

Fault Diagnosis for Power System Using Time Sequence Fuzzy Petri Net

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Abstract. In this paper, time sequence fuzzy petri net (TSFPN) is proposed to build power system fault diagnosis models. Firstly, on the basis of taking the influence of incomplete and uncertain relay protection alarm information on fault diagnosis into consideration, the structure of TSFPN and the fuzzy inference approach are proposed. Then, the time constraint characteristics of alarm information and the time sequence checking method are introduced. Finally, by several simulation examples, the fault tolerance and validity of the proposed method is testified, even in the situation with complex fault scenario.

Introduction

The fault diagnosis of power system is a process of identifying component failures by analyzing alarm information. At present, a series of artificial intelligence analysis methods have been applied to fault diagnosis field, such as expert system [1], artificial neural network [2], optimization algorithms [3], Bayesian networks [4], petri net [5], etc. In these methods, petri net has strong modeling ability for discrete event systems and can analyze the various processes of events accurately. Thus, petri net possesses abundant application values and has become a research hotspot.

However, in the face of uncertain alarm information of protective relays and circuit breakers, the diagnosis results of traditional petri net are often difficult to meet the requirements. As a result, the concept of fuzzy petri net is put forward. In [6], the authors use fuzzy petri net to build fault diagnosis models, and the malfunction components are judged according to the values of the component places. In [7], the authors propose a method based on directional weighted fuzzy petri net, which builds models in every possible fault spread direction of bus or line. The weights of transition input arcs and output arcs are modified in [8]. In [9], incidence matrix is used to describe time sequence characteristics of alarm information. In [10], a time constraint checking method is introduced, and the results show that the method can improve the accuracy of fault diagnosis in some degree.

Under the above background, a power system fault diagnosis method based on time sequence fuzzy petri net (TSFPN) is proposed in this paper. The adverse influence of incomplete and uncertain alarm information on fault diagnosis is effectively relieved by the establishment of TSFPN model. In addition, through making full use of the time constraints of protective relays and circuit breakers, inconsistent time sequence information can be removed. At last, the fault tolerance and validity of proposed method is testified by several simulation examples.

Basic Concepts of TSFPN

Definition. TSFPN can be defined by a 6-tuple set:

$$\text{TSFPN} = \{P, T, I, O, \theta, T_i\}. \quad (1)$$

Where $P=\{p_1, p_2, \dots, p_n\}$ is a finite set of places, and n is the number of places; $T=\{t_1, t_2, \dots, t_m\}$ is a finite set of transitions, and m is the number of transitions; $I: P \rightarrow T$ is a mapping from places to transitions, $I=[\omega_{ij}]$, if there is a directed arc from p_i to t_j , ω_{ij} is the weight of the arc, otherwise $\omega_{ij}=0$; $O: T \rightarrow P$ is a mapping from transitions to places, $O=[\mu_{ij}]$, if there is a directed arc from t_i to p_j , μ_{ij} is the confidence coefficient of the arc, otherwise $\mu_{ij}=0$; $\theta=[\theta_1, \theta_2, \dots, \theta_n]$ is the confidence coefficient matrix of places, θ_i is the probability that the action state of place p_i is true; $T_i=\{T_1, T_2, \dots, T_k\}$ is an operation time set of alarm information, and k is the number of alarm information.

Diagrams. Simple power system is shown in Fig.1, which includes 4 buses ($B_1 - B_4$), 3 lines (L_1-L_3) and 6 circuit breakers ($CB_1 - CB_6$).

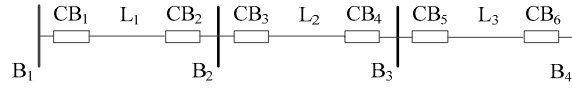


Fig.1 Simple power system

According to the principles of relay protection devices and basic rules of fuzzy inference [6], the TSFPN model of bus B_2 is designed and shown in Fig.2, where p_1 and p_2 are middle places, R is the receive end of line, S is the send end of line, m is the main protection and s is the secondary backup protection.

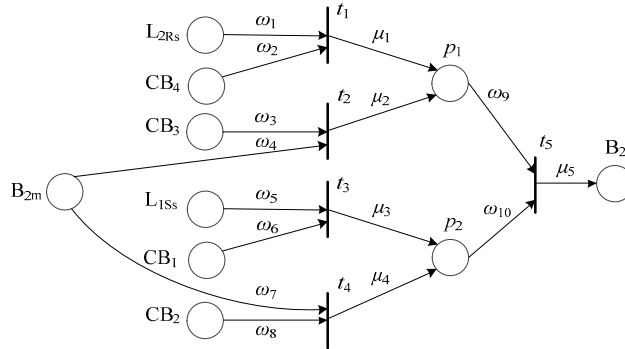


Fig.2 Structure diagram of TSFPN

The structure diagram of TSFPN proposed in this paper contains a combined fuzzy reasoning rule and gives full consideration to the uncertainty of alarm information. In addition, the scale of petri net can be reduced effectively and the calculation speed can be improved.

Inference analysis. In order to make the diagnosis process more clear, the inference of TSFPN adopts the way of matrix manipulation [11]. Let A is $(q \times l)$ -dimensional matrix, B is $(l \times h)$ -dimensional matrix and C is $(q \times h)$ -dimensional matrix.

1) Matrix multiplication \bullet , if $C=A \bullet B$, $c_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \dots + a_{il}b_{lj}$;

2) Multiplication operator \otimes , if $C=A \otimes B$, $c_{ij} = \max_{1 \leq j \leq l} (a_{ij}b_{ij})$.

According to the fuzzy rules and operators, the reasoning process of TSFPN is shown as follows.

$$E^{k+1} = \theta^k \bullet I. \quad (2)$$

Where E^{k+1} is m -dimensional matrix which the element is input probability of transition, k is the number of inference and the initial value is 0.

$$\theta^{k+1} = E^{k+1} \otimes O. \quad (3)$$

Where θ^{k+1} is the confidence coefficient matrix of places after the inference. If only one element in θ^{k+1} is not zero, the inference is over, otherwise let $k=k+1$ and calculate θ^{k+1} again.

Time characteristics of alarm information

Time constraints. Although power system relay protection devices have fixed setting time, the actual operation time of protective relays and circuit breakers cannot be determined accurately. The time constraint characteristics of alarm message are shown in Fig.3.

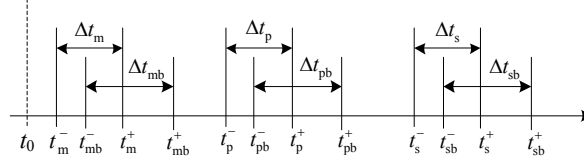


Fig.3 Time constraint characteristics

In Fig.3, t_0 is the time when fault happens, Δt_m , Δt_p and Δt_s are the time constraint intervals of the main protection, primary backup protection and secondary backup protection, Δt_{mb} , Δt_{pb} and Δt_{sb} are the time constraint intervals of the circuit breakers respectively related to main protection, primary backup protection and secondary backup protection, t_m^- and t_m^+ are the minimum and maximum operation time of main protection.

According to the literatures [11, 12], from the moment of component faults, define the delay intervals of main protection, circuit breaker related to main protection, primary backup protection, circuit breaker related to primary backup protection, secondary backup protection and circuit breaker related to secondary backup protection are [10, 40], [30, 80], [300, 500], [320, 540], [600, 1100] and [620, 1140], where the unit is ms.

Time sequence examination. For the convenience of description, the operation time of main protection, circuit breaker related to main protection, primary backup protection, circuit breaker related to primary backup protection, secondary backup protection and circuit breaker related to secondary backup protection is T_1 - T_6 . According to the occurring sequence of relay protection devices, priority level is formulated, namely the level of main protection is highest. Combined with the operation time, time sequence examination of alarm message can be carried out.

This paper uses the first alarm information as a benchmark at first, then check the other alarm information one by one to judge whether the information meet time constraints. If this alarm information exists, the first alarm information can be used as a reference to screen inconsistent time sequence information. On the other hand, if most information does not meet time constraints, the next information is adopted as a benchmark. Then, repeat the above process until find the reference information. The time constraint conditions of alarm information are shown in Table 1.

Table 1 Time constraint conditions

Time	T_1	T_2	T_3	T_4	T_5
T_1	—	—	—	—	—
T_2	[20,40]	—	—	—	—
T_3	[290,460]	[270,420]	—	—	—
T_4	[310,500]	[290,460]	[20,40]	—	—
T_5	[590,1060]	[570,1020]	[300,600]	[280,560]	—
T_6	[610,1100]	[590,1060]	[320,640]	[300,600]	[20,40]

In Table 1, — means that the order of events does not meet time constraints, and the meaning of bold cell is that if the main protection operates at time T_1 , the circuit breaker related to main protection must trip at time T_2 after 20-40ms.

Power system fault diagnosis based on TSFPN

Process of fault diagnosis. In this paper, the process of power system fault diagnosis based on TSFPN is divided into the following steps:

- 1) Use the method of network topology analysis to search fault areas and acquire suspicious fault components;
- 2) Build the TSFPN models of suspicious fault components;
- 3) Check time sequence of alarm information and get rid of the inconsistent information, then set the initial confidence coefficient of all places;

- 4) Utilize the TSFPN model to carry out fuzzy rational analysis and get the final confidence coefficients of suspicious fault components, then judge the real fault components and the operation situation of relay protection devices.

As is shown in Fig.4, IEEE 30-bus system is used to specify the modeling and reasoning process. In the system, L_{4-12m} , L_{4-12p} , L_{4-12s} and CB_{4-12} represent the main protection, primary backup protection, secondary backup protection and circuit breaker of the side of line L_{4-12} which closes to bus B_4 . L_{12-4m} , L_{12-4p} , L_{12-4s} and CB_{12-4} represent the main protection, primary backup protection, secondary backup protection and circuit breaker of the side of line L_{4-12} which closes to bus B_{12} . B_{4m} represents the main protection of bus B_4 .

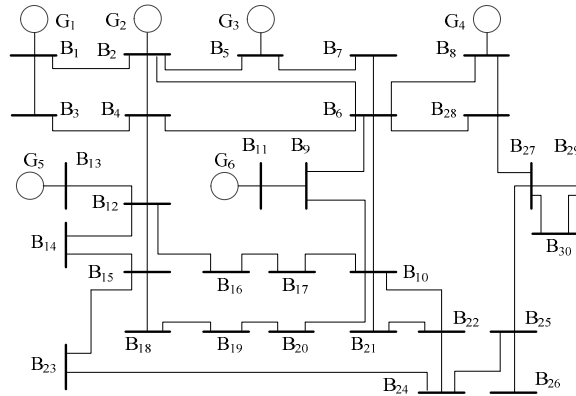


Fig.4 IEEE 30-bus system

Assume that the dispatch center has collected following alarm message: protection B_{24m} (20ms) and L_{22-24s} (750ms) operate, circuit breakers CB_{24-23} (50ms), CB_{24-25} (53ms) and CB_{22-24} (780ms) trip.

Up to now, the method of network topology analysis [13] has been widely used in quick search field, and the related theory has been relatively mature. Based on the above alarm information, this paper adopts the method of network topology analysis and the suspicious fault components are bus B_{24} and line L_{22-24} .

TSFPN models. Take all expected alarm information related to component into consideration and combine fuzzy inference rules mentioned in above section, the TSFPN models of bus B_{24} and line L_{22-24} are shown in Fig.5 and Fig.6.

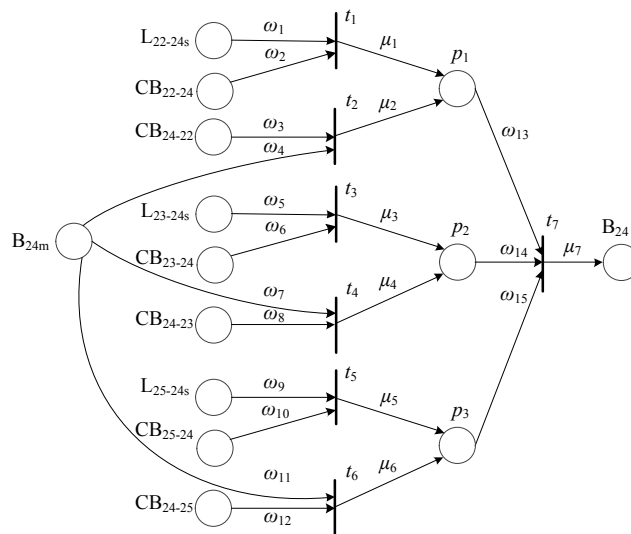


Fig.5 TSFPN model of bus B_{24}

Alarm information screening. In this section, the time constraint conditions are used to examine time sequences of all alarm information.

For bus B₂₄, set the operation time of main protection B_{24m} as a benchmark, so the time intervals between CB₂₄₋₂₃, CB₂₄₋₂₅, L_{22-24s}, CB₂₂₋₂₄ and B_{24m} are 30ms, 33ms, 730ms and 760ms. It is not hard to find that all alarm information meets time constraints according to Table 1.

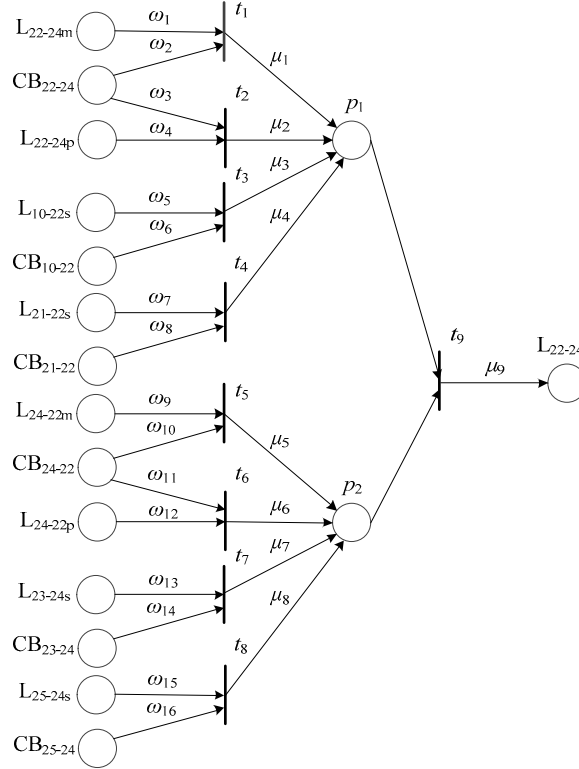


Fig.6 TSFPN model of line L₂₂₋₂₄

According to the research achievements of literature [9], for the alarm information which meets time constraints, set the confidence coefficients of main protection, primary backup protection and secondary backup protection are 0.9, 0.8 and 0.7, and the confidence coefficient of circuit breaker is 0.05 bigger than the related protection. On the other hand, for the other alarm information associated with component, set the confidence coefficients of protection and circuit breaker are 0.2.

Inference analysis. In order to improve the fault tolerance, the confidence coefficient of directed arc from transition to place is defined as 0.95, and all directed arcs from place to transition have the same weight, and the sum is 1 [7].

On the basis of the above principles of parameter settings, fault diagnosis can be carried out by using the analysis method mentioned in above section. As an example, bus B₂₄ is adopted to specify the process of fault diagnosis.

- 1) According to TSFPN model of bus B₂₄, matrices **I**, **O** and initial confidence coefficient matrix θ^0 can be acquired

$$I = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.33 & 0.33 & 0.33 & 0 \end{bmatrix}^T$$

$$O = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.95 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.95 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.95 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.95 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.95 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.95 \end{bmatrix}$$

$$\theta^0 = [0.7, 0.75, 0.2, 0.9, 0.2, 0.2, 0.95, 0.2, 0.2, 0.95, 0, 0, 0, 0]$$

- 2) Calculate the next state of places by using Eq. 2 and Eq. 3, then get $\theta^1 = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.6887, 0.8788, 0.8788, 0]$. At this time the confidence coefficients of middle places can be acquired, then do the calculation again, and get $\theta^2 = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.7669]$.
- 3) Because θ^2 only has one nonzero element, so the inference analysis is over, and the confidence coefficient of terminal place, namely the fault probability of bus B₂₄ is 0.7669.

Similarly, the fault probability of line L₂₂₋₂₄ is 0.3497. This paper fully takes the uncertainty of alarm information into consideration, and defines that if the confidence coefficient of terminal place is greater than 0.65, the corresponding component is faulted. Based on this, the fault component is bus B₂₄. Furthermore, the circuit breaker CB₂₄₋₂₂ refuses to trip, so secondary backup protection L_{22-24s} operates and triggers circuit breaker CB₂₂₋₂₄ after a certain time delay.

Case study

To better demonstrate the effectiveness of the fault diagnosis method proposed in this paper, IEEE 30-bus power system is still adopted. Three simulation examples are carried out, and the fault diagnosis results are shown as follows.

- 1) Simple fault diagnosis with complete information is studied. Suppose that protection B_{23m} (15ms) operates, circuit breakers CB₂₃₋₁₅ (41ms) and CB₂₃₋₂₄ (43ms) trip. Through the analysis of network topology, the suspicious fault component is bus B₂₃. In addition, all alarm information meet time constraints, so by fuzzy reasoning, the confidence coefficient of bus B₂₃ is 0.8348 and bigger than 0.65, which shows that bus B₂₃ is really faulted, furthermore, protective relays and circuit breakers operate rightly.
- 2) Simple fault diagnosis with uncertain alarm information is studied. Suppose that protection L_{19-20m} (23ms), L_{20-19m} (24ms), L_{19-20p} (340ms) and L_{18-19s} (670ms) operate, circuit breakers CB₂₀₋₁₉ (51ms), CB₁₉₋₂₀ (90ms) and CB₁₈₋₁₉ (695ms) trip. In this scenario, the suspicious fault components are line L₁₈₋₁₉ and line L₁₉₋₂₀. By checking the actual alarm information related to each suspicious component, only the information “CB₁₉₋₂₀(90ms) trips” does not meet time constraint. Then, the remaining information is used for fuzzy reasoning and the confidence coefficients of suspicious fault components are 0.4738 and 0.7446, so the actual fault component is line L₁₉₋₂₀. Through further analysis of actual alarm information, it is not hard to find that circuit breaker CB₁₉₋₂₀ refuses to trip. In addition, if this article does not introduce time sequence examination, it may get the wrong conclusion that L_{18-19s} and CB₁₈₋₁₉ mal-operate.
- 3) Complex fault diagnosis with uncertain and incomplete alarm information is studied. Suppose that protection L_{10-21m} (27ms), L_{21-10m} (28ms), B_{22m} (30ms) and L_{21-10p} (130ms) operate, circuit breakers CB₂₂₋₂₄ (53ms), CB₂₂₋₁₀ (54ms), CB₂₁₋₁₀ (59ms), CB₁₀₋₂₁ (60ms) and CB₂₁₋₂₂ (683ms) trip. The suspicious fault components are line L₁₀₋₂₁, bus B₂₁, line L₂₁₋₂₂ and bus B₂₂. By checking the actual alarm information, the information “L_{21-10p}(130ms) operates” related to line L₁₀₋₂₁ does not meet time constraint. Then by calculation, the confidence coefficients of all suspicious fault components are 0.8348, 0.5189, 0.3497 and 0.7148, so the result is that line L₁₀₋₂₁ and bus B₂₂ are all faulted. In addition, after main protection B_{22m} operates, circuit breaker CB₂₂₋₂₁ refuses to trip, so secondary backup protection operates and triggers the corresponding circuit breaker. But only circuit breaker CB₂₁₋₂₂ trips at 683 ms, and this information meets time constraint, so the information of secondary backup protection L_{21-22s} is missing.

The above simulation examples show that the fault diagnosis model and reasoning method can accurately judge the fault components and have a good application prospect.

Summary

This paper proposes a power system fault diagnosis method based on TSFPN which not only takes the influence of incomplete and uncertain alarm information on fault diagnosis into consideration, but also utilizes the time constraint characteristics of protective relays and circuit breakers to remove inconsistent time sequence information. Simulation results on IEEE 30-bus power system indicate that this method has high fault tolerance and can obtain satisfying results in the situation with complete, uncertain, inconsistent and missing information.

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