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Fault Diagnosis Research for Power System Based on Timing Constraint Fuzzy Directed Graph

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Abstract

By taking full use of the temporal information of alarm message for quick and accurate diagnosis is very important. This paper presents an effective method for fault diagnosis, based on the time constraint fuzzy directed graph (TCFDG), in order to solve the cases of incomplete alarm information. An improved recognition algorithm is proposed which can effectively recognize misreports, missing messages and timing inconsistencies etc. And false alarms are filtered to overcome the deficiencies of incomplete alarm information, and to provide protection for the precise positioning of faults. Then, a reasoning method based on TCFDG is proposed, and use min operator and multiplication operator to determine the fault source, and use incidence matrix reduction method, reducing the dimension of the matrix, improved operational efficiency. Finally, a typical power system compared with some other typical methods was shown for demonstrating the feasibility and efficiency of the proposed method.

Keywords*: Fault diagnosis, temporal information, directed graph, power system, incidence matrix reduction*

1. Introduction

Accurate and efficient fault diagnosis method has important implications for the rapid fault location, stable and safe operation of power grid and improve the reliability of power supply, which ensure livelihood and economic development. Modern power system fault diagnosis utilizing supervisory-control and data-acquisition systems to obtain the status of relays and the status of the circuit breakers, then using diagnostic methods to locate the fault sources.

In recent decades, various approaches have been proposed to address fault diagnosis problems for power systems. Of these approaches, expert systems[1-2]; artificial neural networks[3-4]; Petri nets[5-6]; optimization models[7]; Data Grid[8]; Cause-effect nets[9-12]; Bayesian networks[13] are the main methods. When obtaining the complete failure information, these methods can basically get satisfactory results [12]. However, when a fault occurs in the power systems, due to the protection switch error alert message caused information uncertainty is particularly evident. In addition, because of the impact of the degree of automation equipment and information transmission, the complete failure information is difficult to obtain. These limitations make the above methods exist some difficulties to identify the fault of large and complex systems. However, Alarm timestamps represent the temporal relationship among event occurrences and consist of rich and useful information for alarm processing. Therefore, taking full use of timing attributes of alert information has important significance for the study of intelligent diagnostic method.

In approaches [9-10], fault diagnosis method was proposed based on the analysis of causality for distribution substations. The key issue of the method is to use the logical relationship between equipment failure and relays, circuit breakers. And the author

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promote the application of paper [9] in paper [11], which proposed a fault diagnosis method based on the analysis of causality for transmission system. On this basis, an approach [12] based on the temporal Cause-Effect Net was proposed, which can effectively deal with misreports, missing messages etc., and can be used to explain the evolution of fault. The authors of [13] established a Bayesian network model which contains the timing attribute, to quantify the uncertainty information, proposed a recognition algorithm to identify the information timing consistency. In paper [14], the author proposed a method based on the fuzzy directed graph. Directed graph is used to represent the relationship between equipment devices and protective devices, and using fuzzy inference algorithm for fault diagnosis. The authors of [15] introduced the abductive reasoning into power grid diagnosis and alarm, the proposed algorithms can identify break alarms, exception alarms and missing alarms which can reduce the uncertainty of diagnosis results. The analysis of Petri Nets provides a good basic for fault diagnosis [16-18], the authors of [16] proposed a fault diagnosis method based on the fuzzy Petri nets to handle uncertain information of protection devices and circuit breakers. And the paper [17], a model of fuzzy hierarchical Petri Net with multi subnets was proposed to minify the scale of Petri net and improve both accuracy and adaptability of power system fault diagnosis. In [18], power system fault diagnosis approach based on fuzzy petri net in consideration of time sequence was proposed.

To summarize, there are still three major issues for power system fault diagnosis: (1) Excessive reliance on the information of the relays and circuit breakers' status obtained by the SCADA system, in the case of the alarm messages is not complete, the diagnostic system fault tolerance is not high. (2) Existing methods flawed: The structure of Petri nets is complex; Bayesian networks need sample training; Expert system rule base is difficult to build, and time complexity is high when query rules; It's urgent need for a simple and effective method for grid structural analysis; (3) With the grid structures complicated, time high time complexity, the troubleshooting procedures need for appropriate diagnostic optimization strategies to ensure real-time fault diagnosis. To deal with these three problems, this paper take full use of the timing attribute and the logical relationship between protection switch operation and circuit breakers, a power system fault diagnosis approach is proposed based on the Time Constraint Fuzzy Directed Graph(TCFDG), to solve the difficulties of incomplete alarm information, like misreports, missing messages and timing inconsistencies etc., improved the ability of fault tolerance, and using incidence matrix reduction method to improve the efficiency of diagnosis and ensure the online real-time diagnostics. The study includes the following three aspects:

(1) The time constraint method proposed in paper [17], when dealing with incomplete alarm information uploaded by the SCADA system, its recognition algorithm is based on the condition that the main protection relays information are true. Therefore, when the main relay alarm message is false, the recognition algorithm will fail. On this basis, this paper proposed a more general incomplete alarm information recognition algorithm, which can recognize the mistakes of main relays and other protection devices.

(2) Building the time constraint fuzzy directed graph model depend on the power grid structures, a certainty factor is introduced during the reasoning procedure, to express the degree of certainty of an event, which improved the accuracy of diagnostic. In calculate the confidence of the suspicious faulty components, all using matrix operations for inference analysis, which simples the calculation and fast.

(3) The reasoning procedure of fuzzy directed graph using matrix operations completed, for the large scale system will influence the dimensions of rule matrix, an incidence matrix reduction method is used to reduce the dimension of the matrix, improved the operational efficiency, ensure the online real-time fault diagnosis.

2. Alarm Information Recognition Method Based on Timing Constraints

2.1. The Timing Characteristics of Alert Information

The alarm messages have timing characteristics [17]. When a fault occurs at the device, the electrical quantities changed, then protection devices begin to operate, finally, corresponding circuit breaker tripped. This paper utilizing the logical relationship between protection switch operation and circuit breakers and their timing characteristics, create the appropriate timing rules to determine an alarm message is normal or not.

For local power system, the protection devices include the main protection relay, backup protective relay, and second backup relay. The delay of protection relay relative to fault is defined as follows:

(1) The delay of the main protection relay relative to fault is:

$$\Delta\tau_{mr} \in [\Delta\tau_{mr}^{min} , \Delta\tau_{mr}^{max}]$$

(2) The delay of the backup protective relay relative to fault is:

$$\Delta\tau_{pr} \in [\Delta\tau_{pr}^{min} , \Delta\tau_{pr}^{max}]$$

(3) The delay of the second backup protective relay relative to fault is:

$$\Delta\tau_{sr} \in [\Delta\tau_{sr}^{min} , \Delta\tau_{sr}^{max}]$$

And the delay of protection relay relative to circuit breaker is defined as follows:

(4) The delay of the circuit breaker relative to main protection relay is:

$$\Delta\tau_{mc} \in [\Delta\tau_{mc}^{min} , \Delta\tau_{mc}^{max}]$$

(5) The delay of the circuit breaker relative to backup protective relay is:

$$\Delta\tau_{pc} \in [\Delta\tau_{pc}^{min} , \Delta\tau_{pc}^{max}]$$

(6) The delay of the circuit breaker relative to second backup protective relay is:

$$\Delta\tau_{sr} \in [\Delta\tau_{sc}^{min} , \Delta\tau_{sc}^{max}]$$

2.2. Error Alert Message Classification

Due to the uncertainty of the protective devices' operation, some cases like malfunction, refuse would be appear in the power systems, and the alarm messages missed during transmission, these conditions may lead to fault diagnosis can't be completed. In a nutshell, error alarm information can be divided into the following three categories:

1. Missing message: such as the protection and switching conditions, missing in the collection and transmission.
2. Misreport/ Malfunction: when fault occurs, the protection devices or the circuit breakers generate error alarms.
3. Refusal: The operation of the circuit breaker fail to trip, which lead to the backup protective relay operate.

2.3. Timing Constraints Information Processing Method

Using δ $(t_1,t_2,t_a,t_b)$and δ^{+} (t_1,t_2,t_a,t_b) to represent the relationship of "earlier" and "later". t_1, t_2 represents the time when event1 and the event2 occurs, $[t_a, t_b]$ represents the time interval constraints. Two events represented by P_1 and P_2, and Event P occurs at time T is defined as $A_{ct}(T,P)$ .The description of reasoning defined as follows:

$$A_{ct}(t_1,p_1)\rightarrow A_{ct}(t_2,p_2),\ \delta^{-}(t_1,t_2,t_a,t_b)$$
$$A_{ct}(t_2,p_2)\rightarrow A_{ct}(t_1,p_1),\ \delta^{+}(t_1,t_2,t_a,t_b)$$

Above-mentioned description represents: event P_1 occurs earlier than event P_2, and the time constrains is $[t_a, t_b]$. Event P_2 occurs later than event P_1, and the time constrains is $[t_a, t_b]$.

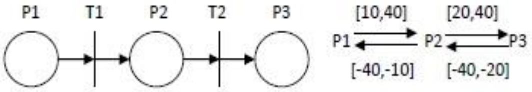

Figure 1. Description of Rules and Constraints

As the directed graph shown in Figure 1, supposed that the event P_1, P_2, P_3 occurs at t_1 、t_2、t_3, the relationship can be described as follows:

Forward:

$$A_{ct}(t_1,p_1)\rightarrow A_{ct}(t_2,p_2),\ \delta^{-}(t_1,t_2,10,40)$$
$$A_{ct}(t_2,p_2)\rightarrow A_{ct}(t_3,p_3),\ \delta^{-}(t_2,t_3,20,40)$$

Reverse:

$$A_{ct}(t_3,p_3)\rightarrow A_{ct}(t_2,p_2),\ \delta^{+}(t_2,t_3,20,40)$$
$$A_{ct}(t_2,p_2)\rightarrow A_{ct}(t_1,p_1),\ \delta^{+}(t_1,t_2,10,40)$$

For example: supposed that t_1=80ms, reverse reasoning on a directed graph, the steps shown as follows:

Step1: Due to $A_{ct}(t_3,p3)\rightarrow A_{ct}(t_2,p2),\ \delta^{+}(t_2,t_3,20,40)$, $t_2\in[40,60]$ can be got.

Step2: Depend on $A_{ct}(t_2,p2)\rightarrow A_{ct}(t_1,p1),\delta^{+}(t_1,t_2,10,40)$ and $t_2\in[40,60]$, $t_1\in[20,30]$can be obtained.

Step3: According to the time when P1 occurs can determine whether the timing consistent relationship meet or not.

2.4. Alert Messages Recognition Algorithm

First, the sets and variables involved in the recognition algorithm should be defined.

1) W_i represents an alarm message.
2) W_j represents W_i alarm information can be generated by W_j, and W_j is W_i' ancestors information.
3) W_k represents W_k alarm information can be generated by W_i, and W_k is W_i' descendant information.
4) S_E represents the alarm information set whose elements in logical contradiction relations with W_i, and the alert information was obtained by SCADA.
5) W_E represents a set includes S_E set and the descendant information of its elements.
6) W_O represents the W_i' descendant alarm information set.
7) P_A represents the index that accepted the alarm information W_i is missing or false information, its value is equal to the number of elements in W_E set, represented

by x.

8) P_R represents the index that refused the alarm information W_i is missing or false information, its value is equal to the number of elements in W_O set, represented by y.

2.4.1. Missing Information and Timing Inconsistent Recognition Algorithm

During the reasoning procedure based on TCFDG, if the alarm information W_i is not observed by SCADA, maybe the alarm information W_i is missing information. Identification procedure as follows:

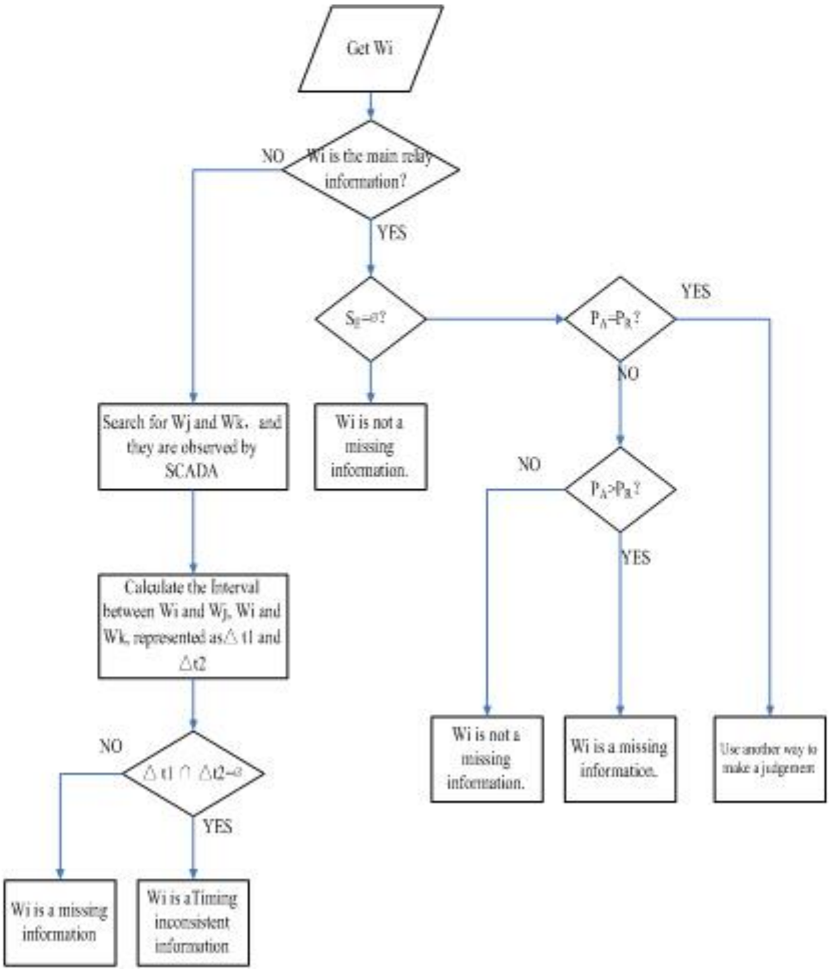

Figure 2. A Flowchart of Missing Information and Timing Inconsistent Recognition Algorithm

2.4.2. Misreport Information Recognition Algorithm

Identify whether W_i is a misreport information as follows:

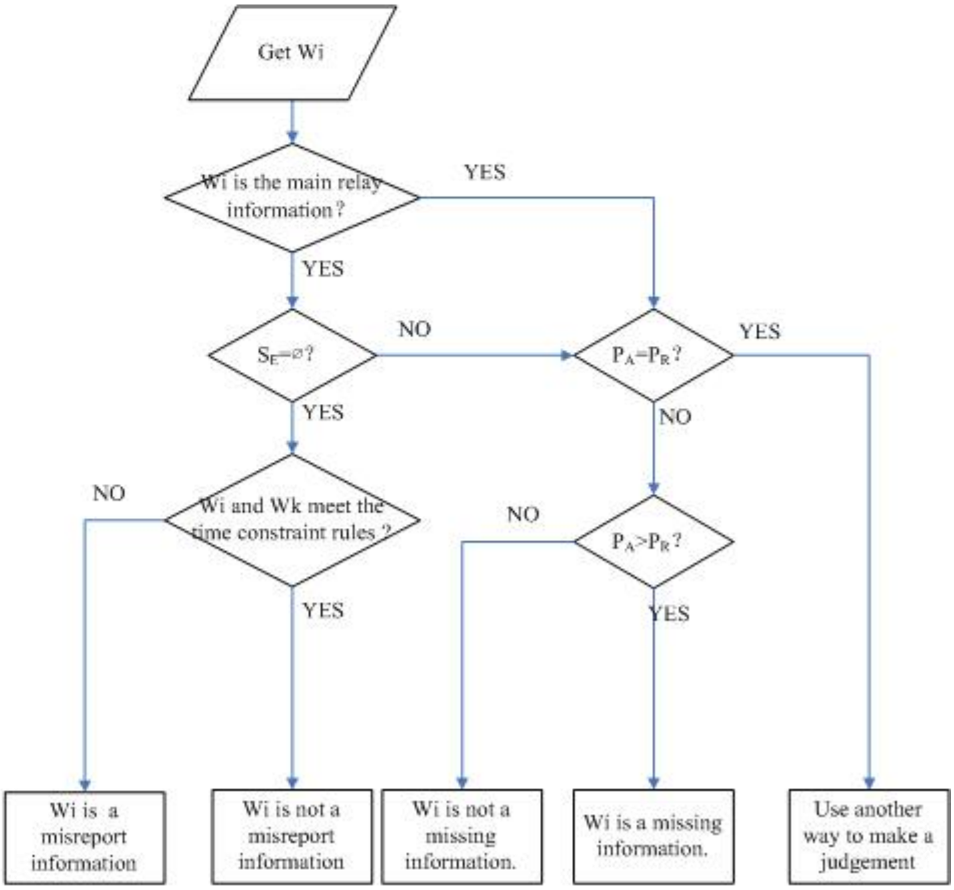

Figure 3. A Flowchart of Misreport Information Recognition Algorithm

3. Description of Fuzzy Directed Graph

3.1. The Definition of Directed Graph

Digraph is a graphical tool, constituted by nodes and directed arcs. The digraph model is useful for the representation of the logical relationship between fault devices, protection devices and circuit breakers. The representation of basic node-arc relationships is depicted in Figure 4. Figure 4(a) can be regarded as a fault section is protected by a relay. (b)The operation of a relay causes the tripping of a circuit breaker. (c) The tripping failure of a circuit breaker causes the operation of a backup relay.

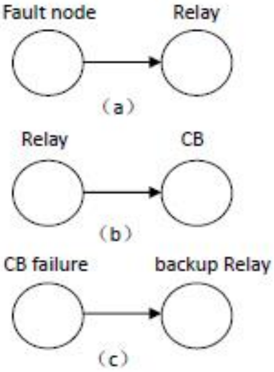

Figure 4. Basic Node-Arc Relationship

A simplified transmission system shown in Figure 5 is used to illustrate the concept of the digraph representation [14]. Supposed that a fault occurs at transmission line L, causes the main relay MLR1 and MLR2 operation, and then lead the circuit breakers CBs tripped. If MLR1 fail to trip CB1, the backup protective relay BLR1 will take over and trips CB1. Digraph model for fault section L is shown in Figure 6.

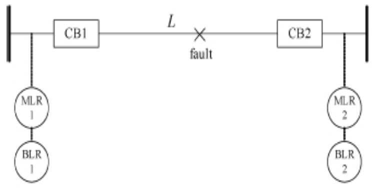

Figure 5. A Simplified Transmission System

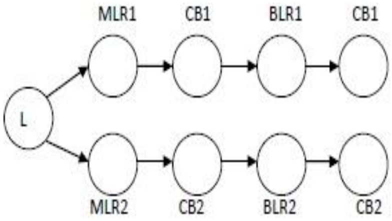

Figure 6. DG of the Transmission-Line L

The node-arc relationship can be described as an IF-THEN rule. For example, Figure 4(a) can be regarded as "IF (relay MLR1 operates) THEN (CB1 tripped)". However, in some situations such as incorrect setting or equipment malfunction, the CB1 cannot operate correctly. As such, to some extent, the classic digraph cannot handle with the problems with uncertainty. To deal with the problem, combine the fuzzy theory with directed graph, and create a model based on the fuzzy directed graph, to deal with the uncertainties.

3.2. Fuzzy Directed Graph

In order to fuzzy the logical relationship between nodes, a numerical value, called a certainty factor (CF), which is a real number between 0 and 1, is used to describe the degree of certainty of an event. The lager the value, the more reliable the event is.

CF is determined by the dispatchers' experience and historical statistics data. In this paper, the fuzzy set for the degree of "true" of the event can be characterized as [AT,ET,VT,T,FT,LT,MT,MMT,NT], each element represents the degree of certainty of an event. Table 1 lists the fuzzy set and their corresponding CF.

Table 1. Fuzzy Sets of "True" and Corresponding CF

Fuzzy Sets elements	CF
AT	1.0
ET	0.95
VT	0.8
T	0.7
FT	0.6
LT	0.3

MT	0.2
MMT	0.09
NT	0.0

The fuzzy reasoning rules are often to describe the relationship of two nodes. For example, supposed C_i and C_j are two nodes in FDG, the fuzzy rule can be represented as follows：

$$\text{IF } C_j \text{ THEN } C_i \ (CF=\mu_{ij}) \quad (1)$$

In equation (1), μ_{ij} is the value of the certainty factor, and $\mu_{ij} \in [0,1]$. As the node-arc relationship shown in Figure 5 [14], which can be represented as follows:

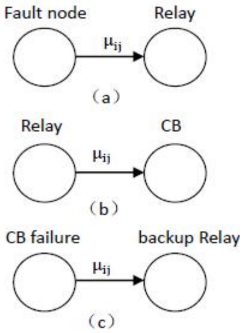

Figure 7. The Normal Relationship of Nodes in FDG

IF (a fault occurs at line L)
    THEN (relay MLR1 operates) (CF=0.95)
IF (relay MLR1operates)
    THEN (CB1 tripped) (CF=0.8)
IF (MLR1 operates and CB1 fails)
    THEN (BLR1 operates) (CF=0.95)
IF (MRL1 and BLR1 do not operate)
    THEN (CB1 tripped) (CF=0.3)

And the FDG model of the fault section line L is shown in Figure 8.

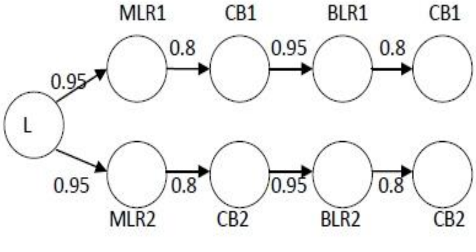

Figure 8. The FDG of Transmission-Line L

4. Fault Diagnosis Based On FTCDG Model

4.1. Create the TCFDG Model

Take the simplified transmission-line L which shown in Figure 5 as an example, and its' TCDFG model is shown in Figure 9.

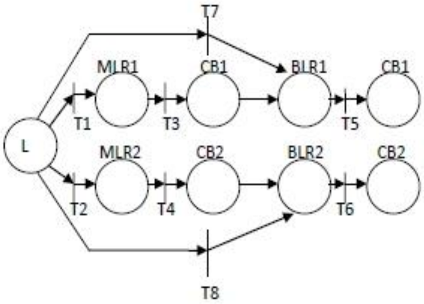

Figure 9. The TCFDG of Transmission-Line L

The specific time delay of protection relay relative to fault is defined as follows:

$$\Delta\tau_{mr} \in \left[\Delta\tau_{mr}^{min}, \Delta\tau_{mr}^{max}\right] = [10,40]$$
$$\Delta\tau_{pr} \in [\Delta\tau_{pr}^{min}, \Delta\tau_{pr}^{max}] = [510,540]$$
$$\Delta\tau_{sr} \in \left[\Delta\tau_{sr}^{min}, \Delta\tau_{sr}^{max}\right] = [1010,1040]$$

And the specific time delay of protection relay relative to circuit breaker is defined as follows:

$$\Delta\tau_{mc} \in \left[\Delta\tau_{mc}^{min}, \Delta\tau_{mc}^{max}\right] = [20,40]$$
$$\Delta\tau_{pc} \in [\Delta\tau_{pc}^{min}, \Delta\tau_{pc}^{max}] = [20,40]$$
$$\Delta\tau_{sr} \in \left[\Delta\tau_{sc}^{min}, \Delta\tau_{sc}^{max}\right] = [20,40]$$

As shown in Figure 9, the time constraint of T_1, T_2 is [10, 40], the time constraint of T_3, T_4, T_5, T_6 is [20, 40], the time constraint of T_7, T_8 is [510, 540].

4.2. The Reasoning Algorithm of CFDG

Prior to describing the reasoning algorithm, the related operators, vectors and matrixes are defined as follows.

(1) Correlation matrix (R): R is an n-by-n fuzzy rule matrix, and its diagonal elements are 1, n is the number of nodes in TCFDG model. The element R[i,j] is defined as:

$$R[i,j] = \begin{cases} \mu_{ij} & C_j \to C_i \\ 0 & \text{else} \end{cases} \quad (2)$$

If C_j is related to C_i and its confidence is μ_{ij}, then R[i, j] = μ_{ij}. Otherwise, the R[i, j] is set to zero.

(2) The Truth state Vector (T): Vector T is employed to represent the status of operating protective devices. If a node operates, in other words, received the node's alarm message, the statue of the node set to 1. Otherwise, the statue of the node set to zero. In paper [14], the paper do not deal with the error alarm messages, this paper using the alarm message recognition algorithm to recognize and analysis the misreport, missing message and timing inconsistent message, correct and filter the error alarm messages. If T[i] is the status of alarm message, the description of correction is defined as:

$$T[i] = \begin{cases} 1 & n_i \text{ missing} \\ 0 & n_i \text{ misreport/malfunction} \\ 0 & \text{refusal} \end{cases} \quad (3)$$

(3) Fault Section Vector (F): Vector F is defined to represent fault section nodes in the digraph. There are n elements included, and F[i] is defined as:

$$F[i] = \begin{cases} 1 & n_i \text{ is fault section node} \\ 0 & \text{else} \end{cases} \quad (4)$$

(4) Fuzzy Min Operator ($\wedge$): It takes fuzzy min operation on the corresponding entry of the two vectors. For example:

$$\begin{bmatrix} 0.8 \\ 0.1 \\ 0.7 \end{bmatrix} \wedge \begin{bmatrix} 0.1 \\ 0.2 \\ 0.3 \end{bmatrix} = \begin{bmatrix} \mathrm{Min}\ (0.8,0.1) \\ \mathrm{Min}\ (0.1,0.2) \\ \mathrm{Min}\ (0.7,0.3) \end{bmatrix} = \begin{bmatrix} 0.1 \\ 0.1 \\ 0.3 \end{bmatrix}$$

(5) Fuzzy Multiplication Operator($\otimes$): The row-by-column matrix product is performed by, respectively, replacing multiplication and addition with the min and max operations. For example:

$$\begin{bmatrix} 0.9 & 0.5 \\ 0.1 & 0.7 \end{bmatrix} \otimes \begin{bmatrix} 0.4 \\ 0.8 \end{bmatrix} = \begin{bmatrix} \mathrm{Max}\left(\mathrm{Min}(0.9,0.4),\ \mathrm{Min}(0.5,0.8)\right) \\ \mathrm{Max}\left(\mathrm{Min}(0.1,0.4),\ \mathrm{Min}(0.7,0.8)\right) \end{bmatrix} = \begin{bmatrix} 0.5 \\ 0.7 \end{bmatrix}$$

The Steps of reasoning algorithm is described as follows:

Step1: Construct the Fuzzy Rule Matrix (R), the Truth State Vector (T), and Fault Section Vector (F).

Step2: Truth State Transformation: The transpose of the correlation matrix R, denoted by R^T, which means that corresponds to the reversal of all directed arcs in the TCDFG model. The equation (5) is called truth state transformation, which is denoted by T^*. This process describes the reasoning process from alarm messages to fault devices.

$$T^* \equiv R^T \otimes T \quad (5)$$

Step 3: Examination: This step checks whether the propagation process is completed by calculating the fuzzy min operation of T^* and F. If the result is a null vector, the updating of the truth state transformation incomplete, so perform the equation (6). When transformation completed, the result of $T^* \wedge F$ contains the confidence level of the fault device.

$$T^*_{k+1} \equiv R^T \otimes T^*_K \quad (6)$$

Step 4: Estimate the Fault Section: When all of the possible fault sections have been evaluated, if a confidence level greater than a predefined threshold, which is selected as a fault section. In this paper, the predefined threshold is set to 0.5.

4.3. The Flowchart of System

The flowchart of TCFDG fault diagnosis is shown in Figure 10.

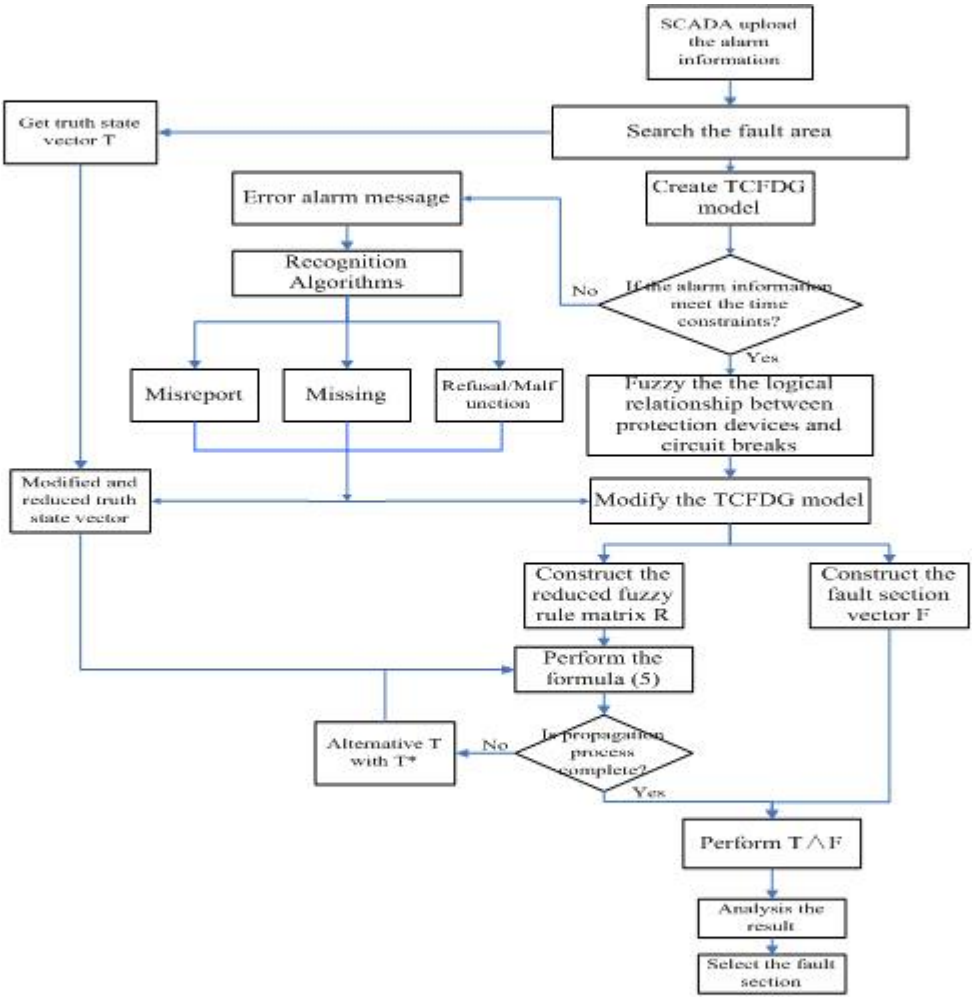

Figure 10. A Flowchart of TCFDG Fault Diagnosis

5. TCFDG Incident Matrix Reduction

Incidence matrix reduction is a prerequisite verification for propositions. Terms for fault diagnosis knowledge base, the incident matrix reduction is to delete the rules and conditions which have nothing to do with reasoning. Preconditions verification will help narrow the target space, and can save a lot of computer memory space and computing time, which is particularly evident in the large knowledge base [19].

Fuzzy rule matrix R is the incident matrix of FDG. At first, find the zero entries in the Truth state vector, which presents they are not associated to reasoning. Then delete the zero entries except the first item, and forming a new vector T' (suppose the number of the Nonzero entries except the first item is n). Based on the reduced truth state vector T, modify the fuzzy rule matrix R^T and keep the corresponding column in the R^T, forming a new (n+1)×(n+1) matrix R^{T}', according to the formula , we can easily and quickly get calculation results.

5.1. Simulation and Analysis

A simplified transmission system shown in Figure 5. Supposed that a fault occurs at transmission line L, the alarm messages uploaded by SCADA system shown in Table 2.

Table 2. Observed SCADA Data

Serial Number	Observed signals
1	MLR1 trip
2	MLR2 trip
3	CB1 open
4	CB2 open

The fuzzy directed graph model based on the SCADA information, as shown in Figure 11.

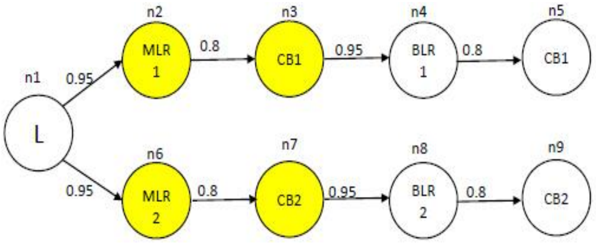

Figure 11. The FDG of Transmisson-Line L1314

According to the reasoning algorithm steps of section 3.2, the components presented as n_1-n_9 from left to right, from top to bottom shown in Figure 11. (The ni described below is same.) We get the fuzzy rule matrix R as follows:

$$R=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.95 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.8 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.95 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.8 & 1 & 0 & 0 & 0 & 0 \\ 0.95 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.8 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.95 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.8 & 1 \end{bmatrix}$$

And the truth state vector T:

$$T=\begin{bmatrix}0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0\end{bmatrix}^T .$$

According to the incident matrix reduction introduced before, delete the zero entries in the vector T, we get the new vector T':

$$\begin{array}{ccccc} n_1 & n_2 & n_3 & n_6 & n_7 \end{array}$$

$$T'=\begin{bmatrix}0 & 1 & 1 & 1 & 1\end{bmatrix}^T$$

And the corresponding matrix R^T becomes a new R^{T}':

$$R^T{}' = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0.95 & 1 & 0 & 0 & 0 \\ 0 & 0.8 & 1 & 0 & 0 \\ 0.95 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0.8 & 1 \end{bmatrix}^T .$$

Then when performing the formula (5), to some extent, improved the computing efficiency. But when performing the formula (6), we still need the original truth state vector T and incident matrix R.

6. The Power System Fault Diagnosis Simulation Based on TCFDG and Performance Analysis.

6.1. Case Study

The local power system shown in Figure 12. The time constraints between protection devices are same with section 3.1.

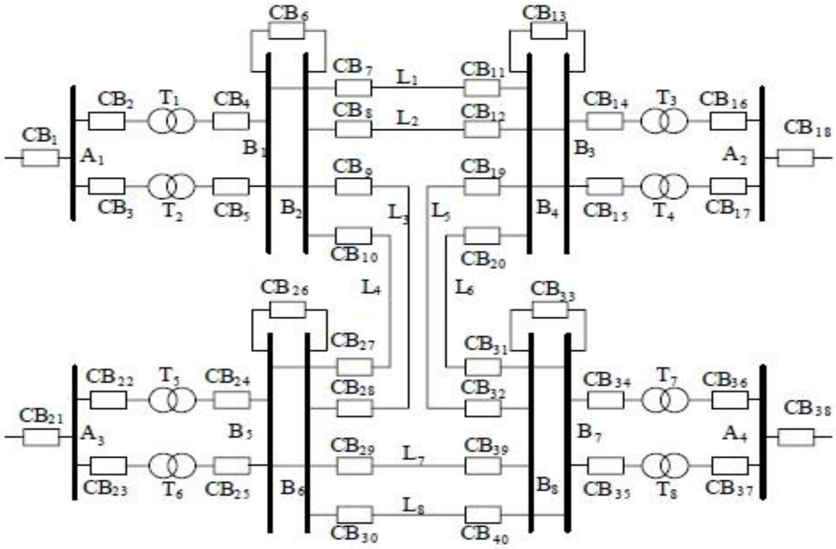

Figure 12. A Typical Power System

Table 3. Alarms Messages of Cases

Case	Obtained alert information	Alert information evaluation	Fault section
1	B_{1m}(50ms), CB4(85ms), CB5(80ms), CB6(82ms), CB7(82ms), CB9(88ms)	None	B1
2	B_{1m}(50ms), L_{2RSLR}(1070ms), L_{4RSLR}(1075ms), CB4(85ms), CB5(87ms), CB6(120ms), CB7(83ms), CB9(84ms), CB12(1095ms), CB27(1100ms)	CB6 Refuse	B1
3	L_{2RMLR}(70ms), L_{2LMLR}(70ms), CB8(85ms)、CB12(87ms)	L_{2RMLR} Misreport L_{2LMLR} Misreport	None
4	B_{1m}(50ms), L_{1RMLR}(60ms), L_{1LMLR}(60ms), L_{3RSLR}(1070ms), CB4(85ms), CB5(87ms), CB6(86ms),	CB9 Refuse	B1,L2

	CB7(83ms), CB11(85ms), CB28(1095ms)		
5	L_{1RSLR}(1070ms), CB4(85ms), CB5(87ms), CB6(83ms), CB9(84ms), CB11(1084ms)	B_{1m} missing CB7 Refuse	B1

Case1: Single Fault without Failure Devices

Searching the fault area, the Bus B1 is a suspicious faulty component. Verify the obtained alarm messages from Case1 in the Table3 one by one:

1) CB4 (85ms): according to the time constrains of CB4, reverse reasoning. We will get $\Delta T(B_{1m}) \in [40,65]$, which meet B_{1m}(50ms). And keep reverse reasoning, we will calculated $\Delta T(B_1) \in [10,40]$.
2) Similarly, CB5 (80ms), CB6 (82ms), CB7 (82ms), CB9 (88ms), all meet the time constraints between the main protection relay and corresponding circuit break.

After judgment, the obtained information are accurate. Then create TCFDG model for Bus1 shown in Figure 13. According to the TCFDG model and the corresponding reasoning algorithms. We get the result as follows:

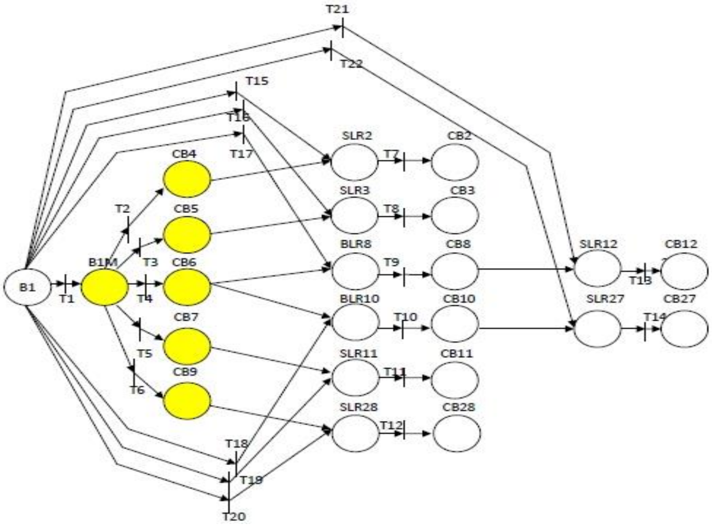

Figure 13. TCFDG Model of Bus1 Depend on the Alarms of Case 1

Step1. Construct the reduced fuzzy rule matrix R and evaluate the reduced truth state vector T.

$$R^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.95 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.8 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0.8 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0.8 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0.8 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0.8 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T$$

$$\begin{array}{cccccccc} & n_1 & n_2 & n_3 & n_4 & n_5 & n_6 & n_7 \\ T = [& 0 & 1 & 1 & 1 & 1 & 1 & 1]^T \end{array}$$

Step2. Perform Truth State Transformation: The truth state transformation can be computed, using formula (5) and the result is listed as follows:

$$\begin{array}{cccccccc} & n_1 & n_2 & n_3 & n_4 & n_5 & n_6 & n_7 \\ T^* = & [0.95 & 1 & 1 & 1 & 1 & 1 & 1]^T \end{array}$$

Step3. Perform the operation of T^* and F with Fuzzy Min Operator: The result of performing the operation of $T^* \wedge F$ is listed as follows:

$$\begin{array}{cccccccc} & n_1 & n_2 & n_3 & n_4 & n_5 & n_6 & n_7 \\ F = & [1 & 0 & 0 & 0 & 0 & 0 & 0] \end{array}$$

$$T^* \wedge F = [0.95 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

The result of $T^* \wedge F$ is not a null vector, so the propagation process is complete. The first element contains the confidence level of the estimated fault section. Therefore, the Bus1 is selected as the fault section with confidence level 0.95.

Case2: Fault with The Circuit Break Refuse To Open.

Searching the fault area, the Bus1 and the transmission-line L2, L4 are suspicious faulty components. Verify the obtained alarm messages from Case2 in the Table3 one by one:

1) CB4 (85ms): according to the time constraint of CB4, reverse reasoning. We will get $\Delta T(B_{1m}) \in [40,65]$, which meet B_{1m}（50ms）. And keep reverse reasoning, we will calculated $\Delta T(B_1) \in [10,40]$.

2) Similarly, CB5 (80ms), CB7 (82ms), CB9 (88ms), all meet the time constraint between the main protection relay and corresponding circuit break.

3) CB6 (120ms): according to the time constraint of CB6, reverse reasoning. We will get$\Delta T(B_{1m}) \in [80,100]$, which doesn't meet B_{1m}(50ms). Therefore, CB6 is a timing inconsistent information. According to section1.4.2, the index that CB6 is a misreport information is 4, and the index that CB6 is not a misreport information is 2, final we get that CB6 refuse to open.

4) CB12 (1095ms): according to the time constraint of CB12, reverse reasoning. We will get$\Delta T(L_{2RSLR}) \in [1055,1075]$, which meet the constraint $L_{2RSLR}(1070ms)$. And keep reverse reasoning, CB8 refuse to open and $\Delta T(B_1) \in [30,60]$.

5) CB27 (1100ms): according to the time constraint of CB27, reverse reasoning. We will get$\Delta T(L_{4RSLR}) \in [1060,1080]$, which meet the constraint $L_{4RSLR}(1075ms)$. And keep reverse reasoning, CB10 refuse to open and $\Delta T(B_1) \in [35,65]$.

After judgment, create the TCFDG model for the suspicious faulty components shown in Figure 14-Figure 16.

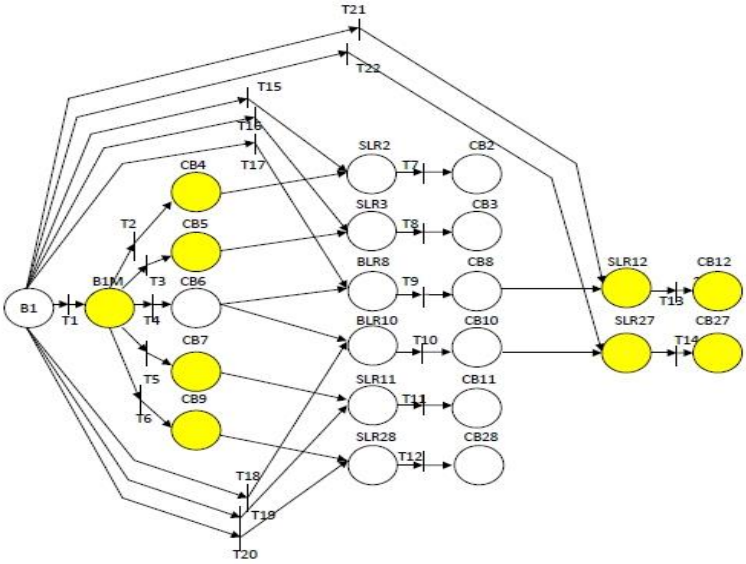

Figure 14. TCFDG Model of Bus1 Depend on the Alarms of Case 2

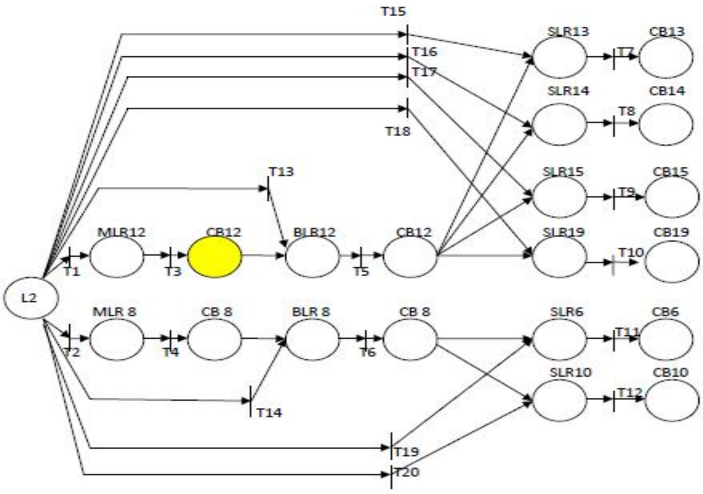

Figure 15. Tcfdg Model Of Transmission-Line L2 Depend On The Alarms Of Case 2

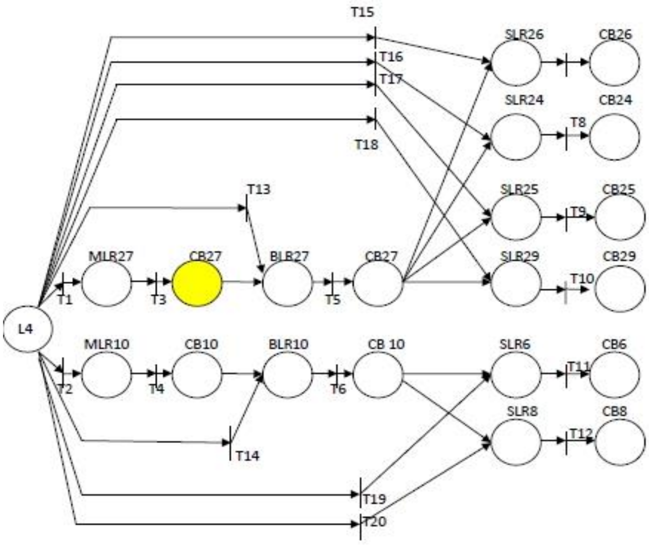

Figure 16. Tcfdg Model Of Transmission-Line L4 Depend On The Alarms Of Case 2

Table 4. Fault Diagnosis Results For Case2

Suspicious faulty components	Nonzero entries in vector T	Nonzero entries in vector T^*	Confidence level
B1	T[2]=1,T[3]=1 T[4]=1,T[6]=1 T[7]=1,T[20]=1 T[21]=1,T[22]=1 T[23]=1	$T^*[1]=0.95,T^*[2]=1$ $T^*[3]=1,T^*[4]=1$ $T^*[6]=1,T^*[7]=1$ $T^*[20]=0.8,T^*[21]=1$ $T^*[22]=0.8,T^*[23]=1$	0.95
L2	T[3]=0.3	$T^*[1]=0.3,T^*[2]=0.3$ $T^*[3]=0.3$	0.3
L4	T[3]=0.3	$T^*[1]=0.3,T^*[2]=0.3$ $T^*[3]=0.3$	0.3

The results are summarized in Table 4 .The fault sections with a confidence level of greater than 0.5 are selected as the most likely fault section. Therefore, Bus1 is selected as fault sections.

Case3: Fault with Main Protection Relays Misreport

Searching the fault area, the transmission-line L2 is the only suspicious faulty component. Verify the obtained alarm messages from Case3 in the Table3 one by one:

1) CB8 (85ms): according to the time constrains of CB8 reverse reasoning. We will get $\Delta T(L_{2LMLR}) \in [45,65]$, which doesn't meet the constraint $L_{2LMLR}(70ms)$. And according to recognition algorithm in section1.4.2, L_{2LMLR} is a main protection alarm information and $S_E=\emptyset$. So L_{2LMLR} is a misreport message.

2) Similarly, analysis CB12 (87ms), we can get that L_{2RMLR} is a misreport message.

After judgment, create the TCFDG model for transmission-line L2 shown in Figure 17.

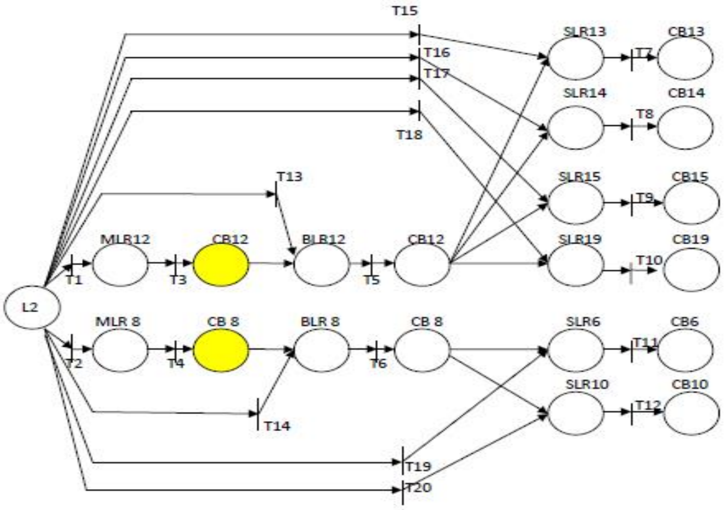

Figure 17. Tcfdg Model Of Transmission-Line L2 Depend On The Alarms Of Case 3

The results are summarized that L_{2RMLR} and L_{2LMLR} are misreport information .The fault sections with a confidence level of greater than 0.5 are selected as the most likely fault section. Therefore, the confidence level of Bus1 is 0.3 is less than 0.5,

Case4: Multiple Faults without Device Failures

Searching the fault area, the transmission-line L1, L3, and Bus1 are the suspicious faulty components. Verify the obtained alarm messages from Case4 in the Table3 one by one:

1) CB4 (85ms): according to the time constraint of CB4, reverse reasoning. We will get $\Delta T(B_{1m}) \in [40,65]$, which meet B_{1m}(50ms). And keep reverse reasoning, we will calculated $\Delta T(B_1) \in [10,40]$.
2) Similarly, CB5 (87ms), CB6 (86ms), CB7 (83ms), all meet the time constraint between the main protection relay and corresponding circuit break.
3) CB28 (1095ms): according to the time constraint of CB28, reverse reasoning. We will get $\Delta T(L_{3RSLR}) \in [1055,1075]$, which meet $L_{3RSLR}(1070ms)$. And keep reverse reasoning, CB9 refused to open and $\Delta T(B_1) \in [10,40]$.
4) CB7 (83ms): according to the time constraint of CB7, reverse reasoning. We will get $\Delta T(L_{1LMLR}) \in [43,63]$, which meet $L_{1LSLR}(60ms)$.
5) CB11 (85ms): according to the time constraint of CB11, reverse reasoning. We will get $\Delta T(L_{1RMLR}) \in [45,65]$, which meet $L_{1RSLR}(60ms)$.

After judgment, create the TCFDG model for Bus1 and transmission-line L1, L3 shown in Figure 18-Figure 20.

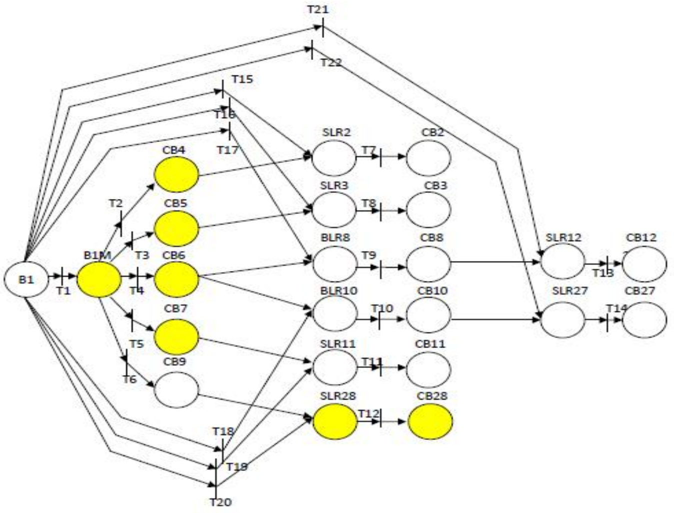

Figure 18. TCFDG Model of Bus1 Depend on the Alarms of Case 4

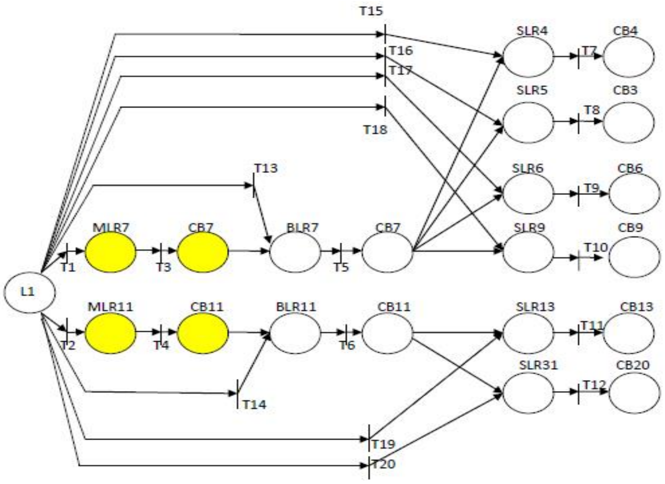

Figure 19. TCFDG Model of Transmission-Line L1depend on the Alarms of Case 4

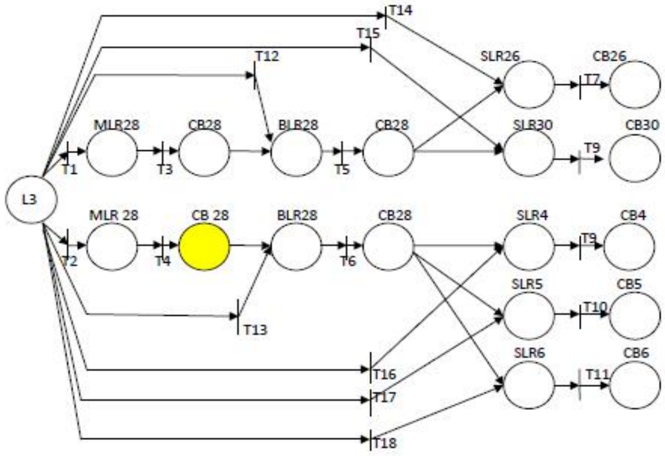

Figure 20. TCFDG Model of Transmission-Line L1 Depend on the Alarms of Case4

The results are summarized in Table 5 .The fault sections with a confidence level of greater than 0.5 are selected as the most likely fault section. Therefore, Bus1 is selected as fault sections.

Table 5. Fault Diagnosis Results for Case5

Suspicious faulty components	Nonzero entries in vector T	Nonzero entries in vector T^*	Confidence level
B1	T[2]=1,T[3]=1 T[4]=1,T[5]=1 T[6]=1,T[18]=1 T[19]=1	T^*[1]=0.95,T^*[2]=1 T^*[3]=1,T^*[4]=1 T^*[5]=1,T^*[6]=1 T^*[18]=0.8,T^*[19]=1	0.95
L1	T[2]=1,T[3]=1 T[14]=1, T[15]=1	T^*[1]=0.95,T^*[2]=0.8 T^*[3]=1,T^*[14]=0.8 T^*[15]=1	0.95
L3	T[3]=0.3	T^*[1]=0.3,T^*[2]=0.3 T^*[3]=0.3	0.3

Case5: Multiple Faults with Failure Devices and Missing Signals

Searching the fault area, the transmission-line L1, L3, transformers T1, T2 and Bus1 are the suspicious faulty components. Verify the obtained alarm messages from Case4 in the Table3 one by one:

1) B_{1m}: The signal B_{1m} isn't obtained by the checking mechanisms, according to the missing information recognition approach in section1.4.1, the index that B_{1m} is a missing information is 11, and the index that B_{1m} is not a missing information is 5, final we get that B_{1m} is a missing information, and CB4, CB5, CB6, CB9 operate correctly.

2) CB11 (1094ms): according to the time constraint of CB11, reverse reasoning. We will get$\Delta T(L_{1RSLR}) \in [1054,1074]$, which meet the constraint $L_{4RSLR}(1070ms)$. And keep reverse reasoning, CB7 refuse to open and $\Delta T(B_1) \in [30,60]$.

3) Analytical procedure of other suspicious faulty components are consistent with the above, not repeat here.

After judgment, create the TCFDG model for Bus1 shown in Figure 21.

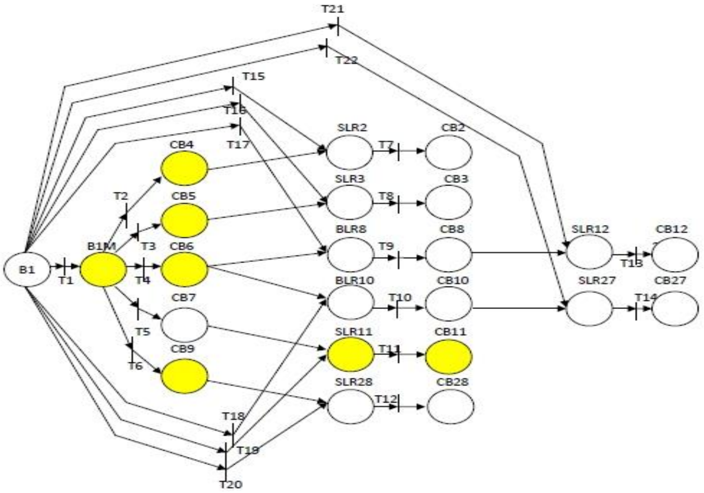

Figure 21. TCFDG Model of Bus1 Depend On The Alarms Of Case 5

The calculation process is similar with the above, the fault sections can be identified by selecting the candidate fault sections with a confidence level greater than 0.5, and Bus1 is identified as the fault section.

6.2 Performance Analysis.

Comparisons between the different methods are summarized in Table 6.

Table 6. Comparison Results among Various Methods

Method / Item	The proposed approach	The approach used in [12]	The approach used in [14]	The approach used in [18]
Uncertainly handling	Yes	No	Yes	No
Applicable to large-scale systems	Yes	No	Yes	No
Protection devices operation evaluation	Handle with timing error information, and recognize the missing or misreport messages.	Handle with timing error information, but cannot recognize the missing or misreport messages.	Can't handle with timing error information	Handle with timing error information, but can't deal with the case3
The accuracy of results	Can get accurate results	Only test on the transmission-line fault, can get accurate results.	Cannot get the correct result on Case3.	Cannot deal with the main protection relays faults

Compare the proposed approach with the approach in paper [12], conclusions are as follows:

1) The approach used in [12] use Boolean reasoning, to some extent, which can not deal with the uncertainty relationship, and it's highly affected by the size of the rule matrix, since the matrix is built with respect to the entire power system. The proposed approach in this paper, use the certainty factor, which improve the accuracy of diagnosis, and use incident matrix reduction, improve the operational efficiency.

2) The approach used in [12] can't recognize the missing or misreport messages. The proposed approach in this paper is capable of recognizing the malfunctioning devices and missing signals, which can get more credible information, improve the accuracy.

Compare the proposed approach with the approach in paper [14], conclusions are as follows:

1) The approach used in [14] doesn't consider the temporal information of the alarm message, when the main protection relays occur faults will influence the results of diagnosis straightly. For example, in case3, the approach will define transmission-line L2 is the fault section.

2) The approach used in [14] can't evaluate the protection devices and circuit breaks correctly. The proposed approach in this paper can handle with timing error information, and recognize the missing or misreport messages.

Compare the proposed approach with the approach in paper [18], conclusions are as follows:

1) The approach used in [18] recognize the alarm messages based on the main protection relays information is correct. As described in case4, if the main protection relays occur failure, the recognition algorithms will lose effectiveness. The proposed

approach can deal with this.

2) The approach used in [18] can't handle uncertainty relationship, and need to create multiple Petri nets to analysis the relationship when the fault area is too large, which lead to a large matrix, and influence the computing speed. The proposed approach in this paper, use the certainty factor, which improve the accuracy of diagnosis, and use incident matrix reduction, improve the operational efficiency.

7. Conclusion

By take full advantage of the temporal information of the alarm message, an alarm information processing and diagnostic method based on the time constraint fuzzy directed graph is proposed. Time constraint fuzzy directed graph provide intuitive representation of information, parallel processing, and an ability to handle uncertainty. The proposed approach is capable of estimating multiple faults, even when subject to malfunctioning devices and missing signals. It's well suited for large-scale and complicated power transmission networks, and have good prospects.

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