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Edge Device Fault Probability Based Intelligent Calculations for Fault Probability of Smart Systems

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Abstract: In a smart system, the faults of edge devices directly impact the system's overall fault. Further, complexity arises when different edge devices provide varying fault data. To study the Smart System Fault Evolution Process (SSFEP) under different fault data conditions, an intelligent method for determining the Smart System Fault Probability (SSFP) is proposed. The data types provided by edge devices include the following: (1) only known edge device fault probability; (2) known Edge Device Fault Probability Distribution (EDFPD); (3) known edge device fault number and EDFPD; (4) known factor state of the edge device fault and EDFPD. Moreover, decision methods are proposed for each data case. Transfer Probability (TP) is divided into Continuity Transfer Probability (CTP) and Filterability Transfer Probability (FTP). CTP asserts that a Cause Event (CE) must lead to a Result Event (RE), while FTP requires CF probability to exceed a threshold before RF occurs. These probabilities are used to calculate SSFP. This paper introduces a decision method using the information diffusion principle for low-data SSFP determination, along with an improved method. The method is based on space fault network theory, abstracting SSFEP into a System Fault Evolution Process (SFEP) for research purposes.

Key words: smart systems; intelligent science; edge device; fault probability; decision method

1 Introduction

The Internet of Things (IoT) represents a new era in the information industry, following the advancements of computers, the Internet, and mobile communication networks. Its objective is to establish seamless connections between physical objects, information technology systems, and individuals across the globe using diverse information sensing devices and intelligent communication systems. Through operations, such as data collection, analysis, prediction, and optimization, IoT aims to enable the management of the physical world. This integration of the physical realm with informational assets forms a sophisticated and intelligent environment.

IoT generates a vast amount of data that requires processing and analysis before their effective utilization. Edge computing plays a crucial role in bringing computing services closer to end users or data sources, such as IoT devices. It primarily extracts the necessary data and functions from various devices through multiple protocol transformations, enabling real-time processing or uploading of the data to cloud platforms. In addition to transmission capabilities, edge computing encompasses essential functionalities, including data filtering, cleaning, aggregation, and monitoring. These IoT devices operating at the edge are known as edge devices. These edge devices are the edges of the IoT, people and the environment

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communicate with the IoT through these devices. They form a network structure based on IoT communication, which serves as the foundation of the entire IoT system. The faults of all edge devices directly impact the system’s overall fault, making the fault probability of each edge device to be a determining factor for fault probability of IoT. Thus, all IoT devices, including edge devices, constitute a smart system.

In such a smart system, fault determination is based on causality. Causality describes that faults occur in a particular order on the macrolevel, while on the microlevel, it represents the logical causality of fault occurrence among IoT devices. Therefore, predicting, preventing, and managing these fault processes necessitate a comprehensive study of the fault processes of edge devices. However, existing methods struggle to accurately elucidate the intricate network structure of these processes, logical relationships between faults, dynamic nature of system fault influenced by multiple factors, and processing of fault data information. Consequently, the analytical capability for fault analysis remains limited, leading to Smart System Faults (SSFs), accidents, and disasters. Artificial intelligence-based solutions alone are inadequate. It becomes imperative to leverage intelligent theories in conjunction with the distinctive characteristics of these fault processes to establish suitable intelligent computing methods that address decision problems related to fault prediction and prevention.

Currently, considerable research is focused on smart systems and environments, encompassing various aspects, such as SSFs[1], blockchain faults[2], smart grid faults[3–5], reliability of smart monitoring[6], reliability of smart operations[7], smart grid and cloud computing[8], multiagent faults[9], knowledge smart factory faults[10], smart agriculture[11], smart intercity electric traction systems[12], smart hospitals and healthcare systems[13], energy management systems[14], and smart-city environments[15]. Further, there are studies on topics, such as the IoT paradigm[16], novel machine learning based frameworks[17, 18], and security and privacy in cyberspace[19]. However, there remains a gap in research regarding the abstraction of smart systems based on IoT, which poses challenges in determining the fault conditions of smart systems based on the fault conditions of edge devices in IoT. In other words, calculating the fault probability of smart systems from the fault probability of edge devices is difficult. This difficulty hinders progress in research on the application reliability of smart systems based on IoT in smart environments.

This paper introduces the concept of system faults in terms of System Fault Evolution Processes (SFEP) and proposes a Space Fault Network (SFN) to describe and analyze the processes. This approach aims to establish an intelligent calculation method applicable to determining fault probability in Smart System Fault Evolution Processes (SSFEPs). This paper primarily focuses on investigating SSFs using the SFN, considering four distinct fault data scenarios arising from edge devices. This paper presents methods for obtaining the fault probability, fault number, and fault probability distribution based on the available data.

The paper includes an introduction to the research background in Section 1. The remaining sections are as follows: Section 2 introduces the basic concepts of SFNs. Sections 3 and 4 introduce the system fault calculation method based on Continuity Transfer Probability (CTP) and that based on Filterability Transfer Probability (FTP), respectively. Section 5 provides a calculation method in the case of limited data. Section 6 discusses the improved method discussed in the fifth section, and Section 7 provides some discussions and comparisons. Notably, the study of the SSFEP focuses on system faults, making the fault probability distribution or fault probability statements directly associate with the fault process. The fault probability distribution and fault probability correspond to the abstract SSFEP, essentially conveying the same meaning. Furthermore, the Transfer Probability (TP) can be categorized into two types: in Section 4, TP refers to FTP, while in the remaining sections, TP refers to CTP. Section 8 concludes this paper. Table 1 lists some abbreviations for convenient reference.

Table 1 List of abbreviations.

Abbreviation	Full spelling
CE	Cause Event
RE	Result Event
SFEP	System Fault Evolution Process
SFN	Space Fault Network
CTP	Continuity Transfer Probability
FTP	Filterability Transfer Probability
TP	Transfer Probability
SSF	Smart System Fault
SSFEP	Smart System Fault Evolution Process
SSFPD	Smart System Fault Probability Distribution
SSFP	Smart System Fault Probability
EDFPD	Edge Device Fault Probability Distribution

2 Related Concepts and Our Work on SFN

Smart systems hold importance in meeting specific functional requirements, and the extent of the fulfillment of these requirements is referred to as reliability. System faults are of particular concern as they necessitate the rational allocation of the limited resources to prevent such faults. Therefore, the pursuit of system reliability often translates into the objective of minimizing system faults. A system fault is essentially a deviation in system functionality caused by the combined effects of multiple factors or a single factor. Thus, the process of system faults can be defined as a an SFEP, which captures the changes in these factors. SFEPs comprise numerous events occurring within a topological network evolution process, featuring diverse logical relationships among the events, which are influenced by various factors. SFEPs are ubiquitous, existing in artificial systems consciously designed by humans for specific purposes and natural systems that form spontaneously based on natural laws. SFEPs provide a framework for describing these apparently disparate processes at the system level, abstracting them into a system composed of events, transfers, factors, and logical relationships. Consequently, a challenge lies in effectively describing the abstracted system fault, analyzing related SFEP, and making informed decisions based on this analysis.

The analysis methods of SFEPs must fulfill certain requirements. They should be able to effectively describe, analyze, and make decisions regarding the impact of various factors on events and transfers, logical relationships between events, evolution process on macro and microlevels, interactions among events, and network structures. Although existing analysis methods are available, such as formal concept analysis[20], interpretative structure[21], system dynamics[22], and signed digraph[23], they often lack the ability to simultaneously fulfill all these requirements.

The authors in this paper initially proposed Space Fault Tree (SFT) in 2012[24], which comprises four stages. These stages encompass the fundamentals of SFT[25, 26], intelligent SFT[27, 28], and the development of an SFN[29] for the SFEP. SFN was first built upon the foundation of SFT and inherited the capabilities of multifactor analysis and intelligent logical reasoning causality. The original tree topology of SFT faced challenges in conducting network structure analysis, leading to the introduction of SFN. SFN serves as a method for network topology analysis, representing logical relationships and multifactors using a point-line structure. Hence, SFN is more suitable for fault decision making within SFEPs. In SFN, nodes represent events and entail the logical structure between Cause Events (CEs), while lines represent connections, signifying the transfer relationships between events. These connections indicate the TP, which represents the likelihood of Result Events (REs) being caused by CEs. When a CE cannot cause an RE in general or under certain conditions, the connection is deemed a virtual connection and should be removed, resulting in a TP value of 0. However, if a CE can cause an RE, the TP falls within a range of [0, 100%]. Therefore, SFN forms the basis for decision making within SFEP, particularly when faced with a substantial amount of fault information. It becomes essential to combine intelligent analysis with decision making, leading to the establishment of a system fault decision method with intelligent analysis capabilities. The above discussion indicates that SFEPs can describe SSFEPs, and SFN can serve as a mathematical tool for studying SSFEPs. The concepts introduced in SFEP are applicable to describe the corresponding concepts in SSFEPs, as indicated by the literature. Subsequently, the study will further explore the concepts within SSFEP.

3 SSF Based on CTP

Definition 1 CTP: On the premise that a reasonable logical relationship exists between device faults that cause other device faults (namely, CFs) and device faults caused by other device faults (namely, RFs), the CF probability itself is neglected and only the probability of RFs after CFs is considered structurally.

CTP assumes that no matter what CF probability is, RF occurrence will have a certain nonzero probability. That is the possibility of an RF in case of CF occurrence. This definition is similar to that of TP in the original SFN.

3.1 Intelligent calculation method for Smart System Fault Probability (SSFP)

In SSFEP, an edge device fault (this is equivalent to EF) is generally considered the starting point of an SSFEP, and the SSF is considered the stopping point of the SSFEP, which can also be the fault concerned in SSFEP. Device faults comprise device and fault states. The device state is the external performance of the device, and the fault state is affected by different factors. The device fault probability can be represented by the Edge Device Fault Probability Distribution

(EDFPD)[25] under the influence of multiple factors. Based on four types of fault data, SFN is used to describe the calculation methods of SSFP, smart system fault number, and Smart System Fault Probability Distribution (SSFPD) of SSFEPs. For explanation, an analysis example is provided, and an SFN is shown in Fig. 1[30].

From Fig. 1a, we see the SFN of an SSFEP. By definition, e_1, e_2, e_3, e_6, and e_{11} are edge device faults (namely EFs) in SFN; e_{21} and e_{22} are SSFs; and the remainders are device faults in SSFEP. The subscripts of these events represent the logical relationship between their causal events, where "+" and "·" represent "or" and "and" relationships of the causal event, respectively. The solid arrows indicate connections, and the arrow direction is from CF to RF, containing TP, which is represented by q. Figures 1b–1f show the EDFPD of all EFs. Four intelligent calculation methods for SSFPs are proposed: (1) record EDFP, excluding the influence of factors; (2) record EDFPD; (3) record edge device fault number within the specified conditions; and (4) record the corresponding factor states and EDFPD when an EF occurs.

Case I: Edge device fault probability is recorded only to establish Method I. These probabilities are obtained under device design or test, and are usually numerical values, and there is no corresponding factor state record in case of a specific fault; thus, EDFPD is unobtainable. However, SSFP is obtainable using SFN. Establish the relationship set S between CFs and RFs in the following:

$$S = \mathrm{CF} \to \mathrm{RF} = \begin{cases} q_{\mathrm{RF}} = \coprod (q_{\mathrm{CF}\to\mathrm{RF}} \cdot q_{\mathrm{CF}}), \text{ or;} \\ q_{\mathrm{RF}} = \prod (q_{\mathrm{CF}\to\mathrm{RF}}), \text{ and;} \\ q_{\mathrm{RF}} = q_{\mathrm{CF}\to\mathrm{RF}} \cdot q_{\mathrm{CF}}, \text{ trans} \end{cases} \quad (1)$$

Case I: Edge device fault probability is recorded only to establish Method I. These probabilities are obtained under device design or test, and are usually numerical values, and there is no corresponding factor state record in case of a specific fault; thus, EDFPD is unobtainable. However, SSFP is obtainable using SFN. Establish the relationship set S between CFs and RFs in the following:

Figure 1 shows three basic relationships, "and", "or", and "transfer". For example, faults e_6 and e_5 lead to fault e_7, which is expressed as $q_{e_7} = q_{23} \times q_{e_6} \times q_{22} \times q_{e_5}$ in S (see Eq. (1)). Alternatively, "or" relationship, such as that between e_2 and e_3, leading to e_5, which is expressed in S by Eq. (1) as $q_{e_5} = 1-(1-q_{26} \times q_{e_2}) \times (1-q_{27} \times q_{e_3})$. All CF and RF relationships form a relationship set S. According to the SFN analysis sequence, we start from SSFs to determine its CF, and then continue to determine the CF as an RF until the CF is an EF. Combining all the relationships in S forms the smart system fault probability analytic expression. Equation (2) shows the Smart System Fault Probability Analytic Expression (SSFPAE) of e_{21},

$$\begin{aligned} q_{e_{21}} = & q_1 \times q_7 \times q_{13} \times (1-(1-q_{20} \times q_{e_1}) \times (1-q_{28} \times \\ & q_{21} \times (1-(1-q_{24} \times q_{e_1}) \times (1-q_{25} \times q_{e_2})))) \times \\ & q_{14} \times (1-(1-q_{19} \times q_{21} \times (1-(1-q_{24} \times q_{e_1}) \times \\ & (1-q_{25} \times q_{e_2}))) \times (1-q_{18} \times q_{23} \times q_{e_6} \times q_{22} \times \\ & (1-(1-q_{26} \times q_{e_2}) \times (1-q_{27} \times q_{e_3}))) \times \\ & (1-q_{17} \times q_{e_{11}})) \end{aligned} \quad (2)$$

Case II: EDFPD is recorded to establish Method II. This requirement is essential for using SFN, recording the corresponding fault probability under different factor states. Figures 1b–1f show all EDFPDs. The calculation method is the same as Eq. (1), and the same S is formed. SSFPAE is the same as Eq. (2), except that a single probability value becomes a distribution.

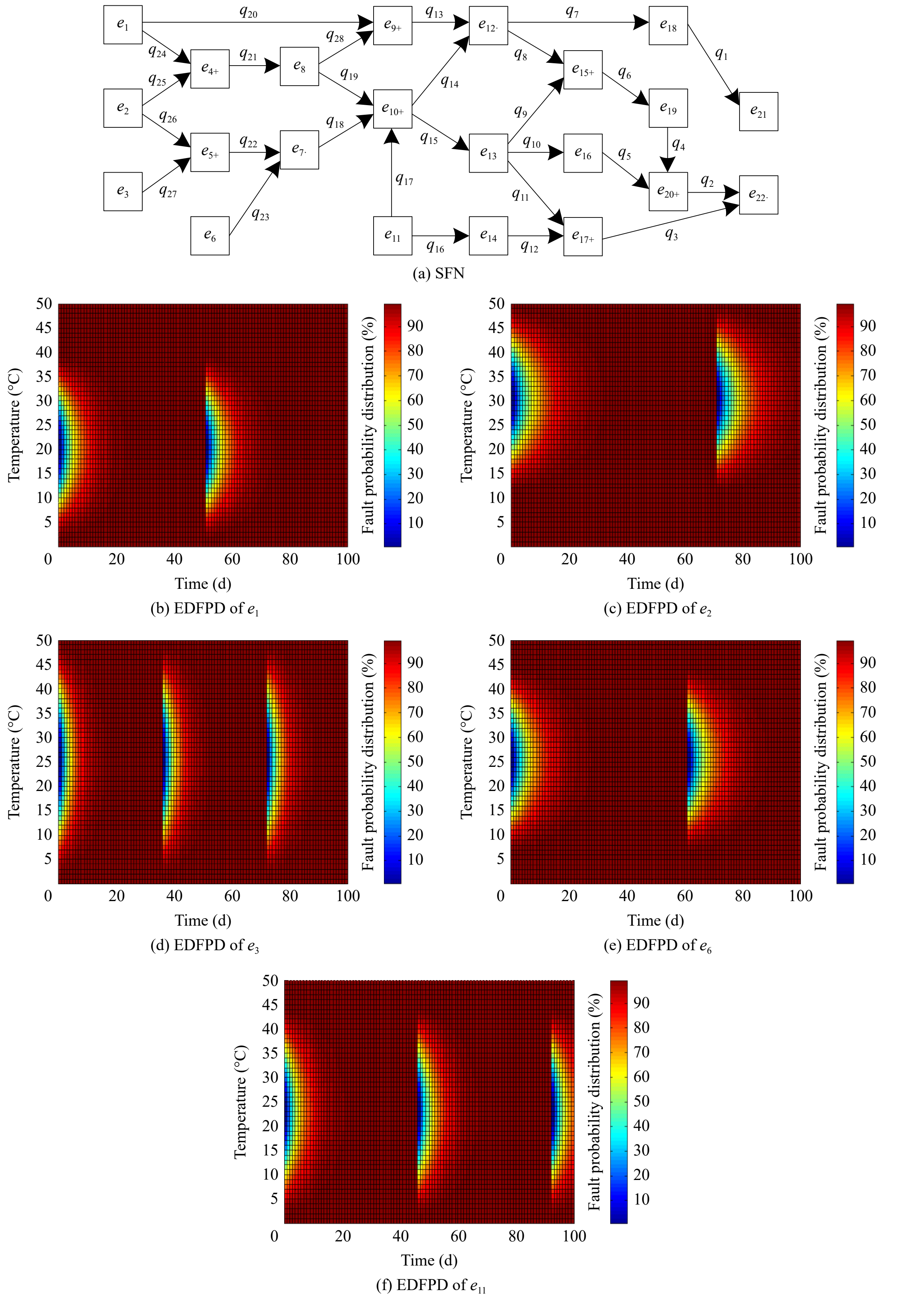
Case III: EDFN within the specified conditions is recorded to establish Method III, and each EDFPD is known. In a certain range, different EDFNs will lead to a change in SSFN. In contrast to the probability logic of Methods I and II, the fault number logic is used to form S, but the method of forming SSFPAE is identical. S is shown in the following:

$$S = \mathrm{CF} \to \mathrm{RF} = \begin{cases} q_{\mathrm{RF}} = \sum (q_{\mathrm{CF}\to\mathrm{RF}} \cdot q_{\mathrm{CF}}), \text{ or;} \\ q_{\mathrm{RF}} = \min (q_{\mathrm{CF}\to\mathrm{RF}} \cdot q_{\mathrm{CF}}), \text{ and;} \\ q_{\mathrm{RF}} = q_{\mathrm{CF}\to\mathrm{RF}} \cdot q_{\mathrm{CF}}, \text{ trans;} \\ q_{\mathrm{RF}} = q_{\mathrm{EF}} \cdot N_{\mathrm{EF}} \end{cases} \quad (3)$$

where q_{EF} is EDFPD and N_{EF} is EDFN.

"or" represents the "or" relationship, as shown in Fig. 1, and the numbers of e_2 and e_3 affect the number of e_5, which is expressed as $q_{e_5} = q_{26} \times q_{e_2} + q_{27} \times q_{e_3}$. Further, "and" represents the "and" relationship, and e_7 occurs at the same time as those of e_6 and e_5, which is expressed as $q_{e_7} = \min\left(q_{23} \times q_{e_6},\ q_{22} \times q_{e_5}\right)$, while the "trans" relationship is expressed as $q_{e_{18}} = q_7 \cdot q_{e_{12}} \cdot q_{\mathrm{EE}} = q_{\mathrm{EE}} \cdot N_{\mathrm{EE}}$ indicating that the EDFPD is amplified by multiplication according to EDFN.

Case IV: EF and the status of corresponding factors are recorded to establish Method IV, and each EDFPD is known. The records include not only the EDFPD



(a) SFN

(b) EDFPD of e_1

(c) EDFPD of e_2

(d) EDFPD of e_3

(e) EDFPD of e_6

(f) EDFPD of e_{11}

Fig. 1 SFN and its EDFPD.

obtained from the analysis but also the actual situation. In the calculation process of Method II, the corresponding positions of all EFs in EDFPD can be changed to 1, and the rest of the distribution remains unchanged. Thus, the fault probability is 1. However, the accuracy depends on the actual EDFN. The formation method of S and SSFPAE is identical to that of Method II.

According to the four fault data characteristics, four SSF calculation methods are proposed based on CTP.

3.2 Example

According to the SFN given in Fig. 1, the states of SSFs in the above four data cases are analyzed. The research range is time $t \in [0, 100]$ d, temperature $c \in [0, 50]$ ℃. Set all TPs as 0.1.

For Case I, set all EDFPs to 0.01, then the SSFPs are $q_{e_{21}} = 1.0404 \times 10^{-6}\%$ and $q_{e_{22}} = 1.2364 \times 10^{-8}\%$.

For Case II, EDFPDs are shown in Figs. 1b–1f, and the SSFPDs of e_{21} and e_{22} are shown in Fig. 2.

As seen from Fig. 2, the SSFPD of e_{21} is two orders of magnitude larger than that of e_{22}. This result is related to the number of the EF and the connections of the SSFEP. If SSFPAE is expanded, multiple polynomials connected by "+" and "–" are obtainable. Each polynomial connected by "+" represents a possibility of an SSF, called the incremental unit fault SSFEP. Since EDFP and TP are smaller than 1, fewer EFs and a smaller number of connections lead to higher SSFP. Moreover, SSFP mainly depends on the incremental unit fault SSFEP with fewer EFs and fewer connections. Therefore, the causes and transfer processes of e_{22} are more complex than those of e_{21}, and more EFs and transfers are needed. Thus, e_{22} requires more conditions, and its SSFPD is two orders of magnitude smaller than that of e_{21}.

For Case III, five EDFPDs are shown in Figs. 1b–1f; they are e_1, e_2, e_3, e_6, and e_{11}, and their values of time are 30, 50, 100, 70, and 25 d, respectively. The distribution depends on the EDFN; that is, when the values of time of e_1, e_2, e_3, e_6, and e_{11} are 30, 50, 100, 70, and 25 d, respectively, the distribution is obtainable. The frequency of e_{21} is approximately 10^{-3}. Therefore, e_{21} may occur once when the EDFN is increased by 10^3. Similarly, the frequency of e_{22} is approximately 10^{-4}. When each EDFN is expanded by 10^4, e_{22} may occur once.

For Case IV, conditions are identical to those of Case III. The probability of EF is set to 1 at the corresponding position in the probability distribution.

4 SSF Based on FTP

Compared with CTP, FTP takes TP as the threshold value and believes that RF may occur only after the probability of CF exceeds TP. TP is FTP in this section.

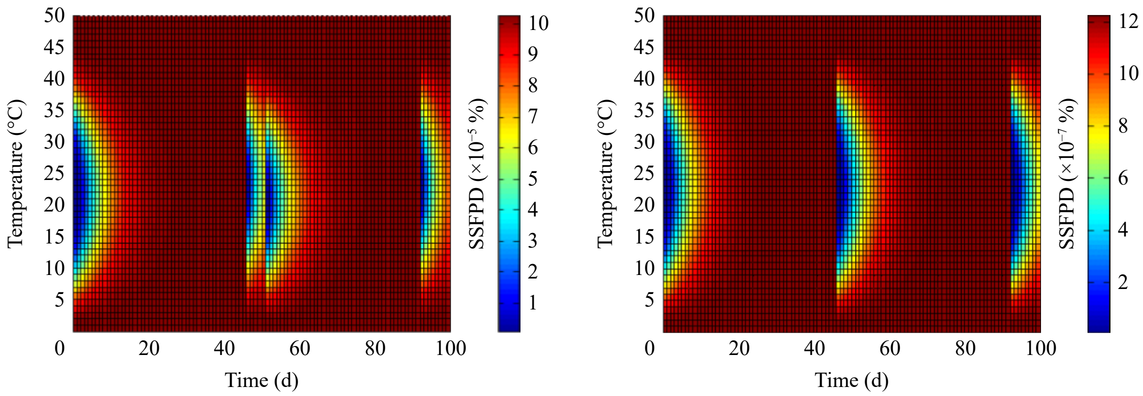
Definition 2 FTP: When the probability of CF exceeds TP, RF occurs; the threshold TP is called FTP.

Let q_1 be CF probability, q_2 be RF probability, and q is TP. Then, when q is CTP, Eq. (4) is the relationship; when q is FTP, Formula (5) is the relationship, as shown in the following:

$$q_1 \times q = q_2 \tag{4}$$

$$\begin{cases} q_1 \geqslant q,\ q_2 = q_1; \\ q_1 < q,\ q_2 = 0 \end{cases} \tag{5}$$

Obviously, according to these two forms of TP, the SSFP of SSFEP is also different. CTP can always obtain nonzero SSFP under the premise of logical relationships between events. However, the probability is usually small. Because in SSFEP, the more EF and



(a) SSFPD of e_{21} (b) SSFPD of e_{22}

Fig. 2 SSFPD obtained by Method II.

connections, the smaller the SSFP. The more EF is, the more complex SSF will be. The more connections, the more complex the SSFEP is. Therefore, after the actual complex SSFEP, SSFP is often very small. Meanwhile, the more EF and connections, the more conditions of SSF are needed, reducing the probability of SSF. FTP only selects the case where the probability of CF is greater than the given probability and passes it to RF. For the fault probability distribution, FTP is only allowed to pass down if it is larger than its probability distribution. Therefore, the nonzero fault probability gradually decreases monotonically, but the SSFPD will be very large. At this time, TP does not participate in the fault probability calculation of SSF but only selects and filters it. Accordingly, CTP allows all probability distributions to pass, but the possibility merits consideration. Therefore, the probability distribution is multiplied by TP to obtain the probability distribution of RF. The two types of TPs have different characteristics, different methods, and different results, so the ranges of use differ.

4.1 Intelligent calculation method for SSFP

According to the characteristics of FTP, three types of data are analyzed.

(1) Method I for Case I. When EDFP is a single value, Eq. (6) completes the calculation of SSFP in the following:

$$S = \mathrm{CF} \to \mathrm{RF} = \begin{cases} q_{\mathrm{RF}} = \coprod q_{\mathrm{CF}} = \begin{cases} q_{\mathrm{CF}} = q_{\mathrm{CF}}, \text{ if } q_{\mathrm{CF}} \geqslant q_{\mathrm{CF}\to\mathrm{RF}} \\ q_{\mathrm{CF}} = 0, \text{ if } q_{\mathrm{CF}} < q_{\mathrm{CF}\to\mathrm{RF}} \end{cases}, \text{ or;} \\ q_{\mathrm{RF}} = \prod q_{\mathrm{CF}} = \begin{cases} q_{\mathrm{CF}} = q_{\mathrm{CF}}, q_{\mathrm{CF}} \geqslant q_{\mathrm{CF}\to\mathrm{RF}} \\ q_{\mathrm{CF}} = 0, \text{ if } q_{\mathrm{CF}} < q_{\mathrm{CF}\to\mathrm{RF}} \end{cases}, \text{ and;} \\ q_{\mathrm{RF}} = q_{\mathrm{CF}} = \begin{cases} q_{\mathrm{CF}} = q_{\mathrm{CF}}, \text{ if } q_{\mathrm{CF}} \geqslant q_{\mathrm{CF}\to\mathrm{RF}} \\ q_{\mathrm{CF}} = 0, \text{ if } q_{\mathrm{CF}} < q_{\mathrm{CF}\to\mathrm{RF}} \end{cases}, \text{ trans} \end{cases} \tag{6}$$

Equation (6) shows that when CF causes RF with an "or" relationship, if the probability of CF is greater than TP, the probability of CF will remain unchanged; if it is less than TP, the probability of CF will be 0; finally, the probability of RF will be calculated according to the "or" relationship. When CF causes RF with an "and" relationship, the probability of RF is calculated according to the rule. When CF causes RF with a "trans" relationship, the probability of RF is calculated according to the rule. SSFPD is the superposition of the relationships in *S*, forming an SSFPAE and calculating the SSFP or distribution.

(2) Method II for Case II. The characteristic is that EDFPD forms, and Eq. (6) calculates the same SSFPD. The difference from Case I lies in a single value and distribution. In fact, fault probability is a statistical probability that is obtainable from the statistics of faults in different states. The characteristic is accurate and easy to handle; the disadvantage is to confuse the faults under the influence of different factors with the fault probability under the same situation and then calculate the probability. The fault probability distribution or fault probability in SFN applies to represent the fault probability under the influence of different factors. Then, the EDFPD of SFN is obtainable by the logical relationship of SSFEP. According to Eq. (6), *S* is obtained, and the EDFPD, rather than a value, is taken into SFN to obtain the SSFPD.

(3) Method III for Case III. On the basis of Method II, the actual faults and their corresponding factors are added. In this way, the fault probability is set to 1 under the condition of the corresponding factors instead of the probability value of the corresponding state of the fault probability distribution. At the same time, considering the probability distribution obtained by theoretical analysis, the actual fault data can also be added to modify the analysis results.

According to the tree fault data characteristics, three SSF calculation methods are proposed based on the FTP.

4.2 Example

Use the example in Fig. 1 for analysis. For Method I, set all TPs to 0.0001. For e_{21},

$$S = \begin{cases} q_{e_5} = 1-(1-(q_{e_2} \bullet (q_{e_2} >= q_{26}))) \bullet \\ \qquad (1-(q_{e_3} \bullet (q_{e_3} >= q_{27}))), \\ q_{e_4} = 1-(1-(q_{e_1} \bullet (q_{e_1 >= q_{24}}))) \bullet \\ \qquad (1-(q_{e_2} \bullet (q_{e_3} >= q_{25}))), \\ q_{e_8} = (q_{e_4} \bullet (q_{e_4} >= q_{21})), \\ q_{e_7} = (q_{e_6} \bullet (q_{e_6} >= q_{23})) \bullet (q_{e_5} \bullet (q_{e_5} >= q_{22})), \\ q_{e_{10}} = 1-(1-(q_{e_8} \bullet (q_{e_8} >= q_{19}))) \bullet \\ \qquad (1-(q_{e_7} \bullet (q_{e_7} >= q_{18}))) \bullet \\ \qquad (1-(q_{e_{11}} \bullet (q_{e_{11}} >= q_{17}))), \\ q_{e_9} = 1-(1-(q_{e_1} \bullet (q_{e_1} >= q_{20}))) \bullet \\ \qquad (1-(q_{e_8} \bullet (q_{e_8} >= q_{28}))), \\ q_{e_{12}} = (q_{e_9} \bullet (q_{e_9} >= q_{13})) \bullet (q_{e_{10}} \bullet (q_{e_{10}} >= q_{14})), \\ q_{e_{18}} = (q_{e_{12}} \bullet (q_{e_{12}} >= q_7)), \end{cases}$$

where "•" represents matrix point multiplication. When EDFP is 0.01, the e_{21} probability is 0; when

EDFP is 0.001, the e_{21} probability is 0; when EDFP is 0.0001, the e_{21} probability is 0.0087%; and when TP is reduced, the e_{21} probability is unchanged.

S of e_{22} is more complex. When EDFP is 0.1, 0.01, 0.001, and 0.0001, the e_{22} probability is 0, 0.23%, 0.23%, and 0.24%, respectively. If TP is reduced, the probability will not change.

For Method II, set all TPs as 0.0001 and EDFPD as shown in Figs. 1b–1f. Figure 3 shows the SSFPDs of e_{22} and e_{21} with different FTPs.

Figure 3 shows the SSFPD of e_{21} and e_{22} under different TP conditions. When TP is less than 0.001, the SSFPD will not change. The SSFPD in Fig. 3 is very different from that in Fig. 1. The region with low fault probability is only in the area with low use time and moderate temperature. Because almost all EFs are near the intermediate-temperature region, the fault rate is low; at the same time, these EFs briefly show a low fault probability. Finally, the SSFPD in Fig. 3 forms. The low fault probability area of e_{22} in Fig. 3 is less than the area of e_{21}. In terms of SFN structure, the EF and the number of e_{22} are greater than those e_{21}, so the cause and transfer complexities of e_{22} are greater than those of e_{21}; that is, the condition of e_{22} is more severe than that of e_{21}, so the SSFPD is smaller.

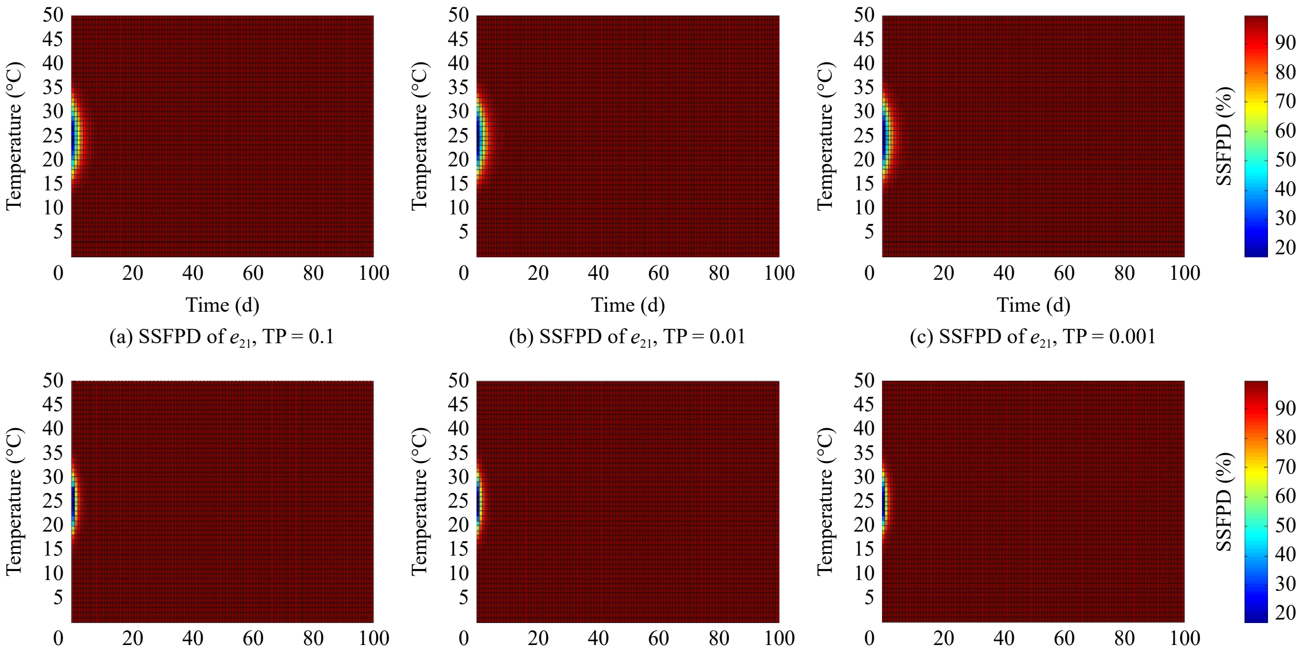
Method III, based on the existing EDFPD, adds the faults that have occurred according to the factor state and is identical to method IV in Section 3.2. Figure 4 shows the SSFPD.

Figure 4 shows the SSFPD of e_{21} and e_{22} for two TP. When TP is less than 0.01, SSFPD does not change. Compared with Fig. 3, the fault probability of 1 is in the low probability area, which is the corresponding position of the actual fault situation in the distribution. Although the difference with Fig. 3 is small, the actual fault condition is considered in method III to correct the probability distribution.

We compare FTP and CTP. With CTP, when TP changes, SSFP or distribution also changes. The smaller the TP, the smaller the SSFP or distribution. The SSFP or distribution is obtainable by FTP and only changes within a certain range of TP. The larger or smaller than this range will not change.

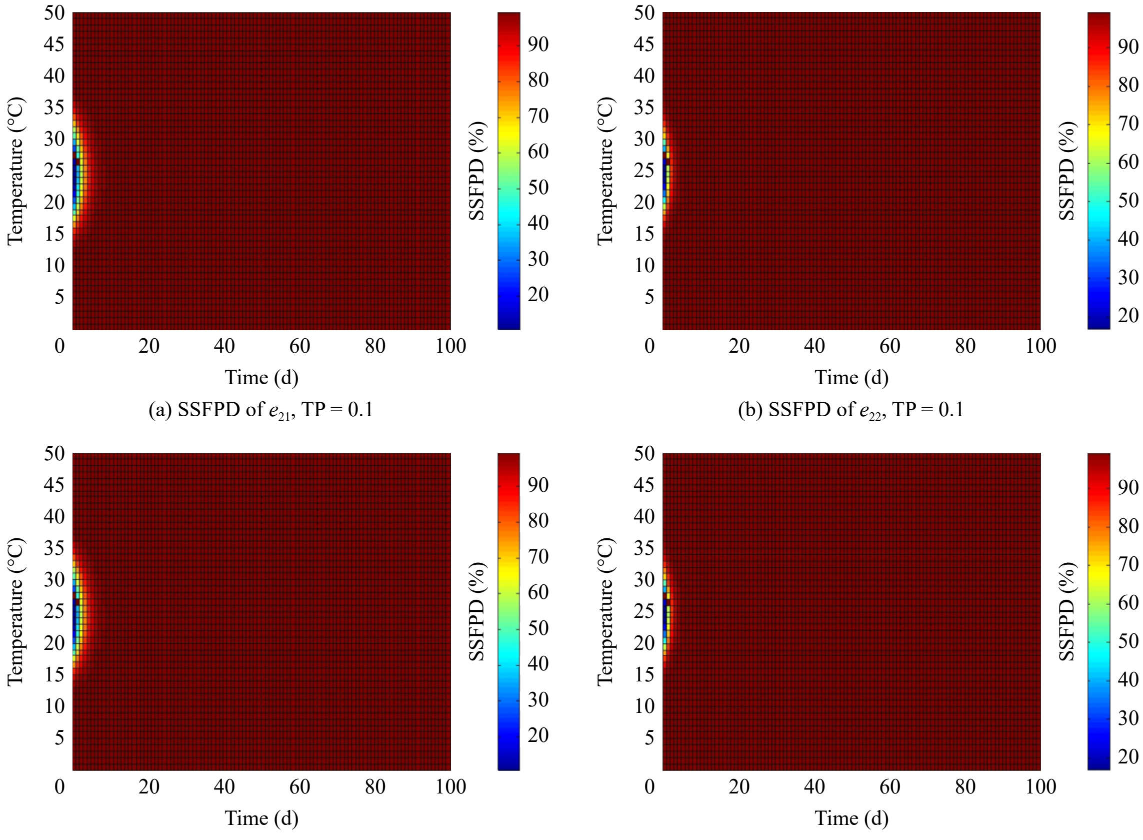
5 Intelligent Calculation Method for SSFP with Limited Data

Based on information expansion, a method for determining the fault probability distribution under the condition of limited fault data is proposed. In practice, it is simple to obtain the fault or accident conditions within the area of system operation conditions. For example, the smart system may work between 0 ℃ and 50 ℃, and the fault time of data statistics is 0 to 100 d. We count the system operation time and



(a) SSFPD of e_{21}, TP = 0.1
(b) SSFPD of e_{21}, TP = 0.01
(c) SSFPD of e_{21}, TP = 0.001
(d) SSFPD of e_{22}, TP = 0.1
(e) SSFPD of e_{22}, TP = 0.01
(f) SSFPD of e_{22}, TP = 0.001

Fig. 3 SSFPD obtained by Method II.



(a) SSFPD of e_{21}, TP = 0.1
(b) SSFPD of e_{22}, TP = 0.1
(c) SSFPD of e_{21}, TP = 0.01
(d) SSFPD of e_{22}, TP = 0.01

Fig. 4 SSFPD obtained by Method III.

temperature at each fault or accident. Taking 0℃ to 50℃ and 0 to 100 d as two distribution factors and fault as the third factor, the coordinate system of fault probability is established. The study area D comprised 0℃ to 50℃ and 0 to 100 d. Then, set the probability of temperature and time factors in the corresponding position in D as 100%. The discrete points of the factor coordinate system are obtained, and then the fault probability distribution is obtained using the idea of information diffusion.

After obtaining the distribution of discrete faults, which needs to be transformed into EDFPD and finally obtain SSFPD. The distribution of discrete fault is expressible as[31]

$$P\left(x_1, x_2, \ldots, x_n\right) = \begin{cases} 100\%, \text{ occurrence;} \\ 0, \text{ nonoccurrence} \end{cases} \tag{7}$$

where $x_1, x_1, \ldots, x_n$ represent the factors, and n represents the number of factors.

The concept of information diffusion is used to transform the discrete point of fault into a normal distribution centered on that point. Taking the probability 1 of this point as the highest point of normal distribution, the corresponding projection position is the intersection point of all factors in D. In addition, we calculate the distribution of this point in D and obtain the probability distribution of a fault (m_j) by referring to the normal distribution form, as shown in the following:

$$P_{m_j}(x_1, x_2, \ldots, x_n) = \exp\left(-\frac{\left(\sum_{i=1}^{n}(x_i - x_{i0})^2\right)^{1/2}}{2\tau}\right), x_1, x_2, \ldots, x_n \in D \tag{8}$$

where x_i represents the value of the i-th factor in D; x_{i0} represents the value of the i-th factor when the fault m_j; D represents the study area composed of change ranges of n factors; τ is the adjustment coefficient to adjust the width of the normal distribution.

Furthermore, in D, multiple faults have been collected, and factor conditions have been recorded, which constitute the fault set $M = \{m_1, m_2, \ldots, m_J\}$, with J events in total. The fault probability distribution in M is synthesized and plotted in D. Notably, the faults in M are the same object under the influence of different factors. Therefore, the faults do not occur at the same time and have no transfer relationship with each other. Then, each fault can be considered independent. In this way, the fault distribution in D is obtainable by taking the maximum value of all positions in D from the independent distribution of all events according to Eq. (2), as shown in the following:

$$\begin{aligned}&P_M(x_1, x_2, \ldots, x_n) = \\ &\max(P_{m_j}(x_1, x_2, \ldots, x_n)) = \\ &\max\left(\exp\left(-\frac{\left(\sum_{i=1}^{n}(x_i - x_{i0})^2\right)^{1/2}}{2\tau}\right)\right), \\ &m_j \in M,\ j = 1, 2, \ldots, J, \\ &x_1, x_2, \ldots, x_n \in D\end{aligned} \tag{9}$$

Equation (9) applies to studying the probability distribution of various faults in D. Equation (9) is applicable to calculating EDFPD in SSFEP. In this way, the fault probability distribution can be determined only by recording a small amount of the EF.

6 Improved SSFP with Limited Data

The fault probability distribution is formed comprehensively using the fault probability distribution and the Information Diffusion Fault Probability Distribution (IDFPD) to improve the method in Section 5.

6.1 Improved calculation method for the SSFPD

The determination of SSFPD is divisible into the following steps: determination of EDFPD, determination of IDFPD of EF, synthesis of two distributions, and obtaining SSFPD according to SFN.

First, EDFPD can use the fault probability distribution, as shown in the following:

$$P_M(x_1, x_2, \ldots, x_n) = 1 - \prod_{k=1}^{n}\left(1 - P_M^{x_k}(x_k)\right) \tag{10}$$

where $x_1, x_2, \ldots, x_n$ are the value of factors; and $P_M^{x_k}(x_k)$ is the characteristic function of fault M for the k-th factor.

Equation (10) forms a space with factors $x_1, x_2, \ldots, x_n$ as dimensions, i.e., study area D; the distribution surface is $P_M(x_1, x_2, \ldots, x_n)$, i.e., the EDFPD of M. Once M occurs as m_j, it obtains a point of the information diffusion distribution, as shown in Eq. (8). In Section 5.1, M is a collection of different faults. Here is a collection of multiple occurrences of the same fault. When M occurs J times in D, that is, multipoint information diffusion takes place, the maximum value of the information diffusion distribution at all points under the same factor value is determined as the EDFPD of M, as shown in Eq. (9). In D, the larger of the two distributions is taken as the comprehensive distribution, as shown in the following:

$$\begin{aligned}&P_M(x_1, x_2, \ldots, x_n) = \\ &\max\left[\begin{aligned}&\max\left(1 - \prod_{k=1}^{n}\left(1 - P_{m_j}^{x_k}(x_k)\right)\right), \\ &\max\left(\exp\left(-\frac{\left(\sum_{i=1}^{n}(x_i - x_{i0})^2\right)^{1/2}}{2\tau}\right)\right)\end{aligned}\right]\end{aligned} \tag{11}$$

Finally, we obtain the SSFPAE represented by EDFPD and calculate the SSFPD.

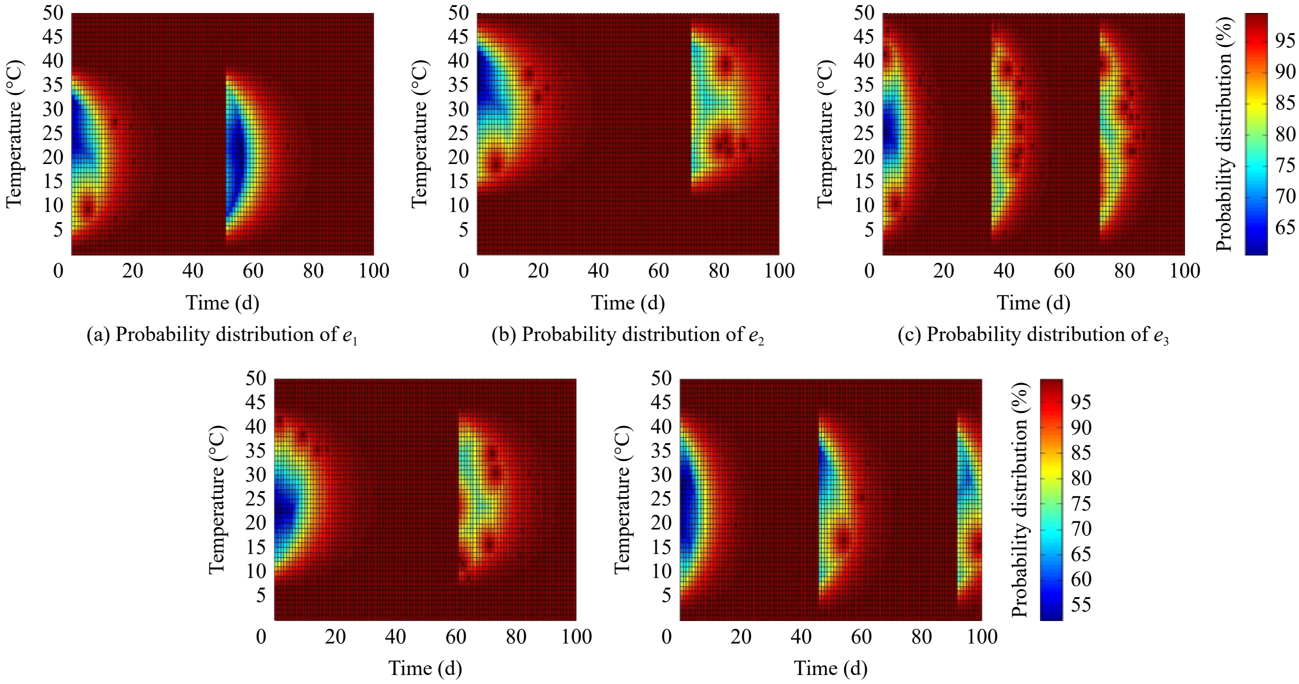
6.2 Example

An example is shown in Fig. 1. According to the existing research results[25] and Eq. (10), the probability distributions of p_{e_1}, p_{e_2}, p_{e_3}, p_{e_6}, and $p_{e_{11}}$ are obtained, as shown in Fig. 1. Further, according to Eq. (11), five EDFPDs and IDFPDs are integrated to obtain the five new EDFPDs, as shown in Fig. 5.

Compared with Figs. 1b–1f, Fig. 5 shows the theoretical value of the probability distribution of actual faults. It contains the theoretical calculation information obtained by the laboratory and the actual fault situation. It is the actual situation correction of the theoretical value of SSFPD. Finally, the SSFPAE of e_{21} and e_{22} are obtained according to Eq. (1), such as Eq. (2).

Instead of p_{e_1}, p_{e_2}, p_{e_3}, p_{e_6}, and $p_{e_{11}}$ in Eq. (2), the EDFPDs obtained in Fig. 5 are used to obtain the probability distribution of $p_{e_{21}}$ and $p_{e_{22}}$, as shown in Fig. 5.

Comparing Figs. 2 and 6, we can also understand some features. First, the corresponding SSFPD values are of the same order of magnitude: e_{21} is 10^{-7}, and e_{22}



(a) Probability distribution of e_1 (b) Probability distribution of e_2 (c) Probability distribution of e_3

(d) Probability distribution of e_6 (e) Probability distribution of e_{11}

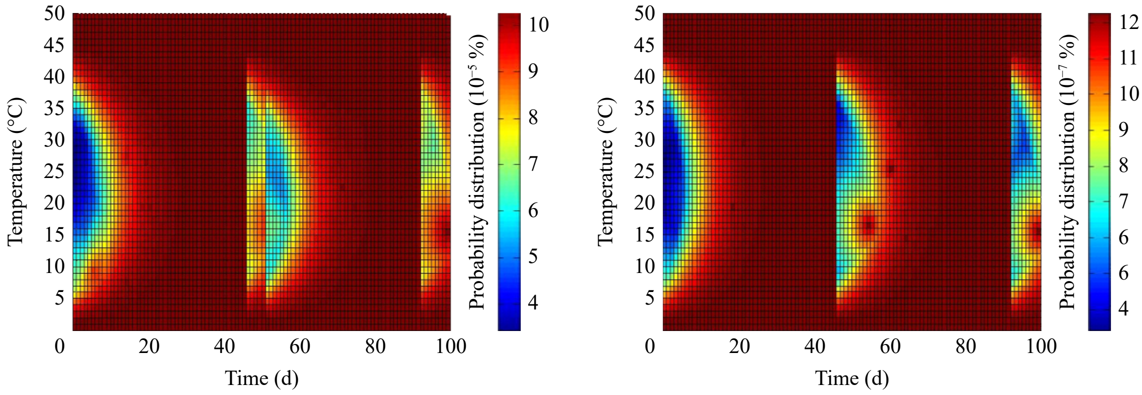
Fig. 5 Probability distribution of edge device faults (composite value).

is 10^{-9}. This result is related to e_{21} and e_{22} related EDFPD, EF number, TP, connection number, and logical relationships between events. According to the order of magnitude of e_{21} and e_{22}, we know that e_{22} has experienced more evolution and more EFs. In addition, the cause of e_{22} is more complex, and the fault process is more complex, so more conditions are needed for e_{22} occurrence, and the probability value of e_{22} is lower. Similarly, the distributions in Figs. 2 and 6 are similar, but Fig. 6 modifies the actual fault state, which is closer to the actual situation.

7 Discussion and Comparison

On the basis of the methods and data used in the above discussion, we can discuss and compare the following items.

SSFEPs are complex. In particular, the complexity of different fault data elicits difficulties in analyzing and calculating fault probability. According to different cases of fault data, the corresponding fault probability distribution calculation methods are proposed. These methods are applicable for determining the SSFP under different conditions, thus enabling the prediction and



(a) Probability distribution of e_{21} (b) Probability distribution of e_{22}

Fig. 6 Probability distribution of SSF.

prevention of SSF processes and realizing intelligent processing.

According to the comprehensiveness and difficulty of obtaining basic fault data, the SSFP calculation methods of SFN in four data cases are obtained based on FTP, including Methods I, II, III, and IV. Methods I, II, and IV employ the probability logic, and Method III employs the frequency logic. The characteristics of FTP in SFN are studied, and the calculation method is proposed. The methods are provided for three data types, and SSFP and its distribution under different TP conditions are obtained. Notably, the results differ from those of CTP. SSFPD depends on the EDFN, EDFPD, and the number and value of TP. The more EFs and connections there are, the smaller the SSF distribution and value will be.

The methods of EFs and SSFPD under the condition of limited fault data are studied. According to the factor conditions of EFs, the normal distribution is formed in D with the factor value at the time of fault as the coordinate. The EDFPD of the EF in D is obtainable by taking the maximum value of all distributions under the same factor state. For limited fault data, the modified method of SSFPD is provided: determine the EDFPD and the information diffusion distribution of the EF point, synthesize two types of distributions, and obtain the SSFPD.

Because the method established herein is implemented within the theoretical framework proposed by the authors, the objectives and conditions of the problem solved differ from those of existing methods. Therefore, it is difficult to compare it with existing research. However, the effectiveness, advantages, and characteristics of the obtained results are evident. Further, the results confirm the effectiveness and significance of the method.

8 Conclusion

Edge devices are the foundation of IoT. In a smart environment, the perception of the IoT to the outside world is realized through calculating and processing data from edge devices. Therefore, the IoT based on edge devices and other devices is the basis for realizing smart systems. The network structures of such systems are complex. The peripheral nodes of smart systems are the edge devices, and the communications between these devices connect the nodes. Therefore, the fault of a smart system depends on the edge devices of IoT and the communication network. SSFP depends on the EDFP, but the difference in edge devices also leads to a difference in the number of faults. Therefore, intelligent calculation methods of SSFP under the condition of different EF data are proposed herein. The methods are based on SFN and can analyze multiple factors. According to different cases of fault data, the fault probability distribution calculation methods are proposed. These methods are applicable for determining the SSFP under different conditions and enable the prediction and prevention of fault processes.

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