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## INTERMITTENT FAULT'S PARAMETER FRAMEWORK AND STOCHASTIC PETRI NET BASED FORMALIZATION MODEL

### MODEL PARAMETRYCZNY NIEZDATNOŚCI PRZEJŚCIOWEJ ORAZ MODEL FORMALNY OPARTY NA STOCHASTYCZNEJ SIECI PETRIEGO

*The intermittent fault widely exists in many products and brings high safety risk and maintenance cost. At present there are some different opinions on the notion of intermittent fault and there is no comprehensive parameter framework for fully describing intermittent fault. Also the formalization model which can mathematically describe intermittent fault hasn't been constructed. In this paper, the conception of intermittent fault is discussed. A new definition of intermittent fault is put forward. Then the intermittent fault's parameter framework is presented. After that, the Stochastic Petri Net (SPN) based formalization model for intermittent fault is constructed. Finally an application of the SPN formalization model is shown. The parameters for intermittent fault are computed based on the proposed model and a case study is presented. The result shows the validity of the model. The model could assist the further research such as intermittent fault diagnosis and prognostic of remaining life.*

**Keywords:** *intermittent fault, parameter framework, stochastic Petri net, formalization model.*

*Niezdatność przejściowa charakteryzuje wiele produktów i pociąga za sobą wysokie zagrożenie bezpieczeństwa oraz wysokie koszty eksploatacji. Obecnie istnieje wiele poglądów na temat pojęcia niezdatności przejściowej; nie stworzono jednak kompleksowego modelu parametrycznego pozwalającego w pełni opisać zjawisko niezdatności przejściowej. Nie skonstruowano także modelu formalnego, za pomocą którego można by opisać niezdatność przejściową w kategoriach matematycznych. W pracy omówiono koncepcję niezdatności przejściowej. Zaproponowano nową definicję tego pojęcia a następnie przedstawiono model parametryczny niezdatności przejściowej. Skonstruowano także model formalny niezdatności przejściowej oparty na stochastycznej sieci Petriego (SPN). Wreszcie, pokazano zastosowanie formalizacji SPN. Na podstawie zaproponowanego modelu obliczono parametry dla niezdatności przejściowej. Przedstawiono także studium przypadku. Otrzymane wyniki potwierdzają wiarygodność modelu. Opracowany model może być pomocny w dalszych badaniach dotyczących problemów, takich jak diagnozowanie niezdatności przejściowej czy prognozowanie pozostałego okresu użytkowania produktu.*

**Słowa kluczowe:** *niezdatność przejściowa, model parametryczny, stochastyczna sieć Petriego, model formalny.*

#### 1. Introduction

Intermittent fault (IF) exists in many products, including from small elements to huge complicated equipment. The frequent occurrence of intermittent fault brings on serious troubles and results in high maintenance cost and safety risk. Early in the late 1960s, Hardie[1, 8] had indicated that IFs comprised over 30% of pre-delivery failures and almost 90% of field failures in computer systems. Roberts[17] figured out that up to 80 to 90% of system faults was arisen by IF in some situations. Banerjee[2] indicated that in wireless sensor networks IF was the most frequently occurring. Intermittent faults bring on many maintenance problems, such as No Fault Found (NFF), Can Not Duplicate (CND) and so on[20]. In 2012 a survey among 80 aerospace organizations ranked IF as the highest perceived cause of NFF[23]. NFF problem has been the highest cost source in aerospace maintenance. For example, the annual NFF exchange cost of the F-16 avionics boxes due to the IFs was over \$20,000,000[21, 22].

Many issues of IF have been studied, including fault mechanism[4, 16], depicting parameters[5, 14], fault influence[7, 24], fault model, fault diagnosis[19, 22] and fault tolerance[3, 11, 12]. Sorensen[20] defined IF as any temporary deviation from nominal operating conditions of a circuit or device. Syed[23] defined IF as temporary mal-

function of a device. Upon these definitions the environment induced disturbance may also be regarded as IF. Pan[14] regarded IF as a hardware error which occurs frequently and irregularly for a period of time. Upon the definition the IF could be a hardware fault, but in the early stage, IF may not occur frequently. Prasad[15] proposed three-state Markov model of IF, including normal, IF and permanent fault state. Sedighi[18] constructed an analytical state-space model of a robot-arm and diagnosed it by the residual between the measured output and estimated output of the model. Masson[13] modelled the interconnect system with the undirected graph and analysed its sufficient and necessary conditions for diagnosis. Singh[19] constructed Factorial Hidden Markov Model (FHMM) to diagnose multiple IFs.

By far there are some confusions on understanding IF. In addition, despite some researchers partially characterize the IF, there is no comprehensive framework of parameters to fully depict it. Finally the proposed IF models and diagnosis methods are merely applicable in particular situation. There is no formalization model which can generally and roundly express the IF problem.

In view of the above problems, the conception of IF is discussed in section 2. The systemic intermittent fault event and IF are distinguished. A more appropriate definition of IF is given. In section 3 a comprehensive parameter framework of IF is presented, which can

exhibit the temporal and probabilistic characteristic of IF. Further in section 4, the Stochastic Petri Net (SPN) based formalization model for IF is constructed. Also the model solution is given briefly. After that, in section 5 an application of the SPN formalization model is shown. The parameters proposed before are computed based on the SPN model. The conclusion is in Section 6.

## 2. Conception of intermittent fault

At present the difference between the phenomena of systemic intermittent fault and corresponding cause has not been distinguished. This brings on some confusion. For example, hash electromagnetism may induce an instantaneous pulse and then cause an error. Then it could be inferred as an IF. But in fact the hardware is fault free. In this section, the causes of systemic intermittent fault events are discussed, one of which is IF. Then a new definition of IF is put forward.

### 2.1. Cause of systemic intermittent fault event

When there is an observation that a product intermittently loses its given function, a judgment that IF is occurring may be made. But in fact the intuitionistic observation of IF is just a superficiality which can be called systemic intermittent fault event. As shown in Fig. 1, the reasonable causes for systemic intermittent fault event include as below.

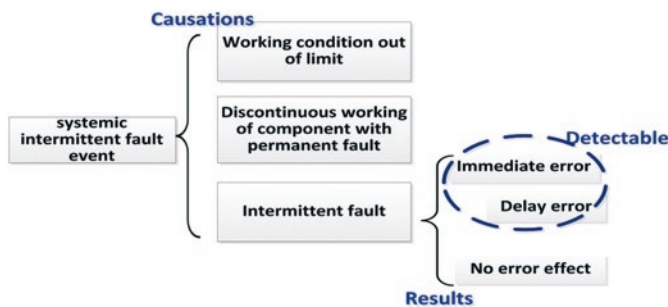


Fig. 1. Correlation between systemic intermittent fault event, IF and IF result

(1) Working condition of beyond limitation. The limitation here isn't the rated working environment, but the practical environment where components can work well. Due to the design defect and process variation, the appropriate working condition may not be consistent with the designed. The reasons of working condition going beyond limitation include variations of exterior environment and interior variations induced by components' working.

(2) Discontinuous activity of one component with permanent fault. As Kleer[6] indicated, there is a kind of IF which can disappear if it is modelled in a more detailed level. For example, when two wires are short-circuited, it looks like that the upper level gate has an intermittent fault. But in fact there is an un-modelled and unwanted connection. Practically in a piece of main equipment, the elements may not be working at the same time. If an element has a permanent fault, the fault appears only when it works. On the contrary, the fault would be temporarily masked if it doesn't work. Thereby the upper level function of this element manifests an intermittent off work.

(3) Intermittent fault. The occurrence of intermittent fault results from the essential physical degradation in products. This causes an intermittent interruption to normal function which will repeatedly manifest in a same characteristic.

### 2.2. Definition of intermittent fault

As shown in Fig. 1, intermittent fault will result in three cases, i.e. no error effect, immediate error and delay error. If there is no error when the IF occurs, it is no error effect. If the error occurs as soon as

the IF occurs, it is immediate error. If the error comes into being after a certain time of IF occurring, then it is delay error.

There are two situations when the IF result is no error effect. When the IF duration is temporary or its induced abnormal signal is slight, then it will not disrupt system's normal performance. In addition, if the product itself has recovery mechanism, then the IF induced error is masked. For example, the network communication protocol supports error detection and retransmission. When the network connector has a slight poor contact, some data packages would be lost and then re-transmitted. Thus the communication function is still accomplished.

Thereby it can be found that IF has three typical characters. First, its occurring moment and duration are stochastic. IF may be in active state when it occurs or inactive state when it is temporarily suspended. Also it can recover without intervention. Second, IF occurs due to the physical injury. Third, when an intermittent fault occurs, an error may be induced or not. Generally only the IF which can induce error is paid attention to.

In summary, IF could be defined as fault that occurs irregularly and repeatedly for a certain time. The definition is formally consistent with the definition of fault[10]. Upon this definition, the IF is a real fault induced by a physical injury. It indicates the temporal intermittent character of IF. So the IF differs from permanent fault. Also the repetitive character distinguishes the IF from transient fault. It may only last for a period of time, as it can be recovered without intervention.

## 3. Intermittent fault's parameter framework

The IF occurs randomly, and its duration is not deterministic. As Guilhemsang[7] indicated, IF can randomly occur for a few times or more and continue from a few nano-seconds to seconds. Wells[25] indicated IFs can hold on from a few cycles to seconds or more, even as long as some days. When the IF occurs, it can be called as an activity. And when the IF temporarily disappears, it can be called as inactivity.

Considering the temporal exhibition and stochastic characteristic of IF, a parameter framework with respect to time and statistical domain is required to fully depict IF.

### 3.1. Temporal parameters of intermittent fault

As below, there are eight parameters in time domain for IF.

- (1) IF activity time  $T_A$ . It denotes the duration of an IF activity.
- (2) IF inactivity time  $T_I$ . It denotes the interval time between two activities.
- (3) IF activity number  $N$ . It denotes the number of activities in specified time length  $T_s$ .
- (4) IF activity frequency  $f_N$ . It denotes the IF activity number in unit time. It can be calculated as the rate of IF activity number  $N$  and time length  $T_s$ .
- (5) IF lasting time  $T_L$ . It denotes the total time in a burst of continuous activities. It can be calculated as Eq. (1):

$$T_L = \sum_{i=1}^N T_A^i + \sum_{i=1}^{N-1} T_I^i \quad (1)$$

Where  $T_A^i$  is the duration of  $i^{\text{th}}$  activity,  $T_I^i$  is the interval time between  $i^{\text{th}}$  activity and its next.

(6) IF pseudo period  $T_p$ . It denotes the average time of a cycle of IF activities. Correcher[5] computes it as the rate in time window of all activities' time and activity number:

$$T_p = \frac{\sum_{i=j}^{i=k} t_{i+1} - t_i}{k - j + 1} \quad (2)$$

Where  $j$  and  $k$  respectively denotes the index of first and last activity in time window.  $t_i$  is the moment when the  $i^{th}$  activity occurs.

(7) Error delay time  $T_d$ . It denotes the time IF has been lasting for when the error occurs.

(8) Error duration time  $T_c$ . It denotes the lasting time of an error. It should be noted that even if the IF had turn into inactivity, the error can still continue for a certain time.

### 3.2. Probabilistic parameters of intermittent fault

Let  $\{IF_n | n=1,2,\dots,M\}$  denotes IF mode set, there are five probabilistic parameters of IF.

(1) IF existing probability  $p^I$ . It is the probability of existing  $IF_n$  and satisfies with  $p_n^I + p_n^N = 1$ , where  $p_n^N$  is the no fault probability.

(2) IF occurring condition probability  $p$ . It denotes the condition probability of given IF occurring when the product is faulty. That is:

$$p_n = \Pr\{IF_n | faulty\} > 0$$

$$s.t. \quad n=1,2,\dots,M, 0 < \sum_{n=1}^M p_n = 1 \quad (3)$$

It is computed as:

$$p_n = \frac{p_n^I}{\sum_{k=1}^M p_k^I} \quad (4)$$

(3) Fault activity probability  $p^A$ . It is the probability of IF in active state when IF is existing. That is:

$$p_n^A = \Pr\{IF_n \text{ is active} | IF_n\} > 0$$

$$s.t. \quad n=1,2,\dots,M, 0 < \sum_{n=1}^M p_n^A \leq M \quad (5)$$

The temporal failure density (TFD) proposed by Correcher[5] denotes the IF average active time in a sliding time window with window width  $W$ . TFD is computed as below:

$$D = \frac{T_C + \sum_{i=j}^{N_W} T_A^i}{W} \quad (6)$$

Where  $N_W$  is the number of activities in the window.  $j$  is the index of first activity.  $T_C$  is the remaining time in window of the fault which occurs before the window.

In fact, there is the relation between  $p_i^A$  and  $D$ :

$$p^A = \lim_{W \rightarrow 0} D \quad (7)$$

The parameter  $p^A$  will increase with time. This corresponds to the fact that IF is due to the physical degradation.  $p^A$  will grow with the degradation process, so it can be used to prognosticate the remaining life and determine the optimum time for maintenance or exchange.

(4) Fault inactivity probability  $p^{IA}$ . It is the probability of IF in inactive state when it exists. That is:

$$p_n^{IA} = \Pr\{IF_n \text{ is inactive} | IF_n\} > 0 \quad (8)$$

It satisfies with  $p_n^A + p_n^{IA} = 1$

(5) Causing error probability  $p^E$ . It is the probability of inducing an error when IF is active.

### 4. Stochastic Petri Net based formalization model for intermittent fault

The existing IF models don't cover all of the IF states and characters, or they can only be applied in particular situations. So a formalization model which is more general for different fields and more properly expresses the different states should be constructed. Petri Net (PN) can suitably depict complicate dynamic system[9]. Compared to Markov model, PN can model the transition with temporal character. In Stochastic Petri Net (SPN) the time between enable and firing of a transition is a stochastic variable which submits to a random distribution. So it is well consistent with the state transition of IF. That is the reason for adopting SPN to model IF.

In this section, the SPN of IF and corresponding Markov chain are drawn up. Then the SPN model is solved to obtain the transition probability matrix, the state probability distribution with time and the steady probability distribution.

#### 4.1. Construction of SPN formalization model

Only single IF is considered. The SPN model is shown in Fig. 2. The inhibitor arc and condition arc are introduced into the model to extend its expression efficiency on state transition. The arc with a

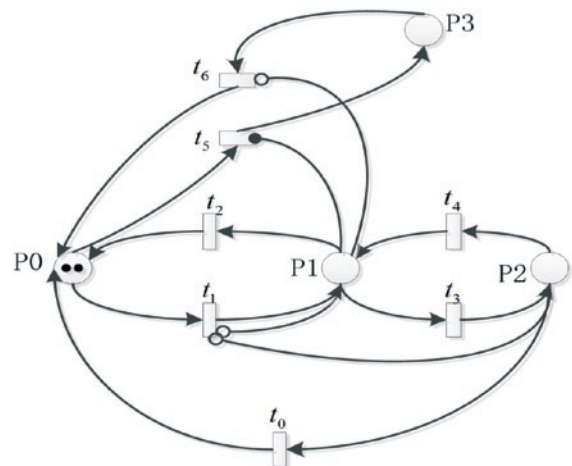


Fig. 2. SPN formalization model for single intermittent fault

white circle end is the inhibitor arc. It is enabled when its input place has zero token. The arc with a black dot end is the condition arc. It is enabled when its input place has defined tokens. The physical meanings of different places and transitions are listed in Table 1. The transition firing rate denotes the average firing times in unit time when it is enable. According to the physical meaning, there will be  $a_0 = a_2$ .

As shown in Fig. 2, it can be seen that the SPN model can effectively exhibit the IF characters such as state transition, temporal randomness and fault influence.

The SPN model for IF can be expressed as a septuplet.

$$SPN = \langle P, T, F, E, W, M_0, R \rangle \tag{9}$$

Where  $P = \{P_0, \dots, P_3\}$  represents the set of places,  $T = \{t_0, \dots, t_6\}$  represents the set of transitions,  $F$  represents the arcs,  $E = \{E_0, \dots, E_6\}$  represents the enable function of transitions,  $W$  represents the weight of arcs.  $M_0 = \{m_0, \dots, m_3\}$  represents the initial number of tokens in the places.  $R = \{a_0, \dots, a_6\}$  represents the set of transition firing rates.

Assume that the transition firing rate is subjected to negative exponential distribution. The SPN model will be homogeneous with finite Markov chain. After analysing, the IF SPN model is converted into a Markov chain, as shown in Fig. 3. The physical meanings of different states and the corresponding tokens in different places is shown in Table 2.

From Fig. 3, we can obtain the transition rate matrix  $Q$ :

Table 2. Markov states' meanings and token numbers in different places

M	P0	P1	P2	P3	Meanings
M0	2	0	0	0	NO IF, NO Error
M1	1	1	0	0	IF active, NO Error
M2	1	0	1	0	IF inactive, NO Error
M3	0	1	0	1	IF active, Error
M4	0	0	1	1	IF inactive, Error
M5	1	0	0	1	NO IF, Error

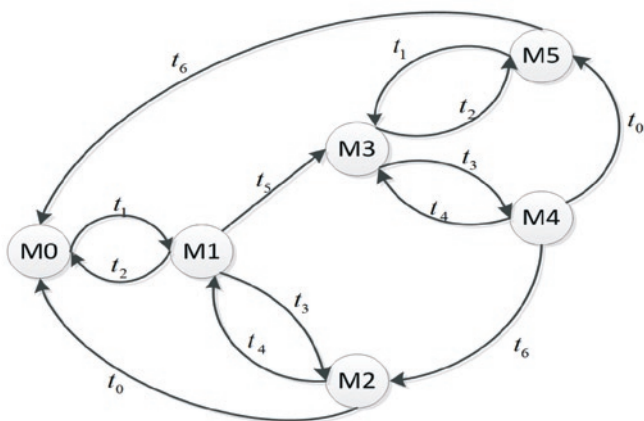


Fig. 3. Isomorphic Markov chain of SPN model

$$Q = [q_{ij}]_{6 \times 6} = \begin{bmatrix} -a_1 & a_1 & 0 & 0 & 0 & 0 \\ a_2 & -(a_2+a_3+a_5) & a_3 & a_5 & 0 & 0 \\ a_0 & a_4 & -(a_0+a_4) & 0 & 0 & 0 \\ 0 & 0 & 0 & -(a_2+a_3) & a_3 & a_2 \\ 0 & 0 & a_6 & a_4 & -(a_0+a_4+a_6) & a_0 \\ a_6 & 0 & 0 & a_1 & 0 & -(a_1+a_6) \end{bmatrix}$$

where  $\{q_{ij} \mid i, j = 0, 1, \dots, 5\}$  is the transition rate from state  $i$  to state  $j$ .

4.2. Probabilities solution of SPN formalization model

(1) Solution of transition probability

The transition probability matrix  $P(t)$  is:

$$P(t) = \begin{bmatrix} p_{00} & p_{01} & \dots & p_{05} \\ p_{10} & p_{11} & \dots & p_{15} \\ \vdots & \vdots & \ddots & \vdots \\ p_{50} & p_{51} & \dots & p_{55} \end{bmatrix}$$

where  $\{p_{ij} \mid i, j = 0, \dots, 5\}$  is the transition probability from state  $i$  to state  $j$ . Based on the Kolmogorov forward equation, the time derivative of  $P(t)$  is:

$$\dot{P}(t) = P(t) \times Q \tag{10}$$

Eq. (10) is solved to obtain:

$$P(t) = e^{Qt} = \sum_{k=0}^{\infty} \frac{(Qt)^k}{k!} \tag{11}$$

(2) Solution of state probability distribution

The probability of residing in state  $i$  at time  $t$  is  $p_i(t)$ , and then the state probability distribution at time  $t$  is:

$$F(t) = [p_0(t) \ p_1(t) \ \dots \ p_5(t)] \tag{12}$$

According to Fokker-Planck equation, the time derivative of  $F(t)$  is:

$$\dot{F}(t) = F(t)Q \tag{13}$$

Assume that the initial distribution is  $F(0) = [1 \ 0 \ 0 \ 0 \ 0 \ 0]$ , and then it can be obtained via the Laplace transform as follows:

$$F(s) = [1 \ 0 \ 0 \ 0 \ 0 \ 0] \times [sI - Q]^{-1} \tag{14}$$

So the state probability distribution at time  $t$  can be obtained via the inverse Laplace transform of Eq. (14). It satisfies with:

$$F(t) = [1 \ 0 \ 0 \ 0 \ 0 \ 0]P(t) \tag{15}$$

(3) Solution of steady state probability distribution

$\{P_i | i = 0, 1 \dots 5\}$  is the steady probability of residing in state  $i$ .

The steady state probability distribution is:

$$P_s = [P_0 \ P_1 \ \dots \ P_5] \quad (16)$$

Then Fokker-Planck equation is:

$$P_s Q = 0 \quad (17)$$

Solve Eq. (17) to obtain  $P_s$ . It is a linear equation set.

### 5. Application of the SPN formalization model

The SPN formalization model can mathematically express IF well. In this section the IF parameters defined previously are calculated based on the model.

#### 5.1. Computation of intermittent fault parameters

As can be seen, the fault activity number  $N$  depends on the evaluating time length. Activity frequency  $f_N$  depends on the activity number. IF lasting time  $T_L$  depends on the variation of environment such as vibration and temperature. IF occurring condition probability  $p_i$  is only considered when there are multiple IF modes. Fault inactivity probability  $p^{IA}$  can be calculated by subtracting fault activity probability from 1. So these parameters are not analysed by the SPN model.

(1) The expectation time of residing in different states can be calculated as:

$$T_i^E = E[T_i] = -\frac{1}{q_{ii}} \quad i = 0, \dots, 5 \quad (18)$$

(2) The expectation of IF activity time is:

$$\begin{aligned} T_A^E &= E[T_A] = E[T_1] + E[T_3] \\ &= -\frac{1}{q_{11}} - \frac{1}{q_{33}} = \frac{1}{a_2 + a_3 + a_5} + \frac{1}{a_2 + a_3} \end{aligned} \quad (19)$$

(3) The expectation of IF inactivity time is:

$$\begin{aligned} T_I^E &= E[T_I] = E[T_2] + E[T_4] \\ &= \frac{1}{a_0 + a_4} + \frac{1}{a_0 + a_4 + a_6} \end{aligned} \quad (20)$$

(4) The expectation of IF pseudo period is:

$$T_P^E = T_A^E + T_I^E \quad (21)$$

(5) The expectation of error delay time is:

$$T_d^E = E[T_d] = \frac{1}{q_{13}} = \frac{1}{a_5} \quad (22)$$

(6) The expectation of error duration time:

The stepping route of error states is shown in Fig. 4. There are two cyclic return paths. The expectation of error duration time is the summation of time in all the states.

When it is in state M4, the expectation time of one-step transition is:

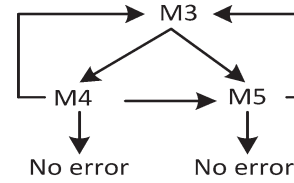


Fig. 4. Stepping route of error states in one cycle

$$T_c^{M4} = T_4^E + (p_{43}T_3^E + p_{45}T_5^E + p_{44}T_4^E) \quad (23)$$

When it is in state M5, the expectation time of one-step transition is:

$$T_c^{M5} = T_5^E + (p_{53}T_3^E + p_{55}T_5^E) \quad (24)$$

When it is in state M3, the expectation time of one-step transition is:

$$T_c^{M3} = T_3^E + (p_{34}T_4^E + p_{35}T_5^E + p_{33}T_3^E) \quad (25)$$

Because M3 is the initial state of the error cyclic route, so substitute  $T_4^E$  in Eq. (25) as  $T_c^{M4}$  and  $T_5^E$  as  $T_c^{M5}$ , the expectation time in one cycle is:

$$\begin{aligned} T_{c1} &= T_3^E + (p_{34}p_{43} + p_{35}p_{53} + p_{33})T_3^E \\ &\quad + (p_{34} + p_{34}p_{44})T_4^E \\ &\quad + (p_{35} + p_{34}p_{45} + p_{35}p_{55})T_5^E \end{aligned} \quad (26)$$

So the total time of error states after  $n$  cycles will be:

$$\begin{aligned} T_{cn} &= T_3^E + A(A+1)^{n-1}T_3^E \\ &\quad + B(A+1)^{n-1}T_4^E \\ &\quad + C(A+1)^{n-1}T_5^E \end{aligned} \quad (27)$$

Where  $A = p_{34}p_{43} + p_{35}p_{53} + p_{33}$ ,  $B = p_{34} + p_{34}p_{44}$ ,

$C = p_{35} + p_{34}p_{45} + p_{35}p_{55}$ .

As  $0 < A \ll 1$ ,  $(A+1)^{n-1}$  can be neglected when  $n$  is not large, so the expectation of error duration time can be calculated as:

$$T_c = T_3^E + AT_3^E + BT_4^E + CT_5^E \quad (28)$$

(7) IF existing probability is calculated as:

$$p^J = \frac{P_1 + P_2 + P_3 + P_4}{\sum_{s=0}^5 P_s} \quad (29)$$

(8) Fault activity probability is calculated as:

$$p^A = \frac{P_1 + P_3}{P_1 + P_2 + P_3 + P_4} \quad (30)$$

(9) Causing error probability is calculated as:

$$p^E = p_{13} \quad (31)$$

5.2. Case study

Take a connector’s intermittent contact fault as an example. The parameters are calculated based on the SPN model. Fault occurring rate is 1e-7, other rates is shown in Group 1 of Table 3. As shown in Fig. 5(a) and (b), resident time and steady probability of state M0 is very large, while in other states they are almost negligible. The existing probability of IF is just 9.9999e-6. It is because that the IF occurring rate is very small. As shown in Fig. 5(c) and (d), when IF occurs, fault activity time is greater than fault inactivity time, and fault activity probability is greater than fault inactivity probability. It is because that IF turning into inactivity rate is smaller than IF turning into activity rate. Since IF causing error rate is a little larger than sum of IF recovering rate and IF turning into activity rate, the IF causing error probability is 0.5 plus. The long error duration time is due to the low error recovering rate.

To compare with the generic situation, i.e. Group 1, set the rate of IF recovering, turning into inactivity and turning into activity an extreme value respectively, as shown in sets of Group 2-4 in Table 3. In the table the altered rates compared to Group 1 are marked with bold Italic font. It should be noted that the rate 100 is large enough to exhibit the margin result. The computation results are shown in Fig. 6. Compared to Group 1, in Group 2 the recovering rate is larger, so the IF existing probability is almost zero. IF activity time and inactivity time decreases, a Xiaomi YI nd it is almost always in active state when IF occurs. Compared to Group 1, in Group 3 the rate of IF turning into inactivity is so large that the fault is almost always inactive, so the inactivity time is greater than activity time and the fault activity probability decreases. Compared to Group 1, in Group 4 the rate of IF turning into activ-

ity is very large, thus the fault activity time is larger. Meanwhile both of the causing error probability and error duration time increase. In all the four groups, the causing error rate hasn’t been altered, so the error delay times are the same.

To examine the influence of continuous variety of one rate, set the fault occurring rate comparative with others. It is considered that the rate of IF turning to inactivity is varying from zero to seven and other rates are shown in Group 5 of Table 3. The result is shown in Fig. 7 and Fig. 8. It can be observed that when the rate of fault turning into inactivity increases, the resident time of state M1 and M3 decrease (curve 2 and 4 in Fig. 7(a)) as others keep in constant. It is due to the decrease of activity time (curve 1 in Fig. 8 (a)). Consequently both of the fault causing error probability (curve 3 in Fig. 8(b)) and error duration time (curve 5 in Fig. 8(a)) decrease.

As shown in Fig. 7(b), with the increasing of rate  $a_3$ , the probabilities in inactive state increase (curve 3 and 5), and the probability in

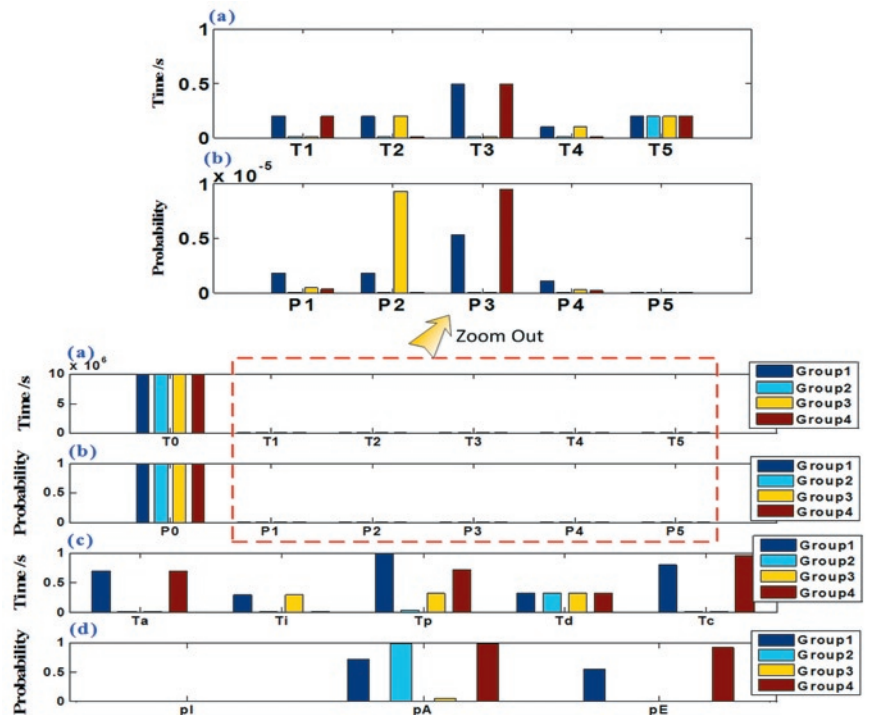


Fig. 6. Parameter solutions for different setting groups (a) resident time of states, (b) state steady probability, (c) different times, (d) different probabilities

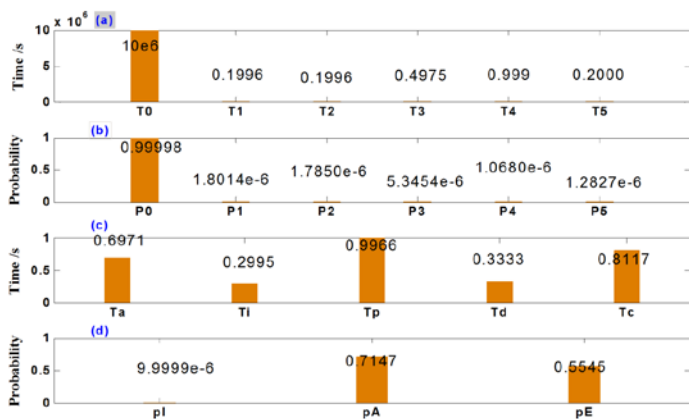


Fig. 5. Parameter solutions of connector intermittent contact fault (a) resident time of states, (b) state steady probability, (c) different times, (d) different probabilities

Table 3. Transition firing rate sets

Meanings	Rate	Group 1	Group 2	Group 3	Group 4	Group 5
IF recovering	$a_0$	0.01	<b>100</b>	0.01	0.01	<b>2</b>
IF occurring	$a_1$	1e-7	1e-7	1e-7	1e-7	<b>4</b>
IF recovering	$a_2$	0.01	<b>100</b>	0.01	0.01	<b>2</b>
IF turn into inactivity	$a_3$	2	2	<b>100</b>	2	<b>0~7</b>
IF turn into activity	$a_4$	5	5	5	<b>100</b>	5
IF causing error	$a_5$	3	3	3	3	3
Error eliminating	$a_6$	5	5	5	5	5

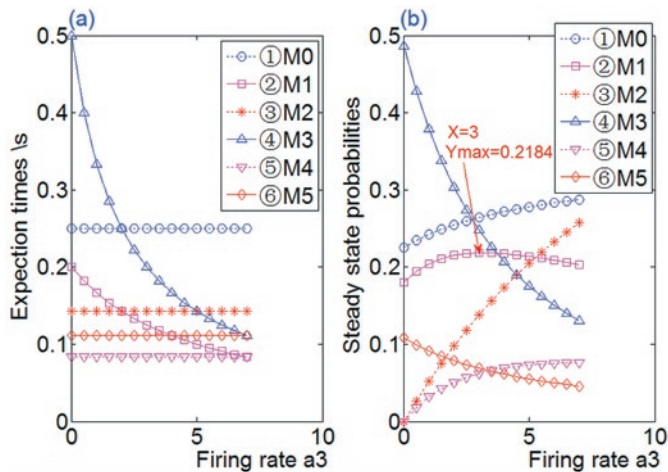


Fig. 7. Solutions of different states varying with IF turning into inactivity rate (a) expectation time, (b) steady state probability

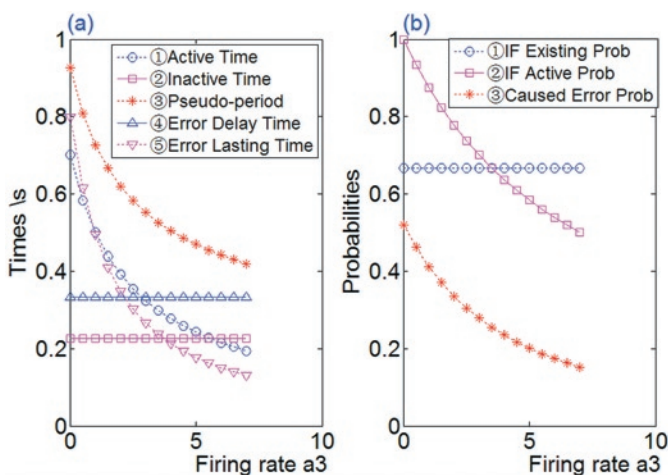


Fig. 8. Solutions of different states varying with IF turning into inactivity rate (a) times, (b) probabilities

error state decreases (curve 6). The reason of steady probability in state M0 increasing (curve 1) is the increasing opportunity of returning M0 from M2 via transition  $t_0$  when the steady probability in M2 increases rapidly (curve 3). The steady probability in state M1 first increases, reaching maximum value when  $a_3$  is three, and then de-

creases. As shown in Fig. 3, when  $a_3$  is zero, state M1 will turn into state M3 or M0. State M0 can return to M1, but state M3 can't return to M1. With the increasing of  $a_3$ , the probability of residing in state M2 increases, and thus the opportunity of returning from state M2 to M1 increases. Consequently the steady probability of M1 increases. But when the rate  $a_3$  is up to three, it is equivalent to the rate of transitioning from state M1 to M3, and then the effect of increasing steady probability of M1 which comes from the return transition from M2 to M1 is no longer predominant, thus the continuous rising of  $a_3$  will result in the increase of fault inactivity probability and decrease of activity probability.

The computation examples above show the availability of the SPN model. The parameters of IF can be analysed and calculated based on the SPN model. So the complicated IF problem is reduced to the study of transition firing rates.

## 6. Conclusions

In this paper the conception of IF is analysed, so as that the confusions on it are clarified. The systemic intermittent fault event and IF are distinguished, thus a more appropriate definition of IF is given out. Considering the statistical and temporal characters of IF, the parameter framework of IF is constructed, which includes the parameters in statistical domain and time domain. These parameters can more fully characterize the IF. And then the SPN formalization model for IF is proposed. This model can mathematically express the IF problem and reduce the complex problem into studying the seven parameters of transition firing rate. As an application of the SPN formalization model, the IF parameters can be calculated based on it. The computation method is given out and a case of calculating these parameters shows the availability of the SPN formalization model.

During the further research, the solution of transition firing rate should be studied, and then the IF diagnosis and prognostic of remaining life could be studied based on the SPN model.

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