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Improvement of Power System Fault Diagnosis Algorithm Based on Petri Net

Tong Tong, Xiaoyan Xu

School of Logistics Engineering, Shanghai Maritime University, Shanghai 201306, China.

Abstract

In order to determine the exact fault power system components, various fault diagnosis method for nearly two decades used in comparative analysis, a power system fault diagnosis method based on Petri net is designed in this paper. Firstly, based on the Petri net, a three-tuple containing the relationship between the library, the transition and the flow is defined. Then the relevant parameters in the power system are mapped to the Petri net, defined as a six-tuple, and two matrices and the trigger are added. Thirdly, an eight-tuple is defined to make the final data more accurate, the identification matrix and the trigger threshold vector are modified, and the transition processing vector set is added. Finally, the test is carried out through the case, and the results show that the conclusions obtained are universal. The improved Petri net designed in this paper has a more intuitive combination model and simpler matrix calculation. It is suitable for diagnosing the changing power system fault network. It can more effectively diagnose the fault location and improve the fault diagnosis accuracy.

Keywords

Power system, Fault diagnosis, Petri net, Improvement of model, Transmission network.

1. Introduction

Electricity is the basic industry of the national economy and people's lives. Its supply and security are related to national security strategy, economic and social development. The scale of my country's power industry continues to expand, and the requirements of power users for power supply reliability, stability and continuity are also increasing. However, as the complexity of the power system increases, especially in the case of multiple faults or incorrect operation of the protection device, the amount of information that needs to be processed is so large that failure of the power system is inevitable. When the system fails, if it cannot be dealt with in time, it will not only cause equipment damage and economic loss, but also cause power outages and affect daily life. More seriously, it may evolve into a bigger accident and bring life-threatening risks. Therefore, once the system breaks down, the operation dispatching staff must quickly, accurately and stably isolate the real fault area, determine the faulty components, and accurately perform maintenance and overhaul in order to put it into operation in time.

With the continuous improvement and development of power system automation, various automatic monitoring devices have been applied to power system networks [1]. Each dispatch center provides information required for fault diagnosis, such as equipped with power quality management systems, relay protection and fault information systems, data acquisition and monitoring systems, etc. When the power grid fails, they will generate a large amount of alarm information by different levels of automation equipment. When multiple faults occur at the same time, they will all flow into the control center. If a small number of failures are not dealt with as soon as possible, due to the passage of time, large-scale failures may result. This will prolong the recovery time of the accident, expand the scope of the accident, and cause more serious power outages.

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In order to ensure the safe and reliable operation of the power system, the system not only needs to operate under normal conditions, but also analyzes various types of electrical faults and relay protection design and operation conditions. In addition, it is necessary to propose corresponding countermeasures for the possible consequences of the failure. For this reason, it is necessary to study a high-quality power system fault diagnosis system to determine and deal with various accidents in a short time. Many countries in the world have conducted a lot of design and research on this problem [2-5]. Literature [6] first proposed the idea of applying Petri nets to power grid fault diagnosis and discussed the practicality of modeling methods. Literature [7] establishes a model including component backup protection to study the influence of uncertain information. Literature [8] divides the Petri net model into two categories: line and bus, the fault process simulation is more clear and accurate. Literature [9] added the timing constraint relationship between protection and circuit breaker action in fault diagnosis to strengthen the accuracy of diagnosis and reasoning. Literature [10] uses the method of changing the enable sequence of the basic unit to obtain the optimal objective function value to realize the diagnosis and identification of grid faults. Literature [11] improves the real-time system to avoid the impact on the precise definition of time.

Compared with the technology of Petri nets, other diagnostic technologies have big deficiencies in some aspects. For example, the system is difficult to maintain, requires a large database, is not easy to form a connection with other databases, lacks the ability to output results, and may lose data [12-16]. Compared with traditional methods, Petri net technology provides a new and systematic method for processing the reasoning process. It has the advantages of shortening processing time, reducing modeling space and improving accuracy, and is more adaptable to changing network configurations. Fast and accurate results are very suitable for online applications. Therefore, the use of Petri nets to diagnose power system faults is a new direction in recent years.

This paper proposes a power system fault diagnosis technology based on Petri nets. It is based on consulting a variety of documents [17-21], through the use of intuitive matrix calculations and clear graphical representation, the integration of existing technologies and based on this Make improvements on it. In fault diagnosis, simple graph combination model and matrix calculation are used, which are clear and easy to understand. Power system fault diagnosis based on Petri net has the following advantages:

(1) Clarify the interrelationship between faulty components and protection and circuit breakers, which is better than discrete events described by certain dependencies.

(2) Use a graphical modeling method to help analyze protection and circuit breakers after diagnosis.

(3) There is no need to build a large number of knowledge bases, making the creation and maintenance of the system easier.

(4) The use of matrix operation form helps to realize online real-time error diagnosis.

(5) It is represented by a combination of graphics, which clearly describes the error component and the corresponding relationship between the circuit breaker and the protection.

In recent years, Petri nets have received extensive attention and research due to their advantages that are more in line with the human thinking judgment model, and have a relatively good development prospect. Under the premise of further research by many experts and scholars, Petri nets have shown their burst and synchronization capabilities. At the same time, at home and abroad, the practical application of power system diagnosis is still in the exploratory stage, and the integration between technical implementation and theoretical systems needs continuous improvement [22-28]. This requires us to continuously improve and revise the technology of Petri nets on the basis of follow-up work.

2. Petri Net

2.1 Petri net definition

The basic concepts of Petri nets are defined as follows [29]:

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(1) Resources: The factors associated with the system involved in the changes of the system, such as events, conditions, and status.

(2) Storehouse (L element): It can mean the place where the resource with the same function is located, and it can also mean that the place has the same resource.

(3) Change (C element): The process of changing the library caused by the generation and use of resources.

(4) Token: the number of resources in the warehouse.

(5) Capacity: The limit of the number of resources that can be stored in the warehouse.

(6) Condition: There are only warehouses with two states of token and without token.

(7) Events: involving changes in conditions.

The static structure of the system refers to a directional structure that includes events and conditions. On this basis, the state information is added to the corresponding event, and then the event storage state information is changed according to the law of condition triggering, which is the dynamic process of the system. In the basic application of Petri nets, place nodes are used to represent events, transition nodes are used to represent conditions, and tokens are used to represent status information. In other words, the transition node and the place node are generally used to describe the static structure, and the token changes in the place node are used to analyze the dynamic process.

Petri net is a network with a weighted flow relationship, in which place nodes and transition nodes are connected by weighted one-way arrows.

(1) The n-dimensional finite set composed of the place nodes is called the place set, which is represented by the letter L, and the elements of L are called place nodes, which are represented by $l_i=(i=1,2,\ldots,n)$, then $L=\{l_1,l_2,\ldots,l_n\}$;

(2) The m-dimensional finite set composed of transition nodes is called transition set, represented by the letter C, and the elements of C are called transition nodes, represented by $c_j=(j=1,2,\ldots,m)$, then $C=\{c_1,c_2,\ldots,c_m\}$;

(3) The $2mn$-dimensional finite set composed of the single-phase arrows between the transition node and the place node is called the flow relationship, represented by the letter G, then $G=\{(l_1,c_1),(c_1,l_1),(l_1,c_2),(c_2,l_1),\ldots,(l_n,c_m),(c_m,l_n)\}$.

Let the triplet be $N=(L,C;G)$, when N satisfies formula (1), then N can be called a Petri net; conversely, when N is a Petri net, it must satisfy formula (1).

$$\begin{aligned}&(a)\, L\cup C\neq\varnothing;\\&(b)\, L\cap C=\varnothing;\\&(c)\, G\subset(L\times C)\cup(C\times L);\\&(d)\, \mathrm{dom}(G)\cup\mathrm{cod}(G)=L\cup C\end{aligned}\tag{1}$$

Where: × is the Cartesian product operation; dom(G) is the new set composed of the first element in the brackets of each dimension in the set G, which means $\mathrm{dom}(G)=\{x\in L\cup C|\exists y\in L\cup C:(x,y)\in G\}$; cod($G$) is a new set composed of the second element in brackets of each dimension in the set G, which means $\mathrm{cod}(G)=\{x\in L\cup C|\exists y\in L\cup C:(y,x)\in G\}$.

2.2 Petri net analysis

The graphical analysis method is to use a limited directed graph to directly show the static structure of the system, and for the dynamic process, it needs to be displayed through a set of limited directed graphs of token changes. The graphical analysis method is an accurate description of a bounded Petri net, but can only be a partial description of an unbounded Petri net. Among the graphical analysis methods, the more common one is the accessibility tree analysis method [30].

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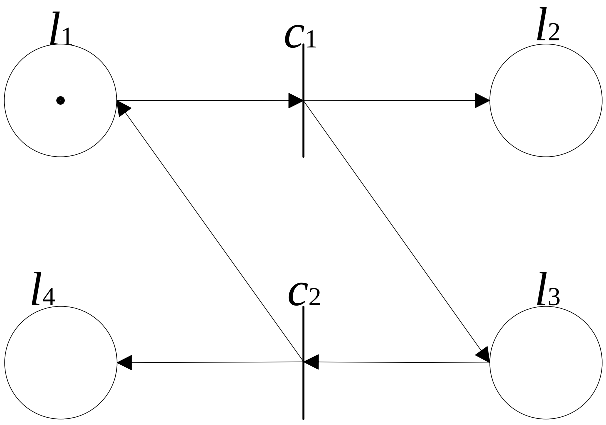

Fig. 1 Graphical analysis method for directed network N= (L, C; G)

Petri net is a directed graph, which is composed of two groups of separable nodes, namely places and transitions. These nodes are connected by one or more directional arrows or arcs. In the Petri net graphical representation, "○" represents the place; the "·" in the corresponding "○" represents the token in the node of the place; "|" represents the change; and "(A,B) "Indicates that the arrow points from A to B, where A and B indicate library nodes or transition nodes. Petri net N is a triplet N=(L,C;G), as shown in Figure 1. Among them, the place set is $L=\{l_1,l_2,l_3,l_4\}$, and the place node l_1 contains a token, the transition set is $C=\{c_1,c_2\}$, and the flow relationship is $G=\{(l_1,c_1), (c_1,l_2), (c_1,l_3), (l_3,c_2), (c_2,l_1), (c_2,l_4)\}$.

When the Petri net is relatively complex, that is, when the power system is too large, in order to avoid the chain effect of failures causing large-scale accidents, experts and scholars have proposed a new method—inductive analysis method [11].

Inductive analysis methods are mainly divided into decomposition and combination in structure. That is, while keeping the nature and characteristics of the system network unchanged, first decompose a relatively complex main system network into several relatively simple subsystems, then analyze each simple sub-network, and finally recombine it into the original main system , Then the original relatively complex system network can be summarized by several relatively simple subsystems.

Matrix analysis method is the most common, basic and most important analysis method in Petri net analysis method. The three matrices used to describe a simple Petri net are defined as follows [8]:

(1) Identification vector M (column vector of $|L|\times 1$): a matrix representing the presence or absence of tokens of all the place nodes in the Petri net.

Initial identification vector M_0: the token distribution of the nodes of the Petri net when the initial is static structure. According to the Petri net graph, judge the token distribution of the nodes of the warehouse. If it can be judged, M_0 is listed according to the specific value. If the conditions are not enough, the token with token defaults to 1, and the token without token defaults to 0. $M_i=(i=1,2,\ldots,n)$ is continuously calculated by M_0 through specific formulas.

Final state identification vector Mn: Stability is the token distribution of the nodes of the Petri net at the end of the dynamic process.

(2) Incidence matrix A ($|L|$ row, $|C|$ column matrix): $A=[a_{ij}]$, which represents the weighted relationship of the directed arrow between the place node and the transition node, as shown in formula (2).

$$A(l,c)=\begin{cases}-W(l,c),(l,c)\in G\\ W(l,c),\quad (c,l)\in G\\ 0,\qquad else\end{cases} \tag{2}$$

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In the formula: (l,c) is the directional path from the place node l to the transition node c; $W(l,c)$ is the weight of the one-way arrow G from the place node l to the transition node c.

Weight determination method: ① If $(x,y)\in G$, the specific value is marked in the Petri net, then $W(x,y)$ is calculated according to the specific value. ② If $(x,y)\in G$, no specific value is marked in the Petri net, then $W(x,y)=1$. From formula (2), we can see that when the transition node c_j points to the place node l_i, $a_{ij}=1$; When the place node l_i points to the transition node c_j, $a_{ij}=-1$; when the place node l_i is not associated with the transition node c_j, $a_{ij}=0$. ③If $(x,y)\notin G$, then $W(x,y)=0$.

(3) Trigger threshold vector T_γ (column vector of $|C|\times 1$): represents the matrix that the transition node in the Petri net meets the trigger condition and can perform the next dynamic movement.

If a transition node is triggered, the corresponding vector set number will be calculated according to the specific value if the specific value is marked in the Petri net; if not marked, the default is 1; otherwise, it is 0.

Based on the formation of the above three types of matrices, Petri nets use the equation of state to describe its dynamic process, changing M_0 continuously, and finally obtaining M_n, as shown in equation (3).

$$M_{n+1} = M_n + A \bullet T_{\gamma n} \tag{3}$$

Since the initial identification matrix M_0 gives the token distribution of the nodes of the initial place, custom weights can be added to A^+ and A^-, T_γ triggers the dynamic process, and the defined triple $N=(L,C;G)$ The weight can only use the default value of 1, and the initial token distribution cannot be judged. Therefore, the definition is further optimized and the Petri net is increased into a six-tuple $N=(L,C;G,M,A,T_\gamma)$.

2.3 Reasoning process

The essential difference between the static structure of the Petri net and the dynamic process is that a graph can only describe the static structure, while the dynamic process requires observing a set of graphs, that is, observing the distribution of tokens in the library nodes in this set of graphs. But the distribution change of token is realized by the triggering of transition nodes. Therefore, the most important step to study the dynamic behavior of the system is to study the changing rules of transition nodes. After the transition is triggered, the capacity of the output warehouse will not exceed the diversity of the input arc, so the transition node in the Petri net can be triggered to meet the following two points:

(1) The input place node of the change contains tokens.

(2) The weight of the one-way arrow between the place and the transition must be less than the token number in each input place of the transition.

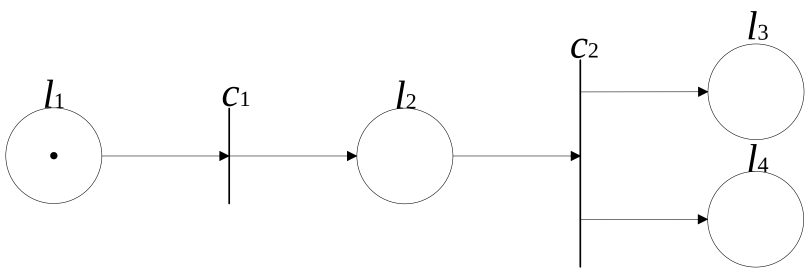

Fig. 2 Petri net N_0

The reasoning process of Petri net for fault diagnosis:

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(1) According to the given graph or condition, match the corresponding initial number of tokens to each input place node of the Petri net to form the initial identification of the Petri net.

(2) If a transition node can meet the trigger condition, then the transition node is activated. First, take a token from each input place node of the transition node, and then put the token into the output place node of the transition node according to the constraint law of the weighted directed arrow. This process can be referred to as completing an identification change of the Petri net.

(3) After multiple identification changes, until there is no transition node that can be triggered in the Petri net. At this time, it has reached the final stable state, forming a steady state mark.

Through the simple Petri net fault diagnosis mechanism, for the triplet $N=(L,C;G)$, as shown in Figure 2, the transition set is $C=\{c_1,c_2\}$. The library set is $L=\{l_1,l_2,l_3,l_4\}$, node l1 contains a token, and the flow relationship is $G=\{(l_1,c_1),(c_1,l_2),(l_2,c_2),(c_2,l_3),(c_2,l_4)\}$.

(1) Graph analysis technology

It can be seen from Figure 2 that since there is a token in the input place node l_1 of the transition node c_1, and the token number is not less than the default weight 1, the trigger condition of c_1 is satisfied, and c_1 is activated. The token is migrated from l_1 to the output place node l_2 of c_1 according to the constraint law of the weighted directed arrow, so that the token in l_1 disappears, and l_2 adds a token. That is, the first identification change of Petri net is completed. Let the Petri net that completes the first identification change be N_1, as shown in Figure 3.

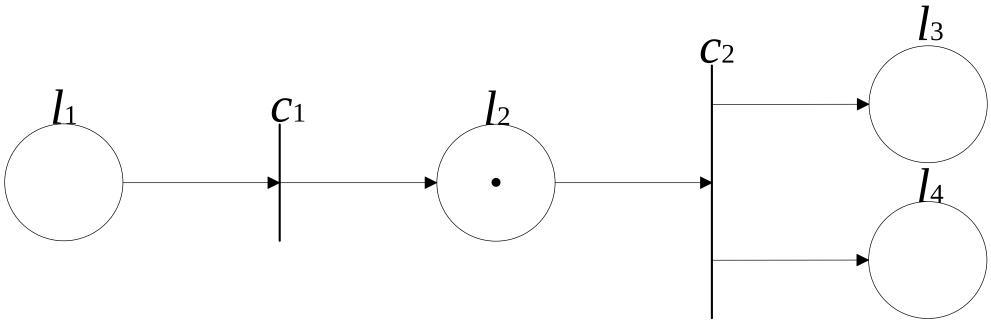

Fig. 3 Petri net N_1

Trigger and migrate in the same way to make the token disappear in l_2, and add a token to l_3 and l_4. That is, the second identification change of Petri net is completed. Since there is no transition node that meets the trigger condition at this time, the Petri net enters the steady state flag. Let the Petri net that completes all identification changes be N_2, as shown in Figure 4.

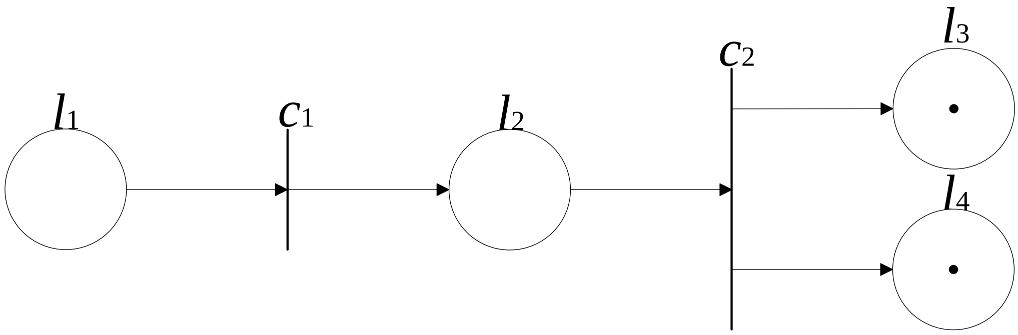

Fig. 4 Petri net N_2

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(2) Matrix analysis technology

According to Figure 2, list the initial identification vector, incidence matrix and trigger vector of Petri net N_0:

$$M_0 = [1 \quad 0 \quad 0 \quad 0]^T$$

$$A = \begin{matrix} & c_1 & c_2 \\ P_1 & -1 & 0 \\ P_2 & 1 & -1 \\ P_3 & 0 & 1 \\ P_4 & 0 & 1 \end{matrix}$$

$$T_{\gamma 1} = [1 \quad 0]^T$$

From the state equation shown in formula (3), the identification vector can be known:

$$M_1 = M_0 + AT_{\gamma 1} = [0 \quad 1 \quad 0 \quad 0]^T$$

It can be seen from the equations of M_0 and M_1 that the token in l_1 migrates to l_2, which completes a change of the Petri net.

$$T_{\gamma 2} = [0 \quad 1]^T$$

$$M_2 = M_1 + AT_{\gamma 2} = [0 \quad 0 \quad 1 \quad 1]^T$$

It can be seen from the equations of M_1 and M_2 that the token in l_2 migrates to l_3 and l_4, which completes the final state identification change of the Petri net.

3. Power system fault diagnosis based on Petri net

3.1 Fault disgnosis mechanism

Various components in the power system, such as bus bars, lines, transformers, etc., are equipped with corresponding protection devices and corresponding circuit breakers. When the equipment fails, the associated protection action is used to start the corresponding circuit breaker to switch off the faulty equipment [31]. Power system fault diagnosis is based on the operation of related protections and circuit breakers to determine fault areas and faulty components. Therefore, the establishment of a power system fault diagnosis model based on Petri nets, the key lies in how to establish the logical cooperation relationship between equipment, protection and circuit breakers, and correspond to the relevant parameters of the power system to the place nodes, transition nodes and tokens of the Petri net.

The fault diagnosis mechanism is basically as follows:

(1) Use the library to represent the protection of various fault components in the power system and the corresponding circuit breakers. When multiple protections operate at the same time, it is necessary to "bridge" the virtual library to form a final state library, where the matrix parameters are used to judge whether the component fails.

(2) Tokens are used to indicate the protection actions of fault components and the tripping of circuit breakers. If it operates normally, no token is added; if it refuses to move and malfunctions, then token is added to the corresponding protection or circuit breaker.

(3) In the diagnosis process, the transition is used to indicate the time span from the detection of the fault current to the relay protection sending the control signal to open the circuit breaker, which is the basic requirement to judge whether it can be triggered.

When the power system fails, first arrange the related phenomena in order, and then draw the graph from the logical relationship of the Petri net, then use the data information to clarify the initial

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identification of the system, and finally diagnose the final faulty component by the matrix analysis method .

3.2 Failure model analysis

For the triplet $N=(L,C;G)$ Petri net, as shown in Figure 5, the transition set is $C=\{c\}$, the place set is $L=\{l_1,l_2,l_3\}$, and the flow relationship is $G=\{(l_1,c),(l_2,c),(c,l_3)\}$. Among them, the place node l_1 is the mapping of relay protection actions; the place node l_2 is the mapping that controls the tripping of the circuit breaker; the place node l_3 is the mapping of suspicious faulty components such as busbars, lines, and transformers. The protection action is detected and the corresponding circuit breaker trips, and tokens are deployed in the place nodes l_1 and l_2. When c satisfies the trigger condition, the tokens in l_1 and l_2 are transferred to the library node l_3, and the suspicious element represented by l_3 is diagnosed as malfunctioning.

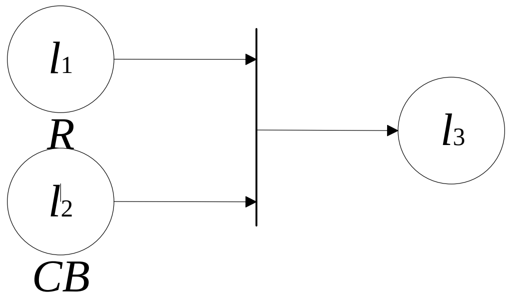

Fig. 5 Petri net model of power system

The power system is composed of many of the above basic models. As shown in Figure 6, a main protection and a near backup protection are installed for the transmission line *L*. Establish its Petri net model diagram, as shown in Figure 7. Among them, $R_{L\text{-}m}$ is the main protection of the line, CB_1 is the main protection and the corresponding circuit breaker, $R_{L\text{-}p}$ is the near backup protection of the line, CB_2 is the circuit breaker corresponding to the near backup protection, and *H* is a virtual library.

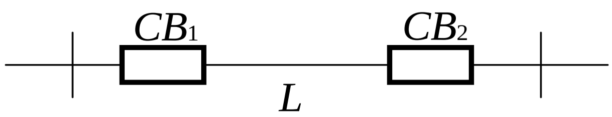

Fig. 6 Transmission line L diagram

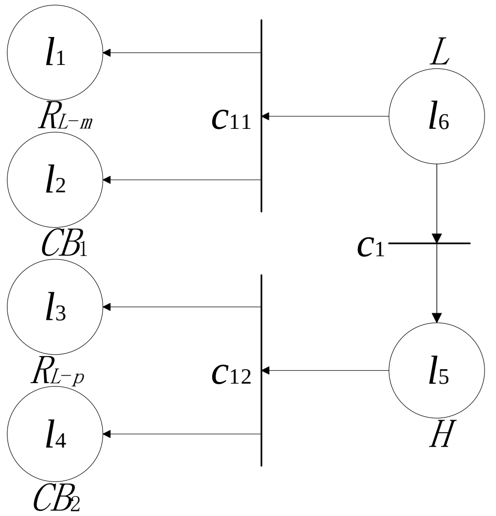

Fig. 7 Petri net model of transmission line L

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When the transmission line L has a fault, that is, l_6 has a token, so assign a value of 1 to l_6 in M. Through c_1 and c_{11}, c_{12} are sent to the place nodes $R_{L\text{-m}}$, CB_1 and $R_{L\text{-p}}$, CB_2 in turn, so that $\{l_1,l_2,l_3,l_4\}$ all have tokens, that is, l_1, l_2, l_3 and l_4 in M are both 1. Therefore, when the transmission line has a fault, the problem of the transmission line fault is solved through the relay protection action and the circuit breaker tripping.

3.3 Failure hypothesis and diagnosis

The above is the establishment of the "forward Petri net" model, which belongs to the fault clearing process. The fault is eliminated and its protection and relays are found. The fault diagnosis process of power system is the opposite, which is called "backward or reverse Petri net" model. The initial state corresponds to the final state of the protection system, and the initial mark only depends on the information of the circuit breaker, that is, through the protection action and the circuit breaker tripping, the fault occurrence area or the fault element is reversed.

Diagnose the "backward or reverse Petri net" model of the transmission line in Figure 6, as shown in Figure 8. The transition set is $C=\{c_1,c_{11},c_{12}\}$, and the place set is $L=\{l_1,l_2,l_3,l_4,l_5,l_6\}$, the flow relationship is $G=\{(l_1,c_{11}),(l_2,c_{11}),(l_3,c_{12}),(l_4,c_{12}),(c_{11},l_6),(c_{12},l_5),(l_5,c_1),(c_1,l_6)\}$.

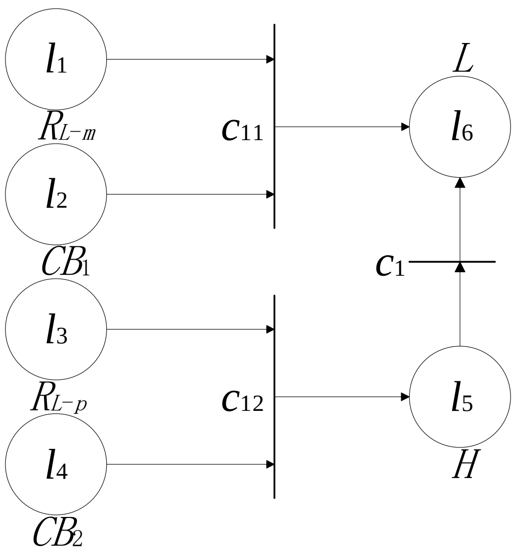

Fig. 8 "backward or reverse Petri net" model of transmission line L

If the main protection $R_{L\text{-}m}$ of the transmission line L is observed to act, the circuit breaker CB_1 trips. After a very short time, the near-backup protection $R_{L\text{-}p}$ is activated and the circuit breaker CB_2 is tripped. which is:

$$M_0=[1\quad 1\quad 1\quad 1\quad 0\quad 0]^T$$

$$A=\begin{array}{c} \\ R_{\mathrm{L-m}} \\ CB_1 \\ R_{\mathrm{L-s}} \\ CB_2 \\ H \\ L \end{array}\begin{array}{c} \begin{array}{ccc} c_1 & c_{11} & c_{12} \end{array} \\ \begin{vmatrix} 0 & -1 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & -1 \\ -1 & 0 & 1 \\ 1 & 1 & 0 \end{vmatrix} \end{array}$$

$$T_{\gamma_1}=[1\quad 1\quad 1]^T$$

$$M_1=M_0+AT_{\gamma_1}=[0,\ 0,\ 0,\ 0,\ 0,\ 1]^T$$

It can be seen from the result that l_6 is 1, that is, there is a token in l_6, and the suspected faulty transmission line L has indeed failed, which is the same as the assumed action information.

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4. Power system fault diagnosis based on improved Petri net

4.1 Extension of Petri net

In real applications, Petri nets are sometimes subject to some restrictions, resulting in inaccurate data. Therefore, experts and scholars have introduced certain factors that can change these limitations on the basis of basic Petri nets, and have achieved certain success, promoting its development in power system fault diagnosis. These extended Petri nets mainly include suppressed arc Petri nets, time-delayed Petri nets, fuzzy Petri nets and probabilistic Petri nets [32-36].

Suppress arc Petri nets change the weight of the one-way arrow between the place node and the transition node, that is, through a large number of cases, data and verification, the arc weight is divided into the input arc weight and the output arc weight, so that the diagnosis result is more Meet the actual failure. The time-delayed Petri net changes the trigger threshold vector of the transition, because for a faulty component, the main protection has priority action. When the main protection refuses to operate, the backup protection operates. There is a time difference between the occurrence of different protection actions, and different triggers are set. The delay time is used to simulate the level difference coordination to ensure that the main protection has priority to the backup protection. The fuzzy Petri net changes the initial identification vector, and defines different initial values for the protection of different components such as busbars, lines, transformers and corresponding circuit breakers when a fault occurs. Probabilistic Petri nets increase the transition processing function to determine the possibility of failure of the area or component. In the normal simulation process, no matter how good the data acquisition and monitoring control system is, there must be uncertainty in the signal, and the probability value is used instead of the final default value 1.

This article refers to various documents related to Petri nets, integrates the above four Petri net extensions, improves the Petri net, controls the trigger delay action time, corrects the initial action probability value and the flow relationship weight, and further follows the input arc and output arc. Divide the incidence matrix.

4.2 Petri net improvements

The basic improved Petri net model is shown in Figure 9, which is an octet N=(L,C;G,M,I,O,D,T_γ).

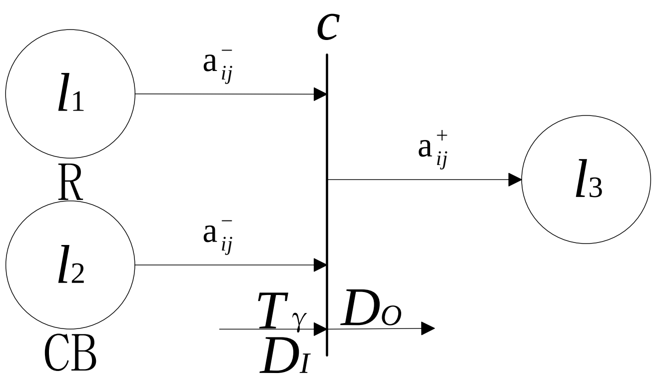

Fig. 9 Basic improved Petri net model

1) Initial identification vector M_0: According to the protection action of the faulty component, assign values to the initial location node to form the initial identification vector M_0. The virtual place and the final state place are initially assigned 0. Protections and circuit breakers may refuse to operate, malfunction, and lose operation information. In order to improve the accuracy of the diagnostic model, a small probability of fault information is obtained when the fault information is incomplete [38], and the corresponding library of non-operated protection requires less The numerical value. Refer to the method of [37], set the initial action probability value of relay protection action and circuit breaker trip, as shown in Table 1.

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Table 1 Probability of relay protection and circuit breaker action

Element	Main protection		Near backup protection		Far backup protection	
	Protection	Breaker	Protection	Breaker	Protection	Breaker
Line	0.99	0.98	0.8	0.85	0.7	0.75
Busbar	0.95	0.98	0.8	0.85	0.7	0.75
Transformer	0.95	0.98	0.75	0.8	0.65	0.7

2) Transition trigger threshold vector T_{Υ}: Since different events have time levels, different trigger delay times are set to simulate level difference coordination. Considering $T_{\Upsilon}\in[0,1]$, and the time delay is very short, the first-level transition and the second-order transition of the model are set to 0.2 and 0.1 respectively.

3) Input weight matrix $I=[a_{ij}^-]$ ($n\times m$ dimensions): a_{ij}^- is the weight of all nodes l_i to c_j in A. There are many reasons for the same kind of failure, and the degree of influence on each input library is different, so different weights are assigned. When all the protections in Figure 8 are activated, different a_{ij}^- values are assigned, as shown in Table 2. According to the principle of relay protection, if a component fails, it will surely cause the relay protection action, and then control the circuit breaker to trip. When assigning a value of 1, the impact on the same protection and the corresponding circuit breaker is similar. In order to ensure that the possibility of action is basically the same, and considering the swiftness of the action time limit and the priority of protection, this paper gives the relay protection warehouse and the circuit breaker warehouse the weights of 0.55 and 0.45 respectively.

Table 2 The weight of the change to the library

Action information	1	2	3	4	5	6
Relay protection	1	0.9	0.8	0.7	0.6	0.55
Breaker	1	0.1	0.2	0.3	0.4	0.45
$R_{L\text{-}m}$	0.79	0.81	0.83	0.85	0.87	0.88
CB_1	0.78	0.96	0.94	0.92	0.9	0.89
$R_{L\text{-}s}$	0.6	0.61	0.62	0.63	0.64	0.645
CB_2	0.65	0.74	0.73	0.72	0.74	0.705

Table 3 The weight of the transition to the library

Action information	1	2	3	4	5	6
Main protection	1	1	1	1	1	1
Near backup protection	1	0.6	0.7	0.8	0.9	0.95
Far backup protection	1	0.2	0.4	0.6	0.8	0.9
H	0.1	0.18	0.16	0.14	0.12	0.11

4) Output weight matrix $O=[a_{ij}^+]$ ($m\times n$ dimensions): a_{ij}^+ is the weight of all nodes c_j to l_i in A. The contribution rate of each failure reasoning path to the output library is different, which makes the failure results different, so different weights are assigned. When all the protections of the line in Fig. 8 operate, different a_{ij}^+ values are assigned at this time, as shown in Table 3. When the actual

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component fails, the main protection, the near backup protection and the far backup protection are given different weights in turn. Taking into account the priority and sequence of each protection action and the rapidity of the action time limit, this paper assigns the weights of the main protection, the near backup protection and the far backup protection to the transition output arcs as 1, 0.95, 0.9.

5) The set of processing vectors of the transition $D=\{D_I,D_O\}$: Since the calculation of the composite input vector D_I is based on a_{ij}^- and the initial action values of all the input places of the transition, D_I satisfies the formula (4). Because the calculation to obtain the output vector D_O is based on the composite input value. In order to make the result more accurate, the Gaussian function method is generally used. Reference [11], formula (5) is used as the function of obtaining the output probability, and then D_O is obtained.

$$D_I = I^T \bullet M_0 \tag{4}$$

$$f_\alpha(x) = e^{-3(x-1)^2} \tag{5}$$

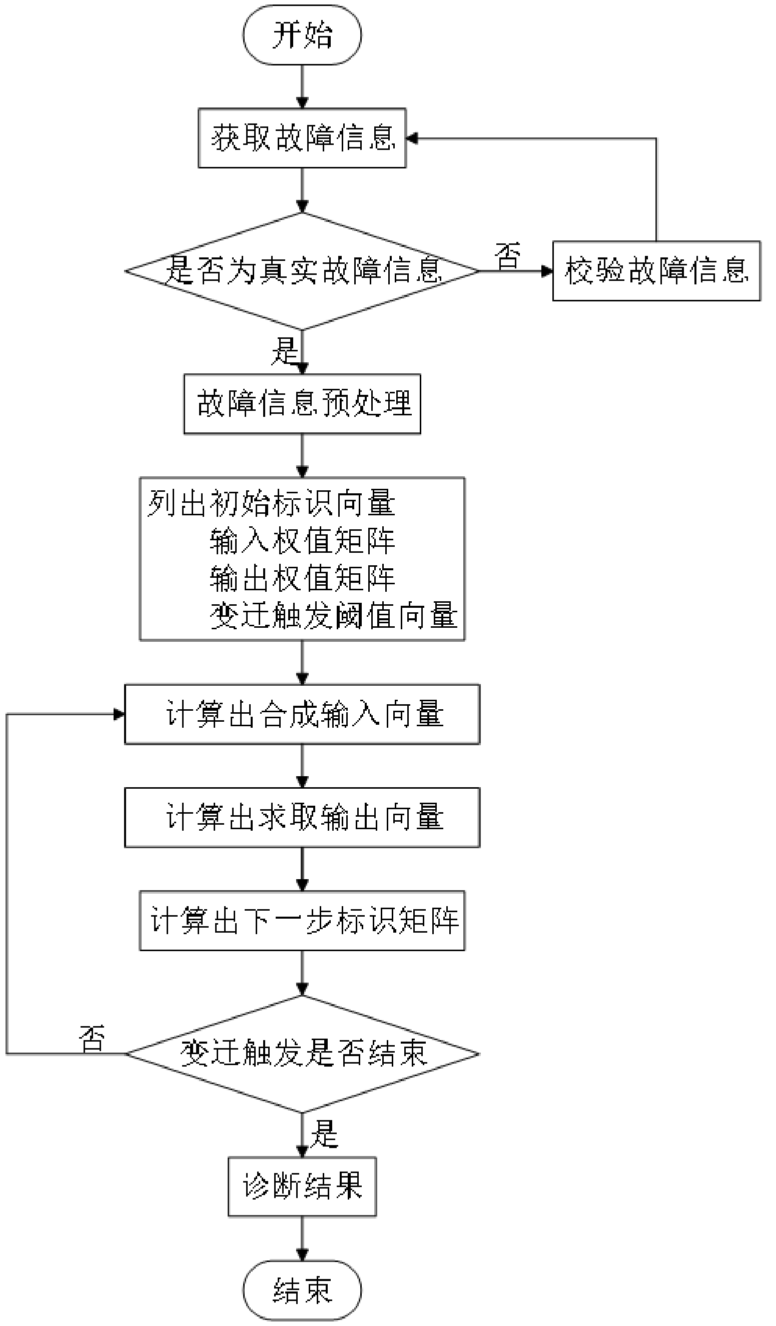

Fig. 10 "backward or reverse Petri net" model of transmission line L

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4.3 Diagnosis process

The flowchart of power system fault diagnosis based on improved Petri net is shown in Figure 10. The specific process is as follows:

(1) The acquired fault information is judged whether it is true or not through the fault information management module.

(2) Judge M_0, I, O and T_γ based on the information of the power system failure relay protection and circuit breaker action or non-action. Where I and O can be listed by A.

(3) According to formula (4), calculate the changed D_I.

(4) According to formula (5), the output function value is obtained by calculation, and then the D_O is formed.

(5) According to formula (6), calculate M_1 and obtain the node value of each place after a transition.

(6) Trigger judgment for each transition through T_γ, repeat the calculation of (2)-(4) until there is no triggerable transition, and use the maximum value as the output value. The diagnosis is over.

$$M_{n+1} = O \bullet D_{On} \tag{6}$$

The relay protection forms of different components in the power system are different. This paper will diagnose common components. Figure 11 is a schematic diagram of a part of a ship's electrical system wiring, using Petri nets to diagnose faults on its busbars, lines and transformers.

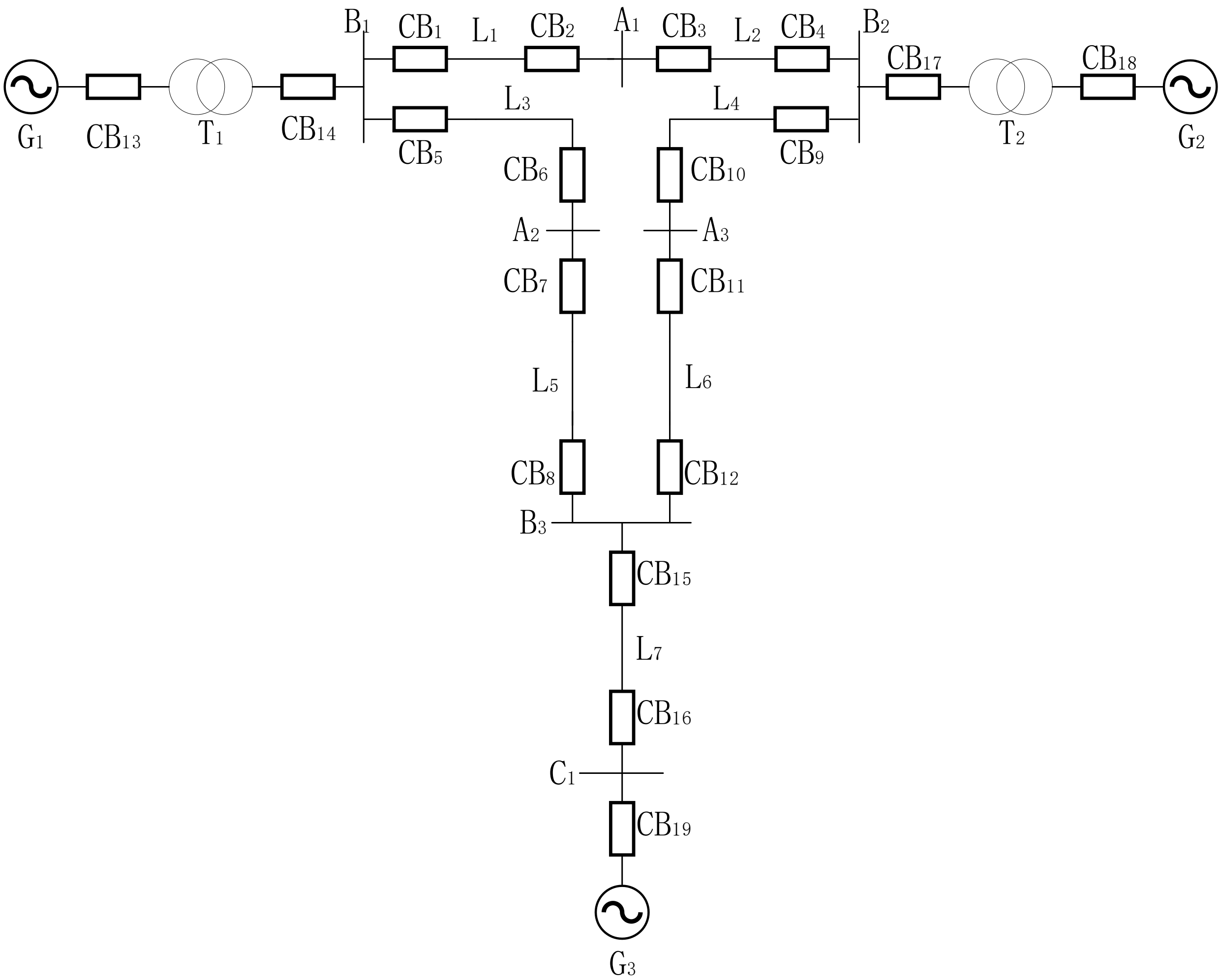

Fig. 11 Wiring diagram of a ship's power system

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Taking bus B_3 in the system wiring diagram, the establishment of an improved Petri net diagnosis model for bus components is studied. If the main protection action of B_3 is observed, CB_8 is not tripped, other circuit breakers are all tripped, remote backup protection is activated, CB_{16} is not tripped, and the others are all tripped. The modeling process is as follows: use $R_{B3\text{-}m}$ and CB_8, CB_{12}, CB_{15} to simulate the corresponding main protection and circuit breaker of B_3; $R_{B3\text{-}s}$ and CB_7, CB_{11}, CB_{16} to simulate the corresponding remote backup protection and circuit breaker of B_3; Place H is a Virtual library.

According to the received information:

$$M_0 = [0.95\ 0.02\ 0.98\ 0.98\ 0.7\ 0.75\ 0.75\ 0.25\ 0\ 0]^T$$

$$I = \begin{array}{c} \\ R_{B3-m} \\ CB_8 \\ CB_{12} \\ CB_{15} \\ R_{B3-s} \\ CB_7 \\ CB_{11} \\ CB_{18} \\ H \\ P \end{array} \begin{array}{ccc} c_1 & c_{11} & c_{12} \\ 0 & 0.55 & 0 \\ 0 & 0.45 & 0 \\ 0 & 0.45 & 0 \\ 0 & 0.45 & 0 \\ 0 & 0 & 0.55 \\ 0 & 0 & 0.45 \\ 0 & 0 & 0.45 \\ 0 & 0 & 0.45 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{array}$$

$$O = \begin{array}{c} \\ R_{B3-m} \\ CB_8 \\ CB_{12} \\ CB_{15} \\ R_{B3-s} \\ CB_7 \\ CB_{11} \\ CB_{18} \\ H \\ P \end{array} \begin{array}{ccc} c_1 & c_{11} & c_{12} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0.9 \\ 1 & 1 & 0 \end{array}$$

$$T_\gamma = [0.2 \quad 0.2 \quad 0.1]^T$$

Use the algorithm program of the improved Petri net to derive the matrix:

$$D_I = [0 \quad 1.4135 \quad 0.1725]^T$$

$$D_O = [0 \quad 0.5987 \quad 0.9146]^T$$

$$M_0 = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0.8231\ 0.5987]^T$$

$$D_{I1} = [0.8231 \quad 0 \quad 0]^T$$

$$D_{O1} = [0.9104 \quad 0 \quad 0]^T$$

$$M_0 = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0.9104]^T$$

Therefore, the probability of B_3 failure is 0.9104.

Taking the transmission line L_6 as an example, the establishment of the improved Petri net diagnosis model of line components is studied. If the main protection action of L_6 is observed, CB_{12} is not tripped, all others are tripped, and the remote backup protection action, except for CB_7, all others are tripped. The modeling process is as follows: $R_{L6\text{-}m}$ and CB_{11}, CB_{12} simulate the corresponding main protection and circuit breaker of L_6; $R_{L6\text{-}s}$ and CB_7, CB_9, CB_{16} simulate the corresponding remote backup protection and circuit breaker of L_6; place H is a virtual place . The matrix derives that the probability of failure of L_6 is 0.9272.

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Perform fault modeling on transformer T_1. If the main protection action is observed, all except CB_{13} trip, and the remote backup protection action, the corresponding circuit breakers are all tripped, and the probability of T_1 failure is 0.9702.

Compared with the basic Petri net that directly judges that a certain component is faulty, the improved Petri net considers the fact that all received signals cannot be judged as correct in the normal simulation process, and gives the possibility of a certain component failure, which improves the Petri net's practicality in power system fault diagnosis.

5. Conclusion

This paper adopts a method of improving the Petri net to locate the fault of the power grid. It uses a typical example to test, and clarifies the uncertainty in the received signal, obtains the correct diagnosis result, and verifies the feasibility of the method. The system can not only be used in real time, but also can assist the personnel in the control center to operate in times of crisis, especially when the complexity of the problem increases. The following aspects can be further studied:

(1) Combine fuzzy set theory with Petri net theory to improve the accuracy of time difference judgment.

(2) Add the idea of suspicious component library and fault tree to judge a fault from multiple angles, making the algorithm more comprehensive, convenient and easy to understand.

(3) Apply the Petri net model to the automated substation with determined topology.

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