Application of Fuzzy Petri Nets in Secondary Device Fault Analysis

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***Abstract*—**Petri nets are a tool for modeling and analysis of distributed systems. Combining with network theory, algebra theory foundation of mathematics, it's suitable to describe and analyze the discrete event system model of concurrent systems. With issues of condition monitoring and fault analysis of IEDs, the paper put forward a kind of knowledge of IEDs fault factors based on fuzzy Petri net representation and reasoning algorithm. The method describes the relationship between the condition monitoring information, the fault symptom, self check information and fault mechanism, providing an effective tool for the presentation of IEDs fault in fuzzy knowledge. The theory and method adopts simple matrix calculation, thereby deduce the probability of a certain type of equipment failure, which improves the efficiency and accuracy of diagnosis.

***Keywords*—**intelligent electronic devices (IEDs), fuzzy Petri nets, fault diagnosis

I. Introduction

At present, the national economy develops rapidly, and social life progress with each passing day, many important power consumers, especially whose are related to people's livelihood, require for the higher and higher reliability of the power supply. As well as for the ordinary consumers, the power supply companies can't cut arbitrarily. The regular maintenance routine is not able to meet the needs of consumers on the quality of power supply, therefore must develop the status monitoring which will be the main ways of maintenance mode.

In substation, primary equipments such as power transformers, circuit breakers and buses, are the most important carriers those carry out the functions of electric transmission and transformation. The status of primary equipments concerns the security of the whole substation. Intelligent electric devices are the main part of the electrical parameters measurement, information processing and status monitoring. These are crucial important for substation too. However, developers and engineers are barely care for the fault diagnosis and analysis of IED.

IED fault diagnosis is based on the accessible nodes of electronic circuit or the ports, and other test information, inferring the condition of equipment, to determine the fault the location of elements, prediction of failure, finally determine the electronic product quality and give the necessary repair prompting method.

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Fault diagnosis mainly includes problems of pattern classification and recognition, that is to say the motion state of that system is divided into normal and abnormal in two classes. The system estimates abnormal signal samples through pattern recognition.

Petri nets can be used to describe the model of asynchronous and concurrency system. These nets build mesh graphic system model based on the physical laws of nature, which can explain the result of system and the significant information of dynamic behavior. The fault diagnosis method based on Petri nets can integrate knowledge representation and diagnosis ratiocination into a whole, and can integrally describe, diagnose and inference the processing of faults. Finally we can get diagnosis result rapidly by matrix calculation.

The fault diagnosis and system reliability analysis of large-scale electronic equipment system are the research stress and difficulty in the domain of aeronautics and astronautics. There are a large number of researches at home and abroad. The paper analyze the fault factors that result in fault of electronic devices, using monitoring and self-check information of IEDs in substation, put forward a kind of production rules forward reasoning model for IED fault based on fuzzy Petri nets, and obtain the true values of various of fault conditions by the matrix formula.

II. The Foundation Of Fault Diagnosis For IEDs

The cores of IEDs are integrated circuit and application software, whose scale will be larger and larger. And for IED, the performance and constitute will be increasingly complex and perfect. Any one electronic unit lose efficacy can lead to the fault of part of device, or even the whole device. Therefore, the needs to make the work of the reliability of the electronic circuit and application software and automatic fault diagnosis are urgent.

The fault of electronic devices is that the devices lose the regular functions, making the system exhibited undesirable. From the point of analysis of the IED function of IED, the fault can be divided into hard and soft faults. The hard fault means that the faults cause by the abnormal hardware, while the software call be called gradual fault or partial failure, which were caused by the parameters of electronic units beyond tolerance range. On this occasion, generally the functions of electronic units don't vanish completely; just create the change of functions.

The faults are mainly in failure of electronic units, short out caused by empty solder in soldering position, failure of PCB, et.al. If the failure exists, the incipient and occasional fault will

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come out in internal test. In engineering applications, the faults of IED are mainly wear-out faults caused by changes of ambient temperature and relative humidity, electromagnetic environment, communication, supercharge of CPU et.al. The faults of IED are connecting with segments such as product design, product manufacturing and test. Generally, the faults are caused by designed badly, poor quality and debugging bad, what will lead to hardware failure and software failure.

Most smart substations realize condition monitoring of IEDs. The objects monitored for IED mainly are AC measurement system, DC operation system, signaling system, communication system and shielding earth system. Unlike the substation primary equipment, the condition monitoring objects of IEDs in substation is not a single element, but a unit or a system.

Specific to the control and measurement, relay protection device, the main objects needed to monitor include:

(1)The status of GOOSE and SV communication channel;

(2) The status of Dc inverter power supply

In addition, IEDs also have strong abilities of "self-check", which have parts of fault diagnosis function, provide a good foundation for the realization of condition based maintenance technology.

However, IED self-diagnosis function also has the following defects:

(1) Only when all the equipment in normal operation, IED is able to use the function of self diagnosis to fault detection in IED. If there is a problem, the whole system will be driven to detect the fault.

(2) The system has some resources used for self-check, what make the performance of IED weakened. So it needs to expand the hardware to compensate for weakening, then the product cost also increases correspondingly.

(3) If a fault emerges in IEDs, the self-check results are not credible, and the self-check method is not standardized, which makes the processing of fault diagnosis complex.

To remedy the defects of self-check in monitoring the IEDs, we can monitor the temperature and moisture, temperature of CPU, CPU load and network card traffic. These monitored items can realize through sensors in itself or add a small electronic module. Then we can combine three information of self-check, status monitor and failure state together to analyze the fault causes in IEDs.

III. Fuzzy Petri Nets

The fuzzy theory is a mathematical theory to describe the uncertainty problem.

Fuzzy fault diagnosis is certain symptoms manifested through equipment membership to solve all kinds of fault factors of membership, requires large sample.

Fault diagnosis method based on Petri net and diagnostic reasoning can be integrated with knowledge representation in expert system, the fault generating process can be described and diagnosis reasoning, which can obtain more complete, rapid diagnostic results through matrix calculation.

A. What are Petri nets?

In the paper, Petri nets based on fuzzy theory are applied. Fuzzy Petri nets $FPN = (\mathrm{S}, \mathrm{T}; \mathrm{F}; \alpha, \beta, \gamma)$ is a hexahydric-combination, it meets:

(1) $PN = (\mathrm{S}, \mathrm{T}; \mathrm{F})$ is a Petri net;

(2) α is a map, $\alpha : \mathrm{S} \to [0,1]$ is the confidence coefficient mapping of places.

(3) β is a map, $\beta : \mathrm{T} \to [0,1]$ is the confidence coefficient mapping of transition.

(4) γ is a map, $\gamma : \mathrm{T} \to [0, \infty)$ is the threshold mapping of transition.

The confidence coefficient of place $\alpha \in [0,1]$, when the threshold of transition $\gamma > 1$,the corresponding transition of γ will never be activated, transition t is dead. So when $\gamma > 1$, the corresponding transition can be removed from the flow relation, and doesn't affect the constitute of FPN . For the transition t when $\gamma = 0$, the threshold of t can be ignored in the graphics system.

$\theta = (\alpha(\mathrm{s}_1), \alpha(\mathrm{s}_2), \cdots \alpha(\mathrm{s}_n))$ is a maker set of fuzzy Petri nets. If the fuzzy Petri net's maker set is M_0 , then the fuzzy Petri net is a fuzzy Petri net with maker.

A fuzzy Petri net is an organic combination of a plurality of inference rules in the field of some domains, while the values of s_1 , s_2 , s_3 $\cdots$ are the initial conditions in the whole referencing process. The conditional true values those s_1 , s_2 , s_3 $\cdots$ standardized represented are not gained from reasoning, but from Observation, measurement or test before reasoning.

B. Representation of Knowledge Rules Based on Fuzzy Petri Nets

In reality, knowledge mostly doesn't have accuracy for problem description, so in the knowledge system further introduces the fuzzy mathematics method, which seems to be more appropriate to say. Fuzzy production rules are a common and effective method to describe the fuzzy knowledge representation. The rule can be basically expressed as:

if d_i then d_j （$CF = \mu_k$）

d_i and d_j are some propositions that includes fuzzy variables, such as humidity, temperature , the temperature of CPU. These values of variables are in 0 and 1. μ_k is the confidence coefficient of rule, its value depends on established credibility of representation rule.

If takes the activation of production rules as transitions, then take the head of rules (i.e. conditions) as input places, and take the tail of rules as Petri nets output rules, so the production rule data base can be a complex Petri nets model.

In Petri nets, the value of the proposition corresponding on place can be represented by the place's mark, and depend on the fact base of the production system. The credibility of transition β is corresponding on and directly determined by the confidence coefficient of production rule. The directed arc between place and transition represents the reference direction in production rule base. Forward reasoning process is the running of fuzzy Petri nets. The problem which appears in the Petri network running process is inference problem of the production system.

Productions of fuzzy rules are the following:

Rule 1: if d_i and d_{i+1} and d_{i+2} $\cdots$ then d_j

Rule 2: if d_i then d_j and d_{j+1} and d_{j+2} $\cdots$

Rule 3: if d_i or d_{i+1} or d_{i+2} $\cdots$ then d_j

Three rules for Petri net can be expressed as:

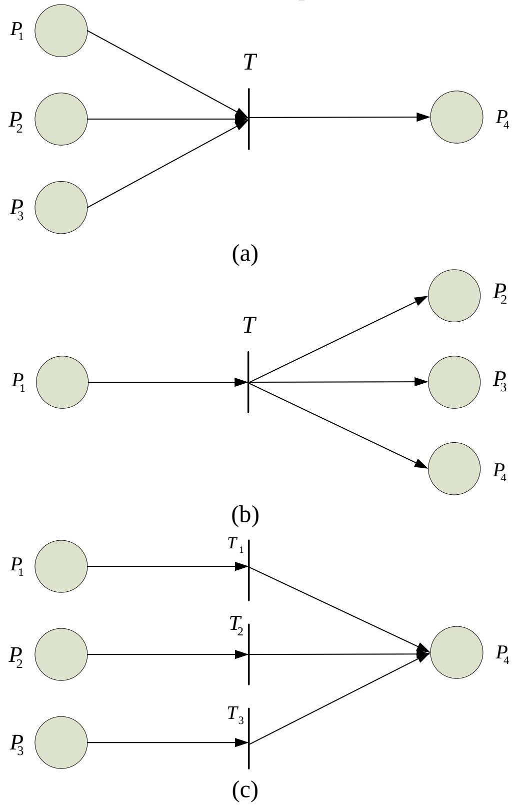

Fig.1 Three Production Rules based on Petri nets

The tokens in places represent the initial status, and the initial status of places can be expressed as $H \in B^{m\times 1}$, and the row number is the number of places. $H = [\mathrm{h}_1, \mathrm{h}_2, \mathrm{h}_3 \cdots \mathrm{h}_m]^T$, $\mathrm{h}_m = 0 \sim 1$, it's the confidence coefficient of propositions place.

C. Reasoning Matrix of Fuzzy Petri nets

This paper uses the confidence method of MYCIN, the main idea of this method

Is that the real value of fuzzy propositional conjunction is the minimum value of each sub type of true value, while the true value of fuzzy propositional disjunctive formula is the maximum value of each sub type of true value. Take these as a basis for the development of uncertainty reasoning method into a practical.

The methods of MYCIN confidence introduce two maximum-algebra operators:

$\oplus$: $\mathrm{a} \oplus b = c$, a , b and c are all n dimension vector, and $c_i = \max(\mathrm{a}_i, \mathrm{b}_i)$;

$\otimes$: $A \otimes b = d$, A is $m \times n$ dimension vector, b and d are separately n and m dimension vector, and $d_i = \max\limits_{i \le k \le n}(\mathrm{a}_{ik} \times b_k)$.

For a Petri nets with m places and n transitions, H_j is the status which is the system forward referencing j steps.

$$H_i = [\mathrm{h}_1(\mathrm{i}), \mathrm{h}_2(\mathrm{i}), \cdots \mathrm{h}_m(\mathrm{i})]^T \quad (1)$$

$$H_{\mathrm{i+1}} = \mathrm{H}_i \oplus \{[\mathrm{D}^+ \times \theta] \otimes [(\mathrm{D}^-)^T \otimes H_i]\} \quad (2)$$

$\theta = [\theta_1 \quad \theta_2 \quad \cdots \quad \theta_m]^T$, θ is the confidence coefficient of the rule and a $1 \times m$ dimension vector.

Definition 1:

D^+ is a output mapping matrix, $D^+ = [\mathrm{d}_{ij}^+] \in B^{m\times n}$, and $B^{m\times n}$ is a binary matrix. The element d_{ij}^+ in matrix D^+ represents that whether has a directed arc from transition T_j to the place P_i . If has, d_{ij}^+ is 1, otherwise 0.

Definition 2:

D^- is input mapping matrix, $D^+ = [\mathrm{d}_{ij}^+] \in B^{m\times n}$, $B^{m\times n}$ is a binary matrix. The element d_{ij}^- in matrix D^- represents that whether have a directed arc from place P_i to transition T_j . If has, d_{ij}^+ is 1, otherwise 0.

Just plug formula (1) into formula (2), after a series of fire operation, until there is no transition can be fired, the operation end. Finally the changes of tokens in H_i are the results of Petri nets.

IV. Fault Models Based on Petri Nets

At present, to implement the project of the unattended substation and reduce the main control building space, the installation way of intelligent electronic devices in substations is gradually changing from installing at the indoor screen cabinet to at the local outdoor cabinet. Electronic device placed outdoors shall be subjected to the test of high temperature, high humidity, strong electromagnetic interference and chemical corrosion. From the view of hardware, the factors of stress which influence electronic components life are electrical stress, thermal stress, radial stress, mechanical stress, climate stress and other types.

Considering that the substation intelligent electronic devices have been put into operation before the type test, electromagnetic compatibility testing, and single device testing, system Cascade adjustable multiple steps, so the equipment is in stable stage. There will be no obvious defects in equipments.

However, IED are continued to be functioned by the temperature, humidity, electromagnetic interference and corrosion environment in the long time running, component are aging and equipment crash. The probability of wearing failure greatly increases.

In the process of normal operation of the equipment, the factors of large CPU loads, dramatic increase in network traffic, software fault and other factors will also cause equipment fault.

Because the software fault problem belongs to another category of fault diagnosis, this paper will not consider the software factors.

In this paper, through the three acquisition device self-test, condition monitoring and fault status information, combined with the fault diagnosis of electronic equipment production rule base, fuzzy Petri net fault model.

According to the collected sample table, draw the Petri net model of IED fault diagnosis:

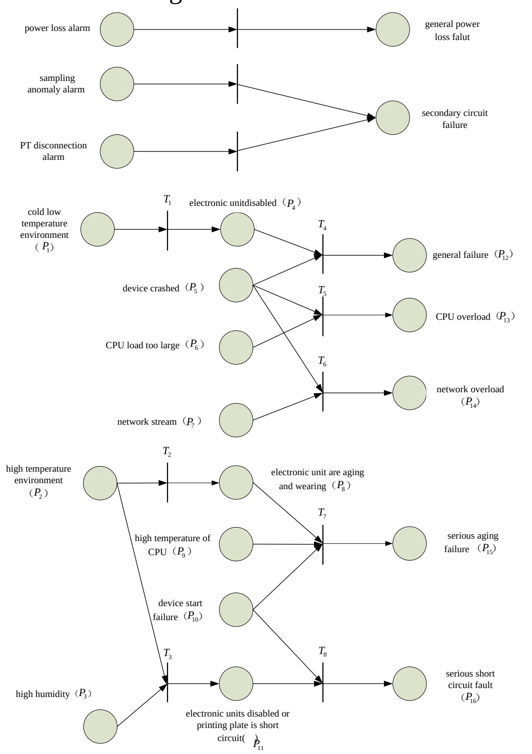

Fig.2 The fuzzy Petri net application of IED fault diagnosis

Rule 1 (T_1): IF the equipment is in the cold low temperature environment (P_1), THEN the electronic unit of the equipment disabled (P_4). The confidence coefficient $CF = 0.7$;

Rule 2 (T_2): IF the electronic unit of the equipment disabled (P_4), AND device crash (P_3), THEN it's general failure at low temperature (P_{12}).The confidence coefficient $CF = 0.7$;

Rule 3 (T_5): IF device crash (P_5), AND the load of CPU is too large (P_6), THEN it's failure of CPU overload (P_{13}). The confidence coefficient $CF = 0.8$;

Rule 4 (T_6): IF device crash (P_5), AND the flow of the network is too large (P_7), THEN it's failure of network overload (P_{14}).The confidence coefficient $CF = 0.8$;

Rule 5 (T_2): IF the equipment is in the high temperature environment (P_2), THEN electronic unit are aging and wearing (P_8). The confidence coefficient $CF = 0.8$;

Rule 6 (T_7): IF electronic unit are aging and wearing (P_8), and the temperature of CPU is high (P_9), AND the equipment can't start, THEN it's serious aging failure (P_{16}).The confidence coefficient $CF = 0.7$;

Rule 7 (T_3): IF the equipment is in the high temperature (P_2) and high humidity (P_3) environment, THEN it's the fault of electronic units or short circuit of printing plate (P_{11}). The confidence coefficient $CF = 0.9$;

Rule 8 (T_8): IF the electronic units disabled or printing plate is short circuit (P_{11}), AND the device can't start (P_{10}),THEN it's serious short circuit fault(P_{16}).The confidence coefficient $CF = 0.8$;

The above knowledge rules shows in Figure 2, and reasoning based on the fuzzy Petri net:

$$D^+ = \begin{bmatrix} 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1 \end{bmatrix}$$

$$D^- = \begin{bmatrix} 1&0&0&0&0&0&0&0 \\ 0&1&1&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&1&1&1&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&1&1 \\ 0&0&0&0&0&0&0&1 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \end{bmatrix}$$

The author participated in a study which has been applied to the engineering field of intelligent transformer component IED test. The IED undertakes processing function of partial discharge in transformer, monitoring of bushing at dielectric loss, color spectrum, vibration and noise monitoring project information, the board member of 8 blocks, severe fever.

Developers made a lot of small apertures on device top panel, aimed at easing the device heating. However, in the process of test for high temperature and high humidity, the tester monitored that the equipment was failure and unable to start.

By using the method described in this paper to analyze the device's failure. Device fault symptom: the equipment was in high temperature (The confidence coefficient is 0.9) and humidity (The confidence coefficient is 0.8) environment, the equipment can't start followed (The confidence coefficient is 1).

The initial status of tokens:

$$H_0 = \{0 \quad 0.9 \quad 0.8 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\} \tag{3}$$

The reliability of rules:

$$\theta = \{0.7 \quad 0.7 \quad 0.8 \quad 0.8 \quad 0.8 \quad 0.7 \quad 0.9 \quad 0.8\} \tag{4}$$

Plug formula (1) into (2), we can gain the iteration's results:

$$H_1 = \{0 \quad 0.9 \quad 0.8 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0.63 \quad 0 \quad 1 \quad 0.72 \quad 0 \quad 0 \quad 0 \quad 0.9 \quad 0.8\} \tag{5}$$

$$H_2 = \{0 \quad 0.9 \quad 0.8 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0.63 \quad 0 \quad 1 \quad 0.72 \quad 0 \quad 0 \quad 0 \quad 0.9 \quad 0.8\} \tag{6}$$

$H_1 = H_2$, the iteration ends.

The calculating results by reasoning machine matrix, IED electronic components aging wear probability is 0.63, the occurrence probability of electronic components or printed circuit is 0.72, the probability of serious fault is 0.8, and the probability of occurrence of serious aging failure was 0.9.

This is consistent with the physical sense equipment overheat condition components, printing plate insulation material is accelerated aging. Facts have proven that the device failure is caused by short and aging factors, open the fault device was found after a panel has a very short burn marks.

V. Conclusion

The example analysis represents that way proposed based on fuzzy Petri nets in the paper is simple and intuitive. The way adopts fuzzy Petri nets knowledge reasoning representation and matrix manipulation, converts complex electronic circuit design and fault analysis problem to computable mathematical problem, and not involved intricate quantitative statistics and probabilistic operations.

This method has a certain ability of artificial intelligence reasoning, for the development of application software to solve the electronic equipment fault diagnosis problem of complex provides a solid theoretical foundation.

In addition, the fuzzy Petri net according to the research progress on the mechanism of fault equipment on reasoning model and knowledge rules to extend and modify, knowledge base maintenance convenient, flexible.

Fuzzy Petri nets analysis constructs on electronic units expert diagnosis system, closed related with electronic circuit's structure. The paper just analyzes some large faults from the macroscopic aspect, need to further refine fault factors, failure mechanism and fault type. For embedded device, the soft faults can be included.

In engineering applications, IED software failure is the most common types of failure mechanism, the next step we will focus on software fault analysis using fuzzy Petri net reasoning method.

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