigned to be 0 [16].

In Fig. 4, X_s and CB_x represent the second backup protective relays and circuit breakers that are not shown in the left part of bus A₁ in Fig. 3. It is assumed that both the second backup protective relays and the circuit breakers should work appropriately. Although the action rules of protective relays and circuit breakers given in Fig. 3 may not be well consistent with the practice, based on which an illustrative example can be given to demonstrate the principle and feasibility of the method proposed in this paper.

B. Logic Testification

1) *Fault Diagnosis With Uncertain Information*: As a diagnostic modeling tool based on FPN, its reasoning mechanism of decision-making can be demonstrated by an example as follows.

Example 1: If operated protective relay L₁S_{L1Rm}, and tripped circuit breakers CB₇CB₁₁, are detected, due to the action information of L₁S_{L1Rm}CB₇CB₁₁, and the truth

values are the initial token of corresponding places, which are set as 0.8, 0.9, 0.85, and 0.95, respectively, and the initial truth value of other middle transiting places and terminal places are 0, from the definition 1 and it can be seen that the truth values

on L₁S_{L1Rm}CB₇, and CB₁₁ are all bigger than $\lambda (=0.05)$, so $t_{L_1(2)}$ and $t_{L_3(3)}$ are fired, and the CF value of these transitions are 0.95. Therefore, the truth value of $p_{L_2(2)}$ and $p_{L_1(1)}$

(3) are $f(0.8, 0.85, 0.95) = 0.829 > \lambda$ and $f(0.9, 0.95, 0.95) = 0.948 > \lambda$, respectively. And then $t_{L_1(14)}$ is fired,

and the truth value of $p_{L_1(14)}$ is $f(0.829, 0.948, 0.95)$

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0.908 > λ. Thus, $t_L(22)$ is fired, and the truth value of L_1

is $f(0.908, 0.95) = 0.972$. In the end, the final value is decided by $\max(0.972, 0, 0, 0, 0, 0, 0, 0) = 0.972$. Therefore,

it is testified that some faults has occurred on line L_1 , and the truth value is 0.972. This reasoning procedure can be understood through Fig. 4(a).

Example 2: If operated protective relay B_{1m}, L_{2Rs} , and L_{4Rs} , and tripped circuit breakers $CB_4, CB_5, CB_7, CB_9, CB_{12}$, and CB_{27} , are detected, due to the action information of $B_{1m}, L_{2Rs}, L_{4Rs}, CB_4, CB_5, CB_7, CB_9, CB_{12}$, and CB_{27} ,

and the truth values are the initial token of corresponding places, which are set as 0.9, 0.7, 0.7, 0.95, 0.95, 0.95, 0.95, 0.75, and 0.75, respectively, and the initial truth value

of other middle transiting places and terminal places are

0, from the definition 1 and it can be seen that the truth

values on $B_{1m}, L_{2Rs}, L_{4Rs}, CB_4, CB_5, CB_7, CB_9, CB_{12}$, , ,

and CB_{27} are all bigger than $\lambda(=0.05)$, so $t_{B_1}(1), t_{B_1}(2), t_{B_1}(4), t_{B_1}(5), t_{B_1}(6)$, and $t_{B_1}(7)$ are

fired, and the CF value of these transitions are 0.95.

Therefore, $p_{B_1}(1), p_{B_1}(2), p_{B_1}(4)$, and $p_{B_1}(5)$ all have the same truth value, $f_\alpha(0.9 \cdot 0.95 \cdot 0.95) = 0.948 > \lambda$. And $p_{B_1}(6)$ and $p_{B_1}(7)$ both have the same truth value, $f_\alpha(0.7 \cdot 0.75 \cdot 0.95) = 0.686 > \lambda$. Then $t_{B_1}(15)$ is fired, and the truth value of $p_{B_1}(15)$ is $f_\alpha(0.948 \cdot 0.948 \cdot 0.948 \cdot 0.948 \cdot 0.686 \cdot 0.686 \cdot 0.95) = 0.542 > \lambda$. Thus $t_{B_1}(22)$ is fired, and the truth value of B_1 is $f_\alpha(0.542 \cdot 0.95) = 0.703$. In the end, the final value is decided by $\max(0, 0.857, 0, 0, 0, 0, 0, 0) = 0.703$. Therefore, it is testified that some faults have occurred on line B_1 , and

the truth value is 0.703. This reasoning procedure can be understood through Fig. 4(b).

2) *Fault Diagnosis With Incomplete and Uncertain Information:* Similarly, this model can also be used to diagnose “mal-function” and “false alarm” at the same time.

L_{1Rp}

For instance, in the first example above, if the protective relay is detected to have acted simultaneously (protective relay malfunction), then the initial truth value of place L_{1R} is $0.8 > \lambda$, and the initial truth value of corresponding circuit breaker is

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$0.85 > \lambda$. So in the reasoning process, $t_L(4)$ is also fired, then

the truth value of $p_{L_1}(4)$ is $0.829 > \lambda$. Successively, $t_{L_1}(16)$

is fired, and the truth value of $p_{L_1}(16)$ is $0.835 > \lambda$. There-

fore, $t_{L_1}(24)$ is fired, and another truth value of L_1 is 0.938, is

obtained. Finally, there are two values, 0.972 and 0.938, in L_1 . Due to the rule defined in definition of FPN, the result is the

maximal one of all values, that is to say, L_{1R} is malfunction or false alarm.

If a CB malfunctions, but its relative protective relays do not trip, then relative transition will not be fired, then there will not be able to obtain a result according to the reasoning of Petri nets. For example, in the first case above, if CB_4 is detected to have failed, but the relative protective relay T_{1s} is not detected to trip, so $t_L(5)$ is not fired, and the corresponding calculation is ended. It can be seen from the Fig. 4(a), if protective relay T_{1s} also malfunctioned, then $t_L(5)$ is fired, and in this situation, circuit breaker CB_3, CB_2, CB_7 , and protective relay

T_{2s}, L_{2Rs}, L_{2Rs} all malfunction at the same time, transition (17) will be fired. But this probability is low.

In addition, not only can these fault diagnosis models diagnose a single fault, but also it can deal with different cases of multiple faults (i.e., if two or more truth value of the system elements in S_i is not zero, then there are multiple faults occur

in system). In fact it is the outstanding features of Petri nets with which the multiple faults are concurrently diagnosed, so that the diagnosis speed can be accelerated.

Furthermore, under those situations when some tripping information of protective relays is not detected, the initial truth

values of these places are set as (L_{Pact}) (i.e., 0.1 to MPRs, 0.2 to the primary BPRs, 0.3 to the second BPRs). Therefore, in the first example, if the tripping of L_{1sp} is not detected, then its initial truth value is 0.2, and the truth value of $p_{L_1}(2)$ is $f_\alpha(0.2 \cdot 0.85 \cdot 0.95) = 0.3483 > \lambda$ and $p_{L_1}(3)$ is still $0.948 > \lambda$, hence $t_{L_1}(14)$ is fired, and the truth value of $p_{L_1}(14)$ is $f_\alpha(0.3483 \cdot 0.948 \cdot 0.95) = 0.4933 > \lambda$. Then $t_{L_1}(22)$ is fired, and the final truth value of L_1 is $f_\alpha(0.4933 \cdot 0.95) = 0.6547$. If the final value in L_1 is λ_{TH} is bigger than $\lambda_{TH} = 0.5$ (suppose

is selected as a threshold to judge whether a fault occur or not), then it can be judged that a fault occurred in L_1 . It is obvious that the threshold value, λ_{TH} , is a key factor to support the decision-making of fault diagnosis, which is generally determined based on some expertise experience and experiment records.

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IV. CASE SIMULATION

In order to testify the effectiveness of the methods presented by this paper, seven representative cases from [2], [4] are ex-tracted to carry out case simulations. The model and its diag-nosis analysis presented in this paper are simulated and testified by the data from [2], [4]. Because detailed logical reasoning pro-cesses have been illustrated in Section, the detail judge proce-dure will not given here. For example, **Example 1** is one situ-ation of the testification of case 2, and **Example 2** is just the testification of case 1 as well. The detail reasoning processes of other cases are similar to that of these examples. The diagnosis results of seven cases are shown as follows.

Case 1) **Detecting alarm information:**

Operated protective relays B_{1m}, L_{2Rs}, L_{4Rs} ,
and tripped circuit breakers $CB_4, CB_5, CB_7,$
 CB_9, CB_{12}, CB_{27} are detected.

Diagnosis results:

Bus B_1 is faulted, and its truth value is 0.703.

Case 2) **Detecting alarm information:**

Operated protective relays B_{1m}, L_{1Sp}, L_{1Rm} ,
and tripped circuit breakers $CB_4, CB_5, CB_6,$
 CB_7, CB_9, CB_{11} are detected.

Diagnosis results:

Bus B_1 and line L_1 are faulted, and their truth values are 0.967 and 0.972, respectively.

Case 3) **Detecting alarm information:**

Operated protective relays $B_{1m}, B_{2m}, L_{1Sm},$
 $L_{1Rp}, L_{2Sp}, L_{2Rm}$, and tripped circuit breakers
 $CB_4, CB_5, CB_6, CB_7, CB_8, CB_9, CB_{10}, CB_{11},$

CB_{12} are detected.

Diagnosis results:

Bus B_1 , bus B_2 , and line L_1 , line L_2 are faulted, and their truth values are 0.967, 0.985, 0.972, and 0.972, respectively.

Case 4) **Detecting alarm information:**

Operated protective relays T_3, L_7, L_{7R} , and tripped circuit breakers $CB_{14}, CB_{16}, CB_{29}, CB_{39}$ are detected.

Diagnosis results:

Transformer T_3 and line L_7 are faulted, and their truth values are 0.938 and 0.938, respectively.

Case 5) **Detecting alarm information:**

Operated protective relays T_5, T_6 , and tripped
circuit breakers $CB_{22}, CB_{23}, CB_{24}, CB_{25}$ are detected.

Diagnosis results:

Bus A_3 is faulted, and its truth values is 0.648.

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Case 6) Detecting alarm information:

Operated protective relays T_{7m} , T_{8p} , B_{7m} , B_{8m} ,

L_{5Sm} , L_{5Rp} , L_{6Ss} , L_{7Sp} , L_{7Rm} , L_{8Ss} , and tripped circuit breakers CB_{19} , CB_{20} , CB_{29} , CB_{30} , CB_{32} , CB_{33} , CB_{34} , CB_{35} , CB_{36} , CB_{37} , CB_{39} are detected.

Diagnosis results:

Line L_5 , line L_7 , bus B_7 , bus B_8 , transformer T_7 , transformer T_8 , L_8 are faulted, and their truth

values are 0.972, 0.972, 0.703, 0.985, 0.99, 0.938, and 0.693, respectively.

Case 7) Detecting alarm information:

Operated protective relays L_{1Sm} , L_{1Rp} , L_{2Sp} ,

L_{2Rp} , L_{7Sm} , L_{7Rp} , L_{8Sm} , L_{8Rp} , and tripped circuit breakers CB_7 , CB_8 , CB_{11} , CB_{12} , CB_{29}

CB_{30} , CB_{39} , CB_{40} are detected.

Diagnosis results:

Line L_1 , line L_2 , line L_7 , line L_8 are faulted, and their truth values 0.972, 0.938, 0.972, and 0.99, respectively.

The diagnosis results of these cases are completely the same as that of [2], and what is different is that truth values of all faulted system elements in each case are also given in this method, which not only show the diagnosis result but also the its reliability.

V. CONCLUSION

Although many methods are applied to the fault diagnosis of EPS, some current interests are mainly focused on how to deal with uncertainty and incompleteness of protective relays and circuit breakers that greatly influence the effect of fault diagnosis. Because fuzzy logical reasoning has its special ability to solve some difficult problems coupled with uncertain and fuzzy factors, and Petri nets characterizes the concurrent structure, parallel calculation, event modeling and visualization, therefore, a new type of modeling and diagnosis analysis method is presented by using Petri nets with fuzzy logic in this paper. The feasibility and effectiveness of this method is proved through the logical testifying and cases simulation. Meanwhile the merits of easy reasoning, fast diagnosing speed and strong practicability of fault diagnosis models based on FPN are also demonstrated in the paper.

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