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Research on Complex Structures in Space Fault Network for Fault Data Mining in System Fault Evolution Process

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ABSTRACT To study the system fault evolution process, and mine the relationships among the fault data, fault factors and fault events, we propose the theory of space fault network. The paper is composed of three parts. In the first part, the shortcomings of the existing studies on unidirectional ring in space fault network are discussed, and three new network description forms of typical unidirectional rings are formulated and the corresponding space fault tree transformation mechanism. The concepts of ring structure, ordered relation, equivalence event and equivalence connection are defined according to the need. Three methods for calculating the target event probability are given. The second part studies the all event induction fault evolution process. All of its edge events and process events lead to the target event. The meaning of all event induction fault evolution process is discussed. Two methods, general fault evolution process and all event induction fault evolution process, are used to calculate the target event probability in the evolution process of a single route and network structure. In the third part, the impact of some event repeatability on the fault and the time characteristics of the evolution process are studied, and the definitions of event repeatability and timeliness are proposed. The occurrence time and duration of events and connections are given to characterize the time characteristics. Finally, according to repeatability and timeliness, the measures to prevent the target event are given. The paper provides a new theory and method for mining system fault evolution process from fault data, fault factors and fault events.

INDEX TERMS Safety system engineering, space fault network, unidirectional ring structure, all event induction, repeatability and timeliness, fault data mining.

I. INTRODUCTION

Whether it is the process of artificial system fault or natural system disaster, they can be abstracted as the process that some events occur successively according to some certain logical relationships, the process is called system fault evolution process(SFEP). Understanding, describing, modeling and analyzing the processes, and finally finding the methods to prevent the development of faults or disasters, this is of great significance to today's production and life. However, the research of this process needs to combine the relevant theories and knowledge of safety science, data science, intelligent science and system science. Safety science alone can not solve the above problems.

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At present, there are a few studies on SFEP. The research includes mechanical system fault evolution [1]; grid cascading fault evolution [2]; multi-focus strategy optimization model [3]; competitive fault model [4]; hybrid fault model [5]; multi-strategy evolution dynamics [6]; online knowledge community knowledge system evolution [7]; innovation ecosystem performance [8]; urban traffic system evolution [9]; enterprise system evolution [10]; software spatial structure evolution [11], enterprise system evolution [12], and behavior process evolution [13]. The complex structure representation and analysis methods of the system have been studied and applied in medical field [14], project management [15], software evaluation [16], health analysis [17], monitoring video analysis [18], parallel structural analysis [19], and teaching activity analysis [20], Adaptive fault tolerant control [21], Active fault-tolerant control [22], Observer-based leader-following consensus [23], Adaptive Consensus Control [24] etc.. Although the above methods have achieved good results in their respective fields, there are lacks of methodologies at the system level, such as unified description and analysis methods of SFEP.

Based on Space Fault Tree (SFT), the author proposes Space Fault Network (SFN) to describe SFEP. SFN can describe the complex relationship among events in SFEP, and the impact of multiple factors on events. It can also describe the macro-evolution process of many events and the micro-causal relationship among events. Compared with SFT tree structure, SFN can handle more extensive network structure of SFEP, and is a more general method at the system level.

The paper is one of the links in the process of the theory, which is divided into six sections. Sect.I: introduces the background. Sect.II: introduces SFT and SFN, and gives the necessary concepts and definitions. Sect. III: the unidirectional ring of SFN, it includes the meaning of unidirectional ring, the transformation method between unidirectional ring and SFT, and the calculation of event probability (EP). Sect. IV: All event induction fault evolution process (AEIFEP), it includes the meaning of all event induction, target event occurrence probability (means Target Event Probability, TEP) calculation of single route and network structure. Sect.V: the repeatability and timeliness, it includes the repeatability of edge event (EE) and the time characteristics of SFEP. Sect.VI: inadaptability of the methods for describing SFEP. Sect.VII: gives some conclusions.

A. ABBREVIATIONS AND ACRONYMS

Noun	Abbreviation
Space Fault Network	SFN
System Fault Evolution Process	SFEP
Fault Evolution Process	FEP
Space Fault Tree	SFT
General Space Fault Network	GSFN
Multidirectional Ring Space Fault Network	MRSFN
Unidirectional Ring Space Fault Network	URSFN
Edge Event	EE
Process Event	PE
Target Event	TE
Event Probability	EP, means PEO, including FP and FPD
Probability Of Event Occurrence	PEO
Fault Probability /Fault Probability Distribution	FP/FPD
Transfer Probability	TP
Model Span	MS
Model Width	MW
Multidirectional Ring Space Fault Network With The Unidirectional Ring Space Fault Network	MRSFN with URSFN
No Relationship URSFN	NRURSFN
Or Relationship URSFN	ORURSFN
And Relationship URSFN	ARURSFN
Mixed Relationship URSFN	MRURSFN
Cause Event	CE
Result Event	RE
Target Fault Evolution Process	TFEP
Order Fault Evolution Process	OFEP
Unit Fault Evolution Process	UFEP
Incremental Fault Evolution Process	IFEP
Decrement Fault Evolution Process	DFEP
Target Event Occurrence Probability(Target Event Probability)	TEP
Edge Event Induction Fault Evolution Process	EEIFEP
General Fault Evolution Process	GFEP
Ring Structure	RS
Ordered Relation	OR
Equivalence Event	EEv
Equivalence Connection	EC
Equivalence Symbol	ES
All Event Induction Fault Evolution Process	AEIFEP
Formal Concept Analysis	FCA
Interpretative Structural Modeling Method	ISM
System Dynamics	SD
Signed Directed Graph	SDG

B. LIST OF VARIABLES

Variables	meaning
$W = (V, L, R, B, \mathrm{B})$	System of space fault network
v_i	Node
$V = \{v_1, v_2, \cdots, v_I\}$	Node set of the network
p_i	Fault probability /fault probability distribution
l_j	Connect
$L = \{l_1, l_2, \cdots, l_J\}$	Connect set of the network
c	Cause event
r	Result event
e_f	Route
$E = \{e_1, e_2, \ldots, e_F\}$	Route set of the network
$p_{\mathrm{c}\to\mathrm{r}}$	Transfer probability
r_o	Span
$R = \{r_1, r_2, \cdots, r_O\}$	Span set of the network
b_m	Width
$B = \{b_1, b_2, \cdots, b_M\}$	Width set of the network
B	Boolean algebra system
k	Number of fault cycles
η	Target event
δ	Event set of cyclic structure
ii	ii th event in δ
ζ	Connect set in δ
jj	jj th transfer probability in δ
x_k	Value of influencing factors
d_k	Symbols of factors

N	Order of System fault evolution process
W_{fault}	System fault evolution process
$O = \{o_1, o_2, \ldots, o_I,\}$	Object set
$S = \{s_1, s_2, \ldots, s_{II},\}$	State set
$X = \{x_1, x_2, \ldots, x_M\}$	Factor set
$W = (O, S, L, X)$	System of Space fault network
	Simplification of $W = (V, L, R, B, \mathrm{B})$
X_1	The first element in an example
X_2	The second elements in an example
"$\rightarrow$"	Connection
- - -▸	Equivalence connection
"$+, \cdot$"	The logical "or, and" relationship that CE causes RE
$>$	Ordered relation
Q	Number of fault cycles
t	Occurrence time of event and transmission
τ	Duration of event and transmission
$[t, t+\tau]$	The time of the existence and effect of an event
t_f	The occurrence time of TE
τ_f	The duration of TE

II. SPACE FAULT TREE AND SPACE FAULT NETWORK

SFT is a method proposed by the author in 2012 to analyze the relationship between influencing factors and system reliability. In the first stage, continuous space fault tree [25], [26], discrete space fault tree [27], [28], system structure inverse analysis [29] and related fault data processing methods [30] are formed. However, the actual fault data often has randomness, discreteness and fuzziness, but generally show regularity, and the amount of these data is large. Faced with these characteristics, the system reliability needs to be studied in combination with big data and intelligent scientific methods. Therefore, the second stage of SFT development, the intelligent transformation of SFT, is carried out, including the combination of cloud model [31], factor space [32]–[35], and system stability theory. SFT has not only the ability of multi-factor analysis, but also the ability of data processing, causality analysis, reliability stability analysis and system structure analysis.

However, with the research, it is found that the actual system fault or natural disaster is an evolution process consisting of many events. Tree structure of SFT is difficult to analyze the process, so SFN is proposed on the basis of SFT and used in SFEP research as the third stage of SFT. The existing definitions of SFN are given in reference [36]–[38], which is briefly listed here.

Definition 1 (Space Fault Network (SFN)): Topological structure of system fault events, denoted by $W = (V, L, R, B, \mathrm{B})$, where, V: the set of nodes in the network, node is event; L: the set of connections in the network; R: the set of network spans; B: the set of network widths; B: Boolean algebraic system.

Definition 2 Node: Node in SFN represents event in the SFEP, and multiple nodes in the fault network can represent the same event, but not the one time event; one event occurs at a time corresponding to only one node. SFN nodes can be classified into three categories according to the different roles in SFEP. The nodes are represented by $V = \{v_1, v_2, \cdots, v_I\}$, I: number of nodes.

The first category is called **edge event(EE)**, which is the basic event leading to the fault. It is the source of fault. No event in the fault network leads to the EE occurrence, corresponding to basic event of fault tree.

The second category is called **process event(PE)**, which are caused by EEs or other PEs in the SFEP, and also lead to other PEs or final events, corresponding to the middle event of fault tree.

The third category is called **target event(TE)**, which is caused by PE, but does not cause any other event in the SFN, corresponding to top event of fault tree.

Definition 3 (Event Probability(EP)): Event occurrence probability is the same as that defined in SFT, or the fault probability(FP) of the object of event is expressed by p_i; under the influence of multiple factors, it is called fault probability distribution(FPD).

Definition 4 (Connection): Represent transfer between events during a SFEP. Connection exists between two events. The connection is directed, from the cause event(CE) to the result event(RE). A connection is denoted by l_j. All connections are represented by a set of $L = \{l_1, l_2, \cdots, l_J\}$, J: number of connections. C: cause event(CE); R: result event(RE), and the CE results in RE. CE can be EE and PE; RE can be PE and FE.

Definition 5 (Route): a set of connections from one event to another. These connections have a unified direction. Use e_f to represent the route, and route set $E = \{e_1, e_2, \ldots, e_F\}$, F: number of routes.

Definition 6 (Transfer Probability(TP)): The probability that a CE can lead to a TE, that is, the probability that a CE will lead to a TE after it occurs, denoted by $p_{\mathrm{c}\rightarrow\mathrm{r}}$.

Definition 7 (SFN Span): the minimum number of connections between two events. It is used to measure the complexity of SFEP. The maximum span of an event and an EE is called the modal span of the event. The TE span is the largest span in the fault network. The span set is represented by $R = \{r_1, r_2, \cdots, r_O\}$, r_o: oth SFN span; O: number of span.

Definition 8 (SFN Width): the total number of nodes of all EEs involved in an event in a fault network to measure the complexity of fault causes. The maximum width of an event is called the modul width of the event. The modul width of the TE is the maximum width in the fault network. b_m: mth SFN width; the width set is represented by $B = \{b_1, b_2, \cdots, b_M\}$, M: the number of widths.

Definition 9 (Logical Relationship Between Events): PEs and TEs contain the logical relationships of all events that cause them to occur. These logical relationships include "and", "or" and "non", which are the same as those of the fault tree. It is represented by (B, $\vee$, $\wedge$, $\overline{\ \ }$).

Definition 10 (SFEP Order): Order of the SFEP is equal to the maximum number of all EEs, denoted by N. For example, the two-order FEP, N $(p_6p_5) = 2$, and the four-order FEP, N $(p_6^2p_5^2) = 4$.

Definition 11 (Object): the subject of an event is the object that bears the influence of various factors. An event has and has only one object. Object sets $O = \{o_1, o_2, \ldots, o_I,\}$, I: the number of objects.

Definition 12 (State): It is a representation of the existence of an object in an event, and is the response of the object to the influence of factors. An object has many states. The state set $S = \{s_1, s_2, \ldots, s_{II},\}$, II: the number of states.

Definition 13 (Factor): the role of changing the object state and TP in FEP. The factor set $X = \{x_1, x_2, \ldots, x_M\}$, M: the number of factors.

Definition 14 (System Fault Evolution Process (SFEP)): All fault occurrence processes are described by SFN and can be understood as the complete set of FEPs. That is, the $W = (O, S, L, X)$ mentioned above. **Fault evolution process (FEP)** is a route in SFEP, SFEP consists of many FEPs. **TFEP**: SFN is formed with a TE as the research objective, and all the FEPs are attributed to the TE. SFN of TFEP corresponds to SFT, and then TE corresponds to top event. **OFEP**: UFEPs with the same number of EEs after the fault tree structure of TFEP expanded and simplified. **UFEP**: After the fault tree structure of TFEP expanded and simplified, the EE and TP connected by the "and" relationship. UFEP can be further divided into incremental fault evolution process (**IFEP**) and Decrement Fault Evolution Process (**DFEP**). The former indicates that after the completion of the FEP, the SFEP tends to develop in high EP; the latter is on the contrary.

The followings are the follow-up to the previous studies.

III. UNIDIRECTIONAL RING IN SPACE FAULT NETWORK

A. SIGNIFICANCE OF UNIDIRECTIONAL RING

The unidirectional ring structure in SFN is a special kind of structure, called unidirectional ring space fault network(URSFN). In the URSFN, these events are both cause event(CE)s and result event(RE)s, and the connection direction of each event is the same. These events constitute a circular FEP, it is URSFN. Compared with multidirectional ring space fault network(MRSFN), the events in URSFN have the unified connection direction. Previous event lead to the next event and the cycle process is endless.

For example, we study the relationship between stress concentration and fracture development in mechanical experiments. At the beginning of the experiment, the stress applied to the specimen will be concentrated on the heterogeneous and damaged parts because the specimen is not homogeneous and internal damage. After these locations are subjected to stresses, minor damage points gradually appear which will further strengthen the stress concentration. Stress concentration makes the damage point expand and connect to form a crack, and the stress concentration at the tip of the crack is more obvious. If the stress continues, the crack will develop further until it runs through the whole specimen, leading to damage. Another example is the emergence of pipes in soil-rock dams. In the early stage of construction of soil-rock dam, the soil is dense and the flow is difficult to infiltrate into the dam body. However, after the physical and chemical action of water flow scouring, man-made, biology and so on, the erosion point gradually appears in the dam body. The flow moves the sand and stone further by mechanical action near the erosion point. The decrease of sand particles further enlarges the voids and strengthens the role of water flow machinery. Water intrusion and sand erosion reinforce each other until a flow pipe is formed in the soil-rock dam.

The above process of rock mass specimen fault and piping formation can be abstracted as SFEPs. These SFEPs are characterized by the cyclic and progressive strengthening process of events in a certain order of occurrence. In practice, if such a FEP occurs without intervention, the whole system fault is only a matter of time. Moreover, every cycle of the FEPs improves the probability of system fault.

In SFN, the evolution process of this kind of cyclic faults can be represented by a ring structure(RS), which can be divided into four categories. Fig. 1 shows three kinds of ring structures, including no relationship URSFN(NRURSFN), or relationship URSFN(ORURSFN), and relationship URSFN(ARURSFN), except for mixed relationship URSFN(MRURSFN).

The square symbols v_x and v_y in Fig.1 represent the fault network composed of several events. The circular symbols v_1 and v_2 represent two events in the FEP of RS. $v_3 \ldots v_M$ denotes the CEs that cause v_2, and M denotes the total number of events. "$\rightarrow$" denotes a connection and its direction. "$+$, $\cdot$" denotes the logical "or, and" relationship between the CEs and the REs. So v_1 and v_2 can represent any two events in the RS.

The NRURSFN is shown in Fig.1(a), which is the simplest NRURSFN. The characteristic is that each RE has only one CE, and each CE only leads to one RE. Moreover, events are connected in the same order, and no other events are required to participate in the process. ORURSFN is as shown in Fig.1(b), it shows that at least one RE in the RS is caused independently by two or more CEs. As shown in Fig.1(c) of ARURSFN, at least one RE in the RS is caused by two or more CEs at the same time. The MRURSFN is formed by the superposition of the three RSs [37].

RS is the superposition of FEPs, which is the occurrence process of each cycle under the condition of the previous cycle. So this cycle is a conditional probability form of the previous cycle. For the TE in the RS, each fault cycle can be regarded as an independent superposition of multiple cycles. Multiple cycles increase the TEP. That is, each cycle produces a certain ETP, and all the previous cycles are his conditional probability events. Therefore, each cycle enhances ETP, which is different from the "and, or" relationship that each CE leads to RE. It is an orderly process

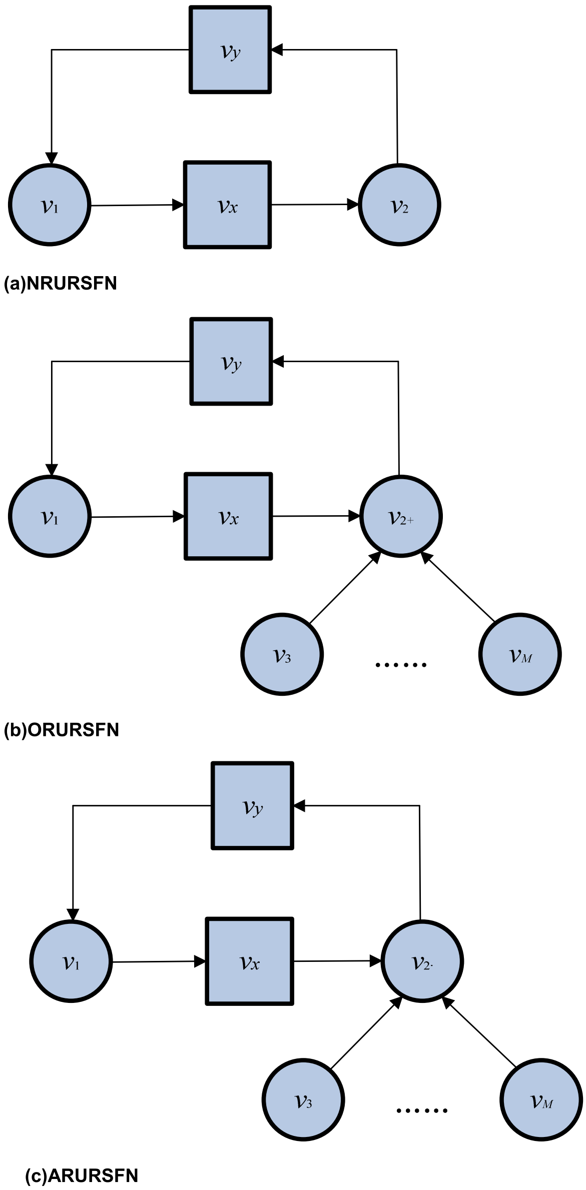


FIGURE 1. Three typical ring networks.

of occurrence and superposition. According to the above discussion, the following definitions are given.

Definition 15 (Ring Structure(RS)): All events in the network are CEs and REs simultaneously, and the connection between events has the same direction, and with all events and connections, a ring route connecting the beginning and the end is formed to represent the cycle superimposed SFEP. It includes NRURSFN, ORURSFN, ARURSFN and MRURSFN. NRURSFN denotes that all CEs lead to a unique RE without "and, or" relationship. ORURSFN indicates that at least one RE in a ring is caused by the "or" relationship of multiple CEs. ARURSFN indicates that at least one RE in a ring is caused by the "and" relationship of multiple CEs. MRURSFN indicates that multiple REs in a ring are caused by the "with, or" relationship of multiple CEs.

Definition 16 (Ordered Relation(OR)): Represent the logical relationship between CEs and REs in a RS; The order represents the sequence of the fault evolutions in cycle processes from the beginning. Each cycle represents the increase of TEP, so the OR is the sum of the TEP of each cycle. The EPs of previous cycles are his conditional event. OR are represented by "$>$" and placed at the lower right corner of the node symbol.

B. URSFN AND SFT TRANSFORMATION METHOD

NRURSFN, ORURSFN and ARURSFN are three basic forms of unidirectional rings, and the mixed structure is the superposition of these three forms. Therefore, this section gives the transformation methods of these three forms and SFT.

Reference [37] gives a method for dealing with NRURSFN. It is considered that the TE in the RS is *n* order of the product of EEs and TPs through *n* cycles. However, with the further study, it is found that this representation is only the *n*th time result that the TE occurred in the RS. In fact, the TE occurs cyclically in the cycle FEP, and will not stop without intervention. Therefore, the TEP should be the superposition of TEPs generated by each cycle, and the occurrence of this TE is the conditional event of the next TE. Probability change of two adjacent TPs is the product of previous TP of the next cycle. The TEP of each cycle is lower than that of the previous one, but actually the TEP after each cycle is the sum of the TEP of all the previous cycles. Therefore, the calculation method of TEP for RS in reference [37] is not the total TEP after multiple cycles, but the TEP of the *n*th.

The transformations of three RSs are given below, as shown in Fig.2.

In Fig.2, three forms of RSs transformed into SFT are given, which correspond to (a), (b) and (c) in Fig.1 respectively.

Describe the symbols in the figure. Firstly, the tree structure is the same as the SFT structure proposed in reference [37], but there are slight differences in the specific representation methods, which are manifested in the symbols, links and logical relations. The original SFT follows the classical fault tree representation method; SFT here is designed to meet the SFN transformation. At present, there are three kinds of event representation symbols: circle, dotted circle and square. A circle event symbol represents a single event, which can be EE, PE, TE, or CE and RE. Square symbol represents a set of events and connections, similar to the transition symbols of the classical fault tree, and are set up to express concisely and conveniently. Dotted circle symbol represents a class of symbols that have no practical significance and are set up only to meet the needs of logical relations. The dotted circle symbol does not exist in SFN, but when it is transformed into SFT. They are transition events and are added between connections in order to establish routes and to distinguish the different logical relationships of CEs lead to REs. Specifically, as shown in Fig.2 (c) the logical relationships between $v_{2\cdot}$ and $v_{2>}$, v_3 … v_M are

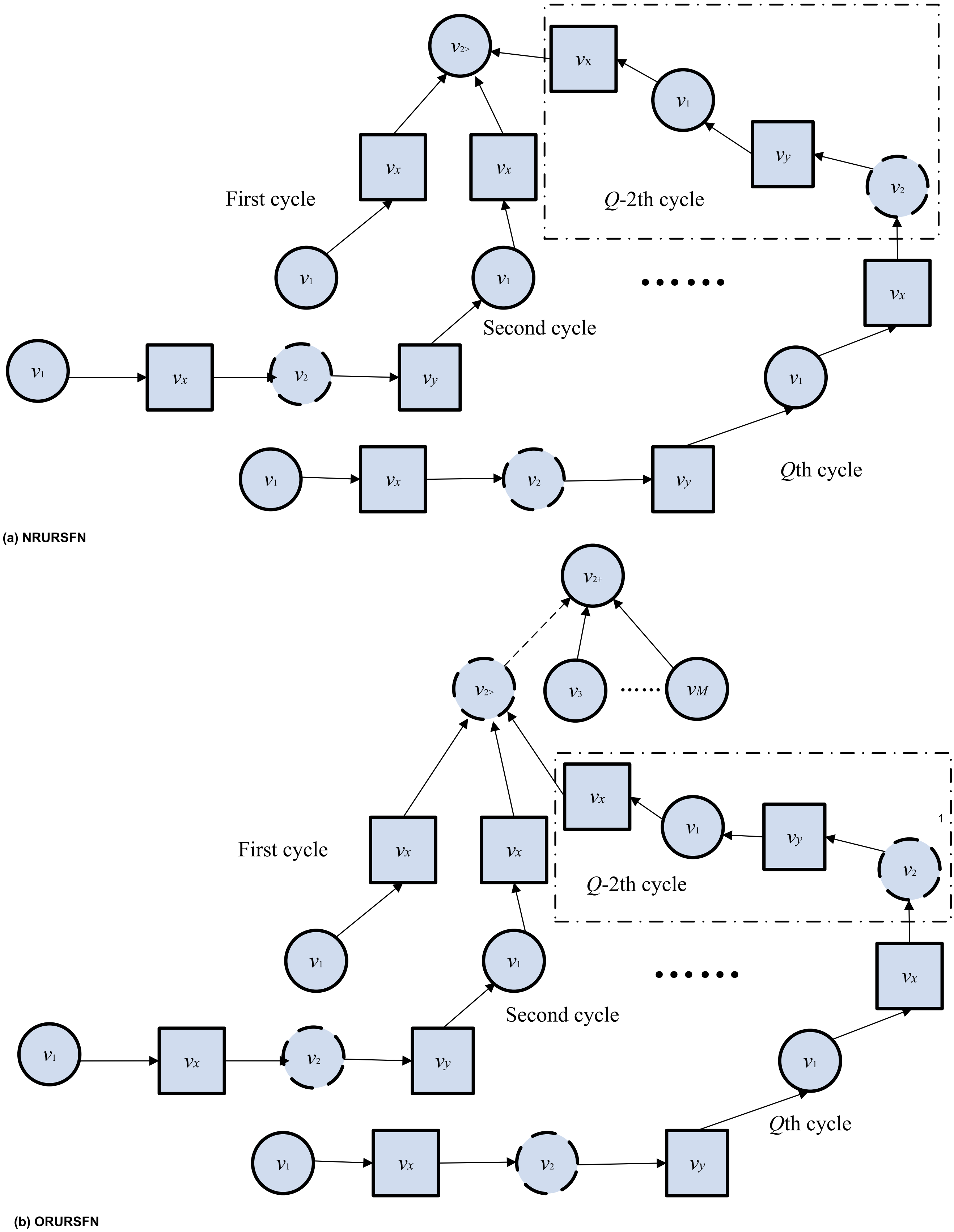
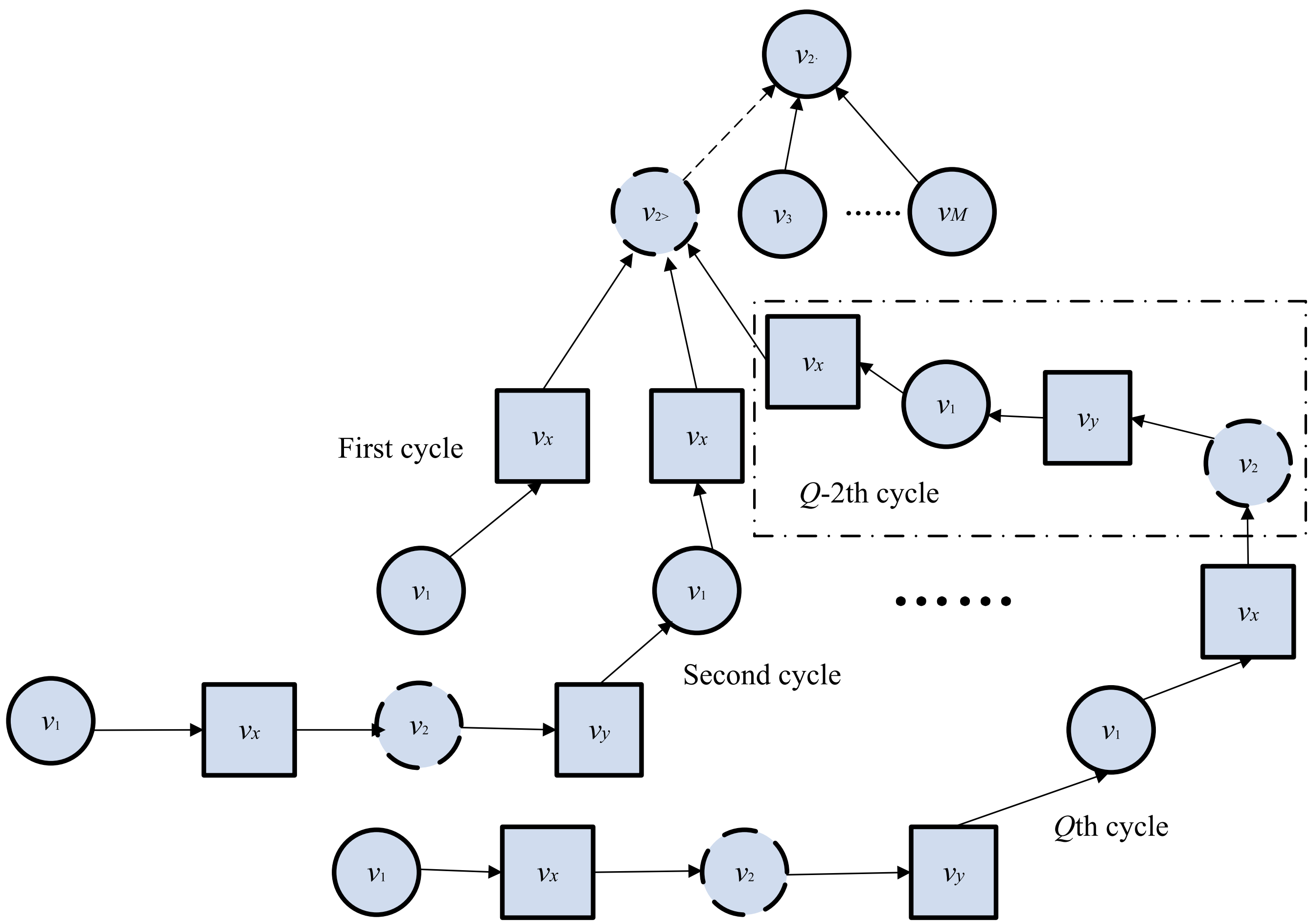


FIGURE 2. Transformation of three forms of ring structures.



(c) ARURSFN

FIGURE 2. ***(Continued.)*** **Transformation of three forms of ring structures.**

"and", but $v_{2\cdot}$ in RS. Therefore, the occurrence probability of multiple cycles of $v_{2\cdot}$ s accumulated by $v_{2>}$ expressing. These accumulations are defined as OR given in Def.16, rather than "and, or" relations. Events represented by dotted circles are called equivalence events.

Definition 17 (Equivalence Event(EEv)): Represents events already existing in SFN, because of the need to distinguish the different logical relationships of REs caused by multiple CEs, CEs with the same logical relationship is categorized as the EEv of the RE, this RE is called event equivalenced(EEd). EEvs have logical significance only when they occupy an event place in the CEs logical classification and connection formation. Equivalence symbol(ES) only exist in SFT transformed. The object and object state of an EEv are the same as those of an EEd.

The connection in Fig.2 (c) has two kinds of "→" and "--->". The former indicates that the connected CE is not an EEv. The latter denotes that the connected CE is the EEv, which is called the equivalence connection (EC).

Definition 18 (Equivalence Connection (EC)): because of the need for the presence of EEv and the need to connect the EEv and EEd to form the connection of CE and RE, the connection is just EC. The TP of EC is 1.

The transformation of Fig.2(a) is explained. Corresponding to Fig.1(a), v_2 is studied as TE. v_2 exists in NRURSFN, so there is only one route through the RS. According to the OR of definition, each cycle has a cumulative effect on TEP. At the same time, the TEP of each cycle is the conditional probability of the next cycle TEP. Therefore, in Fig.2(a), TEP after Q time cycle is represented. If v_1 as EE and v_2 as TE, the first cycle is the left-most route in the figure. After TE occurring of the first cycle, the process enters the second cycle. The first EEv v_2 begins to appear on the second route, but it is connected to v_y, not EC. When the cycle reaches Qth, its route is the rightmost route. There are Q-2 cycles and the first two cycles in this route. These Q fault cycle processes together accumulates TEP, which is an OR and represents the TEP.

Fig.2 (b) and (c) are generated on the basis of Fig.2(a). In Fig.2 (b), TE is in the RS, and there are multiple CEs with "or" relationships. Therefore, on the basis of Fig.2(a), TEv_2 is replaced by an EEv, which corresponds to v_3. v_M is the "or" relationship that causes v_2. At the same time, the EEv and EEd v_2 are connected with the EC. Similarly, TE in Fig.2(c) exists in the RS, and there are multiple CE "and" relationships leading to TE. Therefore, TE v_2 is replaced by an EEv, which is associated with v_3. v_M is the "and" relationship that causes v_2.

The above three basic forms of RS transformation processes are given. Mixed structure can be transformed with reference to the above transformations of three structures.

In addition, SFT transformed by SFN is different from the original SFT due to the need to add and modify the basic components. However, SFT can still be used for reference in analytical methods and related concepts, and SFT's methods and theories can be used after appropriate transformation. Therefore, the tree structure transformed by SFN can also be called SFT.

C. EVENT PROBABILITY CALCULATION

The SFTs obtained from the above three kinds of RS transformations are calculated and the TEPs are obtained. In SFEP, TEP refers to the fault probability of TE objects.

The TEP calculation process of SFT in Fig.2 (a) transformed from Fig.1 (a) is as follows:

Cycle times $Q=1$: $p_{2Q=1}=p_1p_{1\to x}p_{x\to 2}$;

Cycle times $Q=2$: $p_{2Q=2}=p_{2Q=1}+p_1p_{1\to x}p_{x\to 2}p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2}=p_1p_{1\to x}p_{x\to 2}+p_1p_{1\to x}p_{x\to 2}p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2}=p_1p_{1\to x}p_{x\to 2}(1+p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2})$;

Cycle times $Q=3$: $p_{2Q=3}=p_{2Q=2}+p_1p_{1\to x}p_{x\to 2}p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2}p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2}=p_1p_{1\to x}p_{x\to 2}(1+p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2}+(p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2})^2)$.

Summarizing and recurring the above process, we get the TEP of the Qth cycle as shown in Eq.(1).

$$p_2^Q=p_1p_{1\to x}p_{x\to 2}(1+\sum\nolimits_{n=1}^{n=Q-1}(p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2})^n) \tag{1}$$

Then the TEP of NRURSFN is obtained as shown in Eq.(2).

$$p_{TE}=p_{EE}p_{EE\to x}p_{x\to TE}(1+\sum\nolimits_{n=1}^{n=Q-1} \times(p_{TE\to y}p_{y\to EE}p_{EE\to x}p_{x\to TE})^n) \tag{2}$$

Further, the TEP calculation process of SFT in Fig.2 (c) transformed from Fig.1(c) is given. $v_3\dots v_M$ are connected by "and" relationship to lead to v_2, the probability of v_2 is $\prod_{n=3}^{n=M}(p_np_{n\to 2})$. With Eq.(1), the Qth TEP of Fig. 2 (c) is obtained as shown in Eq.(3).

$$\begin{aligned}p_2^Q&=p_2^Q\prod\nolimits_{n=3}^{n=M}(p_np_{n\to 2})\\&=p_1p_{1\to x}p_{x\to 2}(1+\sum\nolimits_{n=1}^{n=Q-1}\\&\quad\times(p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2})^n)\prod\nolimits_{n=3}^{n=M}(p_np_{n\to 2})\end{aligned} \tag{3}$$

where, the p_2^Q at the right of equal sign is the Qth TEP of NRURSFN, the same as Eq.(5).

Then the TEP of the "and" relation is obtained as shown in Eq.(4).

$$\begin{aligned}p_{TE}&=p_{EE}p_{EE\to x}p_{x\to TE}(1+\sum\nolimits_{n=1}^{n=Q-1}\\&\quad\times(p_{TE\to y}p_{y\to EE}p_{EE\to x}p_{x\to TE})^n)\prod\nolimits_{n=3}^{n=M}(p_np_{n\to TE})\end{aligned} \tag{4}$$

Similarly, the TEP calculation process of SFT in Fig.2 (b) is given. $v_3\dots v_M$ are connected by "or" relationship to lead to v_2, the probability of v_2 is $1-\prod_{n=3}^{n=M}(1-p_np_{n\to 2})$. Considering the relationship between RS and them is also "or" relationship, the Qth TEP in Fig. 2 (b) is shown in Eq.(5).

$$\begin{aligned}p_2^Q&=1-(1-p_2^Q)(1-p_3p_{3\to 2})\dots(1-p_Mp_{M\to 2})\\&=1-(1-p_2^Q)\prod\nolimits_{n=3}^{n=M}(1-p_np_{n\to 2})\end{aligned} \tag{5}$$

Eq.(1) is introduced into Eq.(5) and Eq.(6) is obtained.

$$\begin{aligned}p_2^Q&=1-(1-p_1p_{1\to x}p_{x\to 2}(1+\sum\nolimits_{n=1}^{n=Q-1}\\&\quad\times(p_{2\to y}p_{y\to 1}p_{1\to x}p_{x\to 2})^n))\prod\nolimits_{n=3}^{n=M}(1-p_np_{n\to 2})\end{aligned} \tag{6}$$

The TEP of the OR relation is shown in Eq.(7).

$$\begin{aligned}p_{TE}&=1-(1-p_{EE}p_{EE\to x}p_{x\to TE}(1+\sum\nolimits_{n=1}^{n=Q-1}\\&\quad\times(p_{TE\to y}p_{y\to EE}p_{EE\to x}p_{x\to TE})^n))\\&\quad\times\prod\nolimits_{n=3}^{n=M}(1-p_np_{n\to TE})\end{aligned} \tag{7}$$

In summary, three basic forms of RS transformation method and TE calculation method are given. Of course, there is only one EE in the figure. When there are multiple EEs, the transformation method and TE calculation method are more complicated. But we can also calculate with the analogy of the above research process.

IV. ALL EVENT INDUCTION FAULT EVOLUTION PROCESS

A. MEANING OF ALL EVENT INDUCTION

As shown in Def.14, various FEPs in SFN are defined. It is considered that with the increase of complexity of SFN and the extension of evolution process, the order of unit fault evolution process(UFEP) increases gradually and the route extends gradually. Although the influence on TEP decreases with the increase of the order, it should depend on the specific situation. The GSFN and MRSFN of SFN are given to express SFEP, as shown in Eq.(8).

$$W_{fault}=\sum_{\forall N(\prod p_{v_i})}(\sum_{\exists N(\prod p_{v_i})}(\prod_{\forall v_i \text{in} e_f}p_{v_i}\prod_{\forall p_{c\to r}\in e_f}p_{c\to r})) \tag{8}$$

where, $p_{c\to r}\in e_f$: the TP$p_{c\to r}$ of a connection belonging to a route e_f; $\prod_{\forall p_{c\to r}\in e_f}p_{c-r}$: the product of all TPs of route e_f, such as $p_{5\to 4}p_{6\to 4}p_{4\to 3}p_{3\to 1}$; p_{v_i}: the EP of EE corresponding to node v_i; $v_i\text{in}e_f$: EE v_i on route e_f; $\prod_{\forall v_i\text{in}e_f}p_{v_i}$: the product of the EP of all EEv_i on route e_f; $\prod_{\forall v_i\text{in}e_f}p_{v_i}\prod_{\forall p_{c\to r}\in e_f}p_{c-r}$: a FEP of a certain order; $\exists N(\prod p_{v_i})$: any order; $\sum_{\exists N(\prod p_{v_i})}$: all FEPs of any first order; $\forall N(\prod p_{v_i})$: all orders; $\sum_{\forall N(\prod p_{v_i})}$: the sum of all FEPs of all existing orders; $\forall$: all; $\exists$: any one.

Eq.(8) shows that the initial events of the FEP are EEs of all routes. So the hypothesis of the above research is that in the FEP, only the EEs of route are the initial CEs of SFEP, and then the probability of EE is transferred to PE through the TP of connection, final leads to TE occurrence, and then TEP is calculated. This explanation seems to be complete and definite, but ignores the important item of FEP, that is, the role of PE in the FEP.

Although PE is a transitional event in the FEP, PE probability is expressed by the product of EE probability and TPs, but PE also has objects. This means that the object of PE can also withstand the effect of factors, leading to the change of state, and then act as the initiator of FEP. In this way, the basic cause of FEP, that is, the initiator of the fault can also be PE.

From another point of view, the FEP can be described. All events except TE in the process can be regarded as EEs for TEP, namely all event induction fault evolution process(AEIFEP), and its TEP is calculated. AEIFEP and General Fault Evolution Process (GFEP, it is a collective name of processes in Def.14 to distinguish from AEIFEP) are two limit states for fault initiation objects. The fault initiators of former are the objects of EEs and PEs; the latter is only the objects of EEs. The former is that all the events (EEs and PEs) in the FEP leading to TE, and each event leading to TE are the parallel relationship. The latter is that the events (EEs) leading to of PEs and TE, which are progressive relationship. Furthermore, in the FEP of the latter, PE is caused by the objects of EEs, while the former is generated by the objects of PEs and EEs.

AEIFEP can be regarded as the superposition of GFEPs. The condition is that all EEs and PEs in the FEP are regarded as EEs that initiates the fault process. It is the calculation method of the maximum probability of TE in FEP. This method considers that all events in the fault process as the initial event except TE. At the same time, the PE caused by EE and the TE caused by PE spontaneously were considered. Therefore, all EEs and PEs can be regarded as EEs independently to calculate the TEP, and the TE of AEIFEP can be obtained by summing of TEPs. The AEIFEPs with a single fault route and network structure are given below, but URSFN is not calculated here.

The example SFN is given below, and the transformed SFT is obtained from the previous study [36], as shown in Fig.3.

Fig.3 shows a simple network structure of electrical system fault process, each node represents events; each event has an object, that is, components of the electrical system. When these components fail, other components or systems fail because of the relationship between them.

B. CALCULATION OF TEP FOR A SINGLE ROUTE

As the simplest example, AEIFEP is studied in a single route (only one UFEP). Select a fault evolution route in Fig.3, as shown in Fig.4.

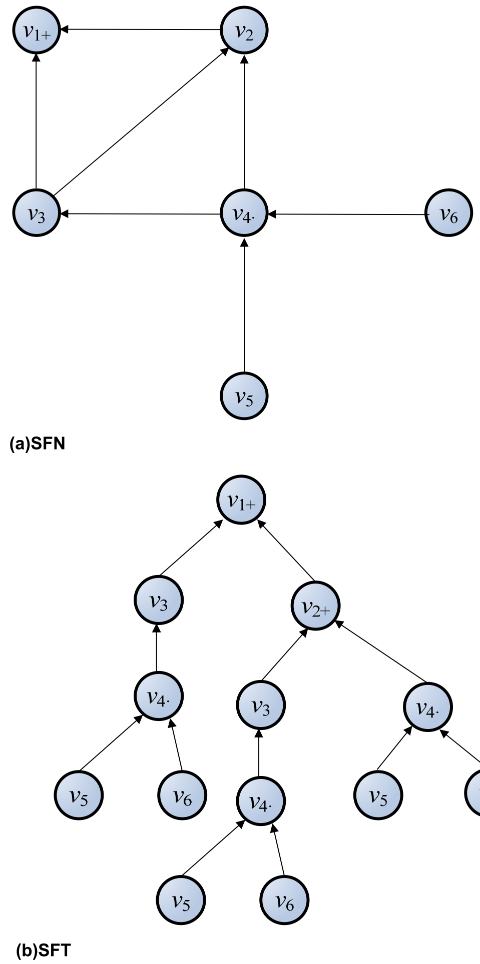


FIGURE 3. Research example.

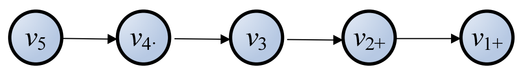
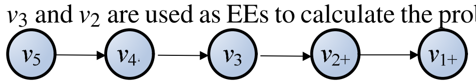
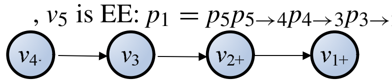


FIGURE 4. Fault evolution process of single route.

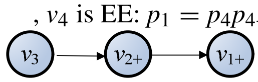
For the process of Fig.4, the "and, or" logical relationship between events is not considered. Then EEv_5 and PEv_4, v_3 and v_2 are used as EEs to calculate the probability of TEv_1.



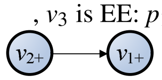
, v_5 is EE: $p_1 = p_5 p_{5\to4} p_{4\to3} p_{3\to2} p_{2\to1}$;



, v_4 is EE: $p_1 = p_4 p_{4\to3} p_{3\to2} p_{2\to1}$;



, v_3 is EE: $p_1 = p_3 p_{3\to2} p_{2\to1}$;



, v_2 is EE: $p_1 = p_2 p_{2\to1}$.

The general TEP is calculated, and $p_1 = p_5 p_{5\to4} p_{4\to3} p_{3\to2} p_{2\to1}$. TEP of AEIFEP is calculated, and $p_1 = p_5 p_{5\to4} p_{4\to3} p_{3\to2} p_{2\to1} + p_4 p_{4\to3} p_{3\to2} p_{2\to1} + p_3 p_{3\to2} p_{2\to1} + p_2\ p_{2\to1}$. It can be seen that the latter considers not only EE as the fault initiator, but also PE as the initiator, which together led to the TE. These are two methods of TEP calculation that are two limit states of TEP. The minimum value is calculated under GFEP, and the maximum value is under AEIFEP. Therefore, any possible TEP of the FEP is between them.

Through single route TEP calculation, we can see the calculation idea of all event induction TEP. Of course, the probability is obtained without considering the logical relationship of events and the order of the FEP. The TEP calculation for a single route is shown in Eq.(9).

$$p_{\mathrm{TE}} = \sum_{\forall v_i \mathrm{in} e_f} (p_{v_i} \prod_{\forall p_{c\to r}\in e_f} p_{c\to r}) \tag{9}$$

C. CALCULATION OF TEP IN NETWORK STRUCTURE

Similar to the single route method, the TEP of AEIFEP is computed in the following steps:

1) Select TE in SFN, as shown in Fig.3, TE is v_1.

2) Transform SFN to SFT with v_1 as the top event of SFT, as shown in Fig.3(b). The specific method is shown in reference [34], which is not elaborated here.

3) Determine EE, in Fig.3(b) shows v_5 and v_6.

4) According to the EE determined in 3), the TEP is calculated as the fault initiator.

5) Remove the EEs that has been computed, and if the remaining events are TEs only, the method stops; otherwise, go to 3).

6) The sum of TEPs caused by different EEs is required, and it is the TEP of AEIFEP.

Fig.3(b) and Fig.5 are EE determination and deletion process.

From SFN to SFT, as shown in Fig.3(a) to Fig.3(b), EEs are v_5 and v_6; these EEs are removed and transformed into Fig.5(a) and EE is v_4; v_4 is removed and transformed into Fig.5(b) and EE is v_3; v_3 is removed and transformed into Fig.5(c) and EE is v_2. According to the SFT structure of Fig.3(b) and Fig.5, the probability of TEv_1 is calculated as follows:

v_2 is EE: $+p_2{}^*p_{2\to1}$, 1 UFEP.

v_3 is EE: ${}^+p_3{}^*p_{3\to2}{}^*p_{2\to1}$, ${}^+p_3{}^*p_{3\to1}$, $-p_3{}^\wedge 2{}^*p_{3\to1}{}^*p_{3\to2}{}^*\ p_{2\to1}$, 3 UFEPs.

v_4 is EE: ${}^+p_{2\to1}{}^*p_4{}^*p_{4\to2}$, ${}^+p_{2\to1}{}^*p_4{}^*p_{4\to3}{}^*p_{3\to2}$, $-p_{2\to1}{}^*p_4{}^\wedge 2{}^*p_{4\to3}{}^*p_{3\to2}{}^*p_{4\to2}$, ${}^+p_4{}^*p_{4\to3}{}^*p_{3\to1}$, $-p_4{}^\wedge 2{}^*p_{4\to3}{}^*p_{3\to1}{}^*p_{2\to1}{}^*p_{4\to2}$, $-p_4{}^\wedge 2{}^*p_{4\to3}{}^\wedge 2{}^*p_{3\to1}{}^*p_{2\to1}{}^*p_{3\to2}$, ${}^+p_4{}^\wedge 3{}^*p_{4\to3}{}^\wedge 2{}^*p_{3\to1}{}^*p_{2\to1}{}^*p_{3\to2}{}^*p_{4\to2}$, 7 UFEPs.

v_5v_6 is EE: ${}^+p_{2\to1}{}^*p_5{}^*p_{5\to4}{}^*p_6{}^*p_{6\to4}{}^*p_{4\to2}$, ${}^+\ p_{2\to1}{}^*p_5{}^*p_{5\to4}{}^*p_6{}^*p_{6\to4}{}^*p_{4\to3}{}^*p_{3\to2}$, $-p_{2\to1}{}^*p_5{}^\wedge 2{}^*p_{5\to4}{}^\wedge 2{}^*p_6{}^\wedge 2{}^*p_{6\to4}{}^\wedge 2{}^*p_{4\to3}{}^*p_{3\to2}{}^*p_{4\to2}$, ${}^+p_5{}^*p_{5\to4}{}^*p_6{}^*p_{6\to4}{}^*p_{4\to3}{}^*p_{3\to1}$, $-p_5{}^\wedge 2{}^*p_{5\to4}{}^\wedge 2{}^*p_6{}^\wedge 2{}^*p_{6\to4}{}^\wedge 2{}^*p_{4\to3}{}^*p_{3\to1}{}^*p_{2\to1}{}^*p_{4\to2}$, $-p_5{}^\wedge 2{}^*p_{5\to4}{}^\wedge 2{}^*p_6{}^\wedge 2{}^*p_{6\to4}{}^\wedge 2{}^*p_{4\to3}{}^\wedge 2{}^*p_{3\to1}{}^*p_{2\to1}{}^*p_{3\to2}$, ${}^+p_5{}^\wedge 3{}^*p_{5\to4}{}^\wedge 3{}^*p_6{}^\wedge 3{}^*p_{6\to4}{}^\wedge 3{}^*p_{4\to3}{}^\wedge 2{}^*p_{3\to1}{}^*p_{2\to1}{}^*p_{3\to2}{}^*p_{4\to2}$, 7 UFEPs.

In theory, the TEP of AEIFEP is the sum of TEPs calculated by v_2, v_3, v_4 and v_5v_6 as EEs, which is the sum of all the above equations, as shown in Eq.(10).

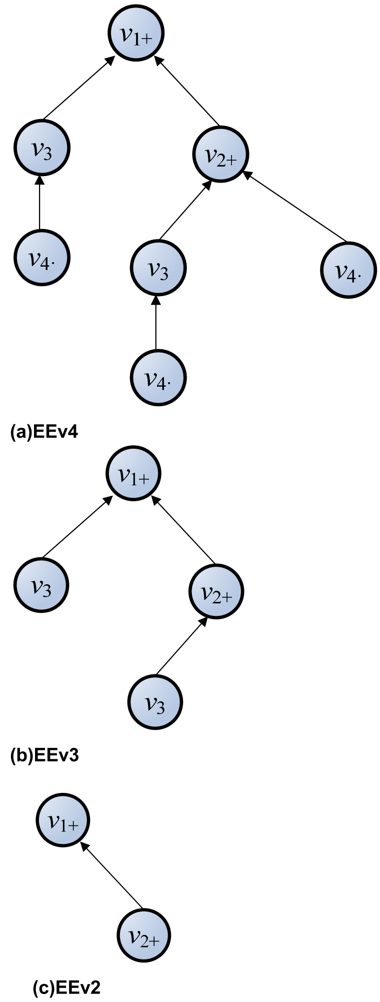


FIGURE 5. Different edge events of Trees.

$$p_{\mathrm{TE}} = \sum_{\forall e_f\in E} \sum_{\forall v_i \mathrm{in} e_f} (p_{v_i} \prod_{\forall p_{c\to r}\in e_f} p_{c\to r}) \tag{10}$$

Note: E is a set of routes that can cause TE to occur when all events except TE are taken as EE separately. Such as the UFEP calculated by the EP of v_1.

However, according to the classification of FEP defined in Def.14, we only focus on the low-order and incremental fault evolution process(IFEP). Because the TEP of high-order FEP is generally lower than that of low-order. Although there are same decrement fault evolution process(DFEP), it has little effect on TEP of SEFP. Therefore, TEP computation can be simplified, and E is defined as the set of EE-constituted routes that all event(except TE) can be taken as EE and lead to TE. These routes are IFEPs with the order equal to the number of EEs. Therefore, the UFEPs are as follows:

One-order UFEP of v_2 as EE: ${}^+p_2{}^*p_{2\to1}$;

One-order UFEPs of v_3 as EE: ${}^+p_3{}^*p_{3\to2}{}^*p_{2\to1}$, ${}^+p_3{}^*p_{3\to1}$;

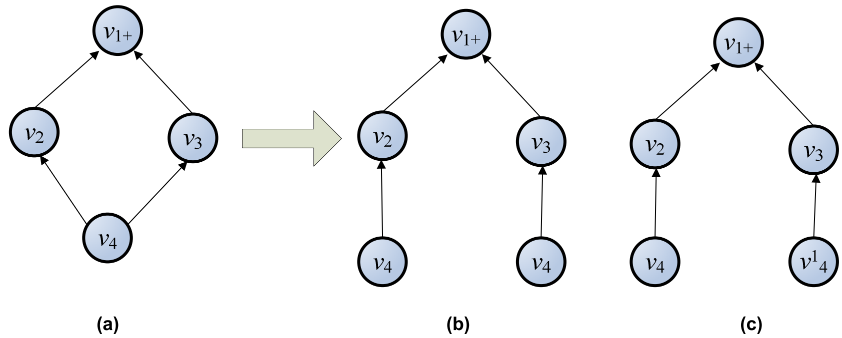


FIGURE 6. Transformation of MRSFN.

One-order UFEPs of v_4 as EE: ${}^{+}p_{2\to1}{}^{*}p_4{}^{*}p_{4\to2}$, ${}^{+}p_{2\to1}{}^{*}p_4{}^{*}\ p_{4\to3}{}^{*}p_{3\to2}$, ${}^{+}p_4{}^{*}p_{4\to3}{}^{*}p_{3\to1}$;

Two-order UFEPs of v_5v_6 as EE: ${}^{+}p_{2\to1}{}^{*}p_5{}^{*}p_{5\to4}{}^{*}p_6{}^{*}\ p_{6\to4}{}^{*}p_{4\to2}$, ${}^{+}p_{2\to1}{}^{*}p_5{}^{*}p_{5\to4}{}^{*}p_6{}^{*}p_{6\to4}{}^{*}p_{4\to3}{}^{*}p_{3\to2}$, ${}^{+}p_5{}^{*}\ p_{5\to4}{}^{*}p_6{}^{*}\ p_{6\to4}{}^{*}p_{4\to3}{}^{*}p_{3\to1}$.

In summary, the probability of TEv_1: $p_1 = p_2{}^{*}p_{2\to1}{}^{+}p_3{}^{*}\ p_{3\to2}{}^{*}p_{2\to1}{}^{+}p_3{}^{*}p_{3\to1}{}^{+}p_{2\to1}{}^{*}p_4{}^{*}p_{4\to2}{}^{+}p_{2\to1}{}^{*}p_4{}^{*}p_{4\to3}{}^{*}\ p_{3\to2}{}^{+}p_4{}^{*}p_{4\to3}{}^{*}p_{3\to1}{}^{+}p_{2\to1}{}^{*}p_5{}^{*}p_{5\to4}{}^{*}p_6{}^{*}p_{6\to4}{}^{*}p_{4\to2}{}^{+}\ p_{2\to1}{}^{*}p_5{}^{*}p_{5\to4}{}^{*}\ p_6{}^{*}p_{6\to4}{}^{*}p_{4\to3}{}^{*}p_{3\to2}{}^{+}p_5{}^{*}p_{5\to4}{}^{*}p_6{}^{*}p_{6\to4}{}^{*}\ p_{4\to3}{}^{*}p_{3\to1}$.

Each item in the equation is a fault mode that may cause TE. Of course, due to the difference of EE and its number, number of connections and TP of each connection, the FEP of each development mode, namely, UFEP is different. Generally, the EP of EE is interpreted by SFT fault probability distribution(FPD), which is only related to the influencing factors and is the fault characteristics of the object itself. FPD is greatly influenced by factors and varies with the change of factors. But it has nothing to do with the TP, and the fault probability in actual is very low, about $10^{-5} - 10^{-4}$. The TP is the probability of RE caused by CE, which varies greatly but is generally less than 10^{-2}. Then the low-order and less connected UFEPs play dominant role in TEP. The processes and results of probability calculation can be further simplified in practical analysis.

V. REPEATABILITY OF EVENTS AND TIMELINESS OF PROCESSES

A. REPEATABILITY OF EE

In the transformation from SFN to SFT, MRSFN has two or more directions in the multi-directional ring. The same EE belongs to two routes. The transformation of this situation is different from the general situation.

Firstly, the definition of event repeatability is given.

Definition 19 (Event Repeatability): the repeatability can be divided into two categories: one is that the same EE is in two routes, and one of them occurs, then they occur and have same nature; the other is that same events occur in different times or multiple similar events occur at the same time, although their natures are the same, they are regarded as two different events.

Fig.6(a) is the simplest MRSFN, and transforms the network into SFT. v_4 in Fig.6(a) reaches TEv_1 through two routes $v_4 \to v_2 \to v_1$ and $v_4 \to v_3 \to v_1$. According to the general SFN transformation rules, $p_2 = p_4{}^{*}p_{4\to2}$; $p_3 = p_4{}^{*}p_{4\to3}$; $p_1 = 1-(1-p_2{}^{*}p_{2\to1})^{*}(1-p_3{}^{*}p_{3\to1})$, then $p_1 = p_2{}^{*}p_{2\to1}{}^{+}p_3{}^{*}p_{3\to1}{}^{-}p_2{}^{*}p_{2\to1}{}^{*}p_3{}^{*}p_{3\to1} = p_4{}^{*}\ p_{4\to2}{}^{*}p_{2\to1}{}^{+}p_4{}^{*}p_{4\to3}{}^{*}p_{3\to1}{}^{-}p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{*}p_4{}^{*}p_{4\to3}{}^{*}p_{3\to1}$. This calculation method of EP of v_1 considers that the EEs in two one-order UFEPs are different, or that the same event occur at different times. Therefore, the above process should correspond to the SFN transformation of Fig.6(c).

Fig.6(a) is transformed to Fig.6(b). As EE, v_4 exists in two routes. However, from SFN, we can know that EEv_4 of these two routes is the same occurrence of one event. Therefore, they should have the same characteristics logically. When SFN is transformed to SFT, the symbols remain unchanged. Its appearance is to meet the need of transforming SFN to SFT, then $p_1 = p_4{}^{*}(p_{4\to2}{}^{*}p_{2\to1}{}^{+}p_{4\to3}{}^{*}p_{3\to1}) - p_4^2{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{*}p_{4\to3}{}^{*}p_{3\to1}$. As shown in Fig.6(c), v_4 and v_4^1 are not the same events occur in different times or multiple similar events occur at the same time. Although v_4 and v_4^1 are the same characteristics, they are not equivalent, then $p_1 = p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{+}p_4^1{}^{*}p_{4\to3}^1{}^{*}p_{3\to1}{}^{-}p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{*}\ p_4^1{}^{*}p_{4\to3}^1{}^{*}p_{3\to1}$. So we can't continue to simplify. Evidently, if v_4 in Fig.6(a), then $p_1 = p_4{}^{*}(p_{4\to2}{}^{*}p_{2\to1}{}^{+}p_{4\to3}{}^{*}p_{3\to1}) - p_4^2{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{*}p_{4\to3}{}^{*}p_{3\to1}$. If only v_4 occurs in Fig.6(c), then $p_1 = p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}$. If only v_4^1 occurs, then $p_1 = p_4^1{}^{*}p_{4\to2}^1{}^{*}p_{2\to1}$. If there is a temporal correlation between them, then $p_1 = p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{+}\ p_4^1{}^{*}p_{4\to3}^1{}^{*}p_{3\to1}{}^{-}p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{*}\ p_4^1{}^{*}p_{4\to3}^1{}^{*}p_{3\to1}$, which is the same as Fig.6(a). Change the logical relationship between v_1 and CE to "and". Then in Fig.6(b), $p_1 = p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{*}\ p_4{}^{*}p_{4\to3}{}^{*}p_{3\to1} = p_4^2 p_{4\to2}{}^{*}p_{2\to1}{}^{*}p_{4\to3}{}^{*}p_{3\to1}$, as long as v_4 occurs. In Fig.6(c), $p_1 = p_4{}^{*}p_{4\to2}{}^{*}p_{2\to1}{}^{*}p_4^1{}^{*}p_{4\to3}^1{}^{*}p_{3\to1}$, which only works when p_4 and p_4^1 occur at the same time.

According to Eq.(8), considering the repeatability of events, the TEP of SFEP is expressed as Eq.(11), as shown at the bottom of the next page.

where, $\prod_{\forall v_i^1 \mathrm{in} e_f^1} p_{v_i^1} \prod_{\forall p_{c^1\to r} \in e_f^1} p_{c^1\to r} + \ldots + \prod_{\forall v_i^n \mathrm{in} e_f^n} p_{v_i^n}$

$\prod_{\forall p_{c^n\to r}\in e_f^n} p_{c^n\to r}$ represents a FEP of a certain order, when the second kind of repetitive event similar to v_i event is FEP of EE.

Eq.(11) shows that if EE is the first kind of repetitive event, the derivation process is the same as that of the original TEP. If EE is the second kind of repetitive event, then all second kind of repetitive events of EE are to be treated differently. Its purpose is to analyze the time characteristics of these FEPs.

This shows that when SFN is transformed to SFT, it is necessary to know whether there is repetitive EE, specially the repeatability of EE in MRSFN. These EEs work differently when transformed to SFT. These EEs added because of the need to supplement logical relationships are the same EE with the same characteristics and occurs simultaneously. The EEs with the same characteristics but different occurrences or some EEs with same occurrence in the SFN are distinguished by the upper corner label. Their methods and results for calculating TEP are different.

For the repeatability of two kinds of EEs, whether their occurrence leads to TE is limited by the many factors and logical relationship. If we assume that all events in the FEP are in the same system and all factors act on these events, then the time factor becomes very special. It can be said that time factor plays a decisive role in the FEP. If the event evolution process does not overlap in time, then the fault will not occur. Therefore, the time characteristics of FEP are discussed below.

B. TIMELINESS OF FEP

Firstly, the definition of time characteristics of FEP is given.

Definition 20 (Timeliness of FEP): time of event evolution, t: occurrence time of event and transmission; τ: duration of event and transmission; therefore, the time of the existence and effect of an event is $[t, t+\tau]$.

Fig.6(c) TE v_1 is caused by v_4 and v_4^1 as EE in two routes, respectively. So how to determine the v_1 occurrence when v_1 and CE have different logic "and, or" relationship is the key problem. If the factor space of FEP is interconnected, the factors influencing the event are overlap, and then it is difficult to determine what factors lead to the final fault.

In the previous SFT study, various factors lead to different fault probability of various components in the system. Faults can be prevented by controlling these factors. If it is difficult to control most of these factors, then the control time factor is more ideal. It takes some time for everything to happen and develop. When an event reaches a certain adverse state, it can be regarded as a fault. Maintaining this state is the continuation of the fault, and losing this state is the end of the fault. If multiple events lead to TE and are "and" relation, then fault duration is the intersection of CEs' fault duration. If "or" relation, then fault duration is the union of CEs' fault duration.

As shown in Fig.6(c) with v_4 and v_4^1 as EE, both events have their occurrence time and duration. At the same time, the transmission process also takes time, so the situation that they cause TE is different. Representation of EP and TP with occurrence time t and duration τ, The time characteristics of TE occurrence caused by the two UFEPs are obtained in Fig.7.

Fig.7 shows the occurrence times of v_4 and v_4^1 as EEs in Fig.6(c), t: the occurrence time of events and transitions, and τ: the duration of events and transitions.

From Fig.7, we can see that the occurrence time t_{n+1} of successive TP must exist between the previous occurrence time t_n and the duration time $t_n+\tau_n$.

If the two routes are "and" relationship to make TE occur, then v_4 as EE: $p_4(t_4,\tau_4)^*p_{4\to2}(t_{4\to2},\tau_{4\to2})^*p_{2\to1}(t_{2\to1},\tau_{2\to1}) = p_4{}^*p_{4\to2}{}^*p_{2\to1}$, and the duration $[t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]$; v_4^1 as EE: $p_4^1(t_4^1,\tau_4^1)^*p_{4\to3}^1(t_{4\to3}^1,\tau_{4\to3}^1)^* p_{3\to1}(t_{3\to1},\tau_{3\to1}) = p_4^{1*}p_{4\to3}^1{}^*p_{3\to1}$, and the duration $[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]$.

Then EP of TE v_1: $p_1 = p_4{}^*p_{4\to2}{}^*p_{2\to1}{}^*\ p_4^{1*}p_{4\to3}^1{}^*p_{3\to1}$, and its duration $[t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]\cap[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]$. If $[t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]\cap[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]=\emptyset$, then TE v_1 does not occur; $[\ t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]\cap[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]\neq\emptyset$. Then $[t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]\cap[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]\neq\emptyset$, then TE v_1 occur, and starting time $t_1 = MAX\{t_{2\to1}, t_{3\to1}\}$, and its duration $\tau_1=[t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]\cap[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]$.

If the two routes are "or" relationship to make TE occur, then EP of TE $v_1 p_1 = p_4{}^*p_{4\to2}{}^*p_{2\to1}{}^+ p_4^{1*}p_{4\to3}^1{}^*p_{3\to1}{}^- p_4{}^*p_{4\to2}{}^*p_{2\to1}{}^*p_4^{1*}p_{4\to3}^1{}^*p_{3\to1}$ and its duration $[t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]\cup[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]$. The starting time of TE $v_1 t_1 = MIN\{t_{2\to1}, t_{3\to1}\}$, and its duration $\tau_1=[t_{2\to1}, t_{2\to1}{}^+\tau_{2\to1}]\cup[t_{3\to1}, t_{3\to1}{}^+\tau_{3\to1}]$.

Then, considering the time characteristics, the TEP of SFEP is expressed as Eq.(12), as shown at the bottom of the next page, where, t_f : the occurrence time of TE, τ_f: the duration of TE.

Eq.(12) shows that the TEP of SFN mainly depends on the EEs and logical relationships in the FEP. When simplified according to the logical relationship of each event in the network, the UFEPs with different orders will be obtained. These processes can lead to TE, but the probability

$$
W_{fault} = \begin{cases} \sum\limits_{\forall N(\prod p_{v_i})} \Big(\sum\limits_{\exists N(\prod p_{v_i})} \big(\prod\limits_{\forall v_i \text{in} e_f} p_{v_i} \prod\limits_{\forall p_{c\to r}\in e_f} p_{c\to r}\big)\Big) & \text{first kind} \\ \sum\limits_{\forall N(\prod p_{v_i})} \Big(\sum\limits_{\exists N(\prod p_{v_i})} \begin{array}{l} \big(\prod\limits_{\forall v_i \text{in} e_f} p_{v_i} \prod\limits_{\forall p_{c\to r}\in e_f} p_{c-r} + \prod\limits_{\forall v1_i \text{in} e1_f} p_{v1_i} \prod\limits_{\forall p_{c1\to r}\in e1_f} p_{c1\to r} \\ +\ldots+ \prod\limits_{\forall vn_i \text{in} en_f} p_{vn_i} \prod\limits_{\forall p_{cn\to r}\in en_f} p_{cn\to r}\big) \end{array} \Big) & \text{Second kind} \end{cases} \tag{11}
$$

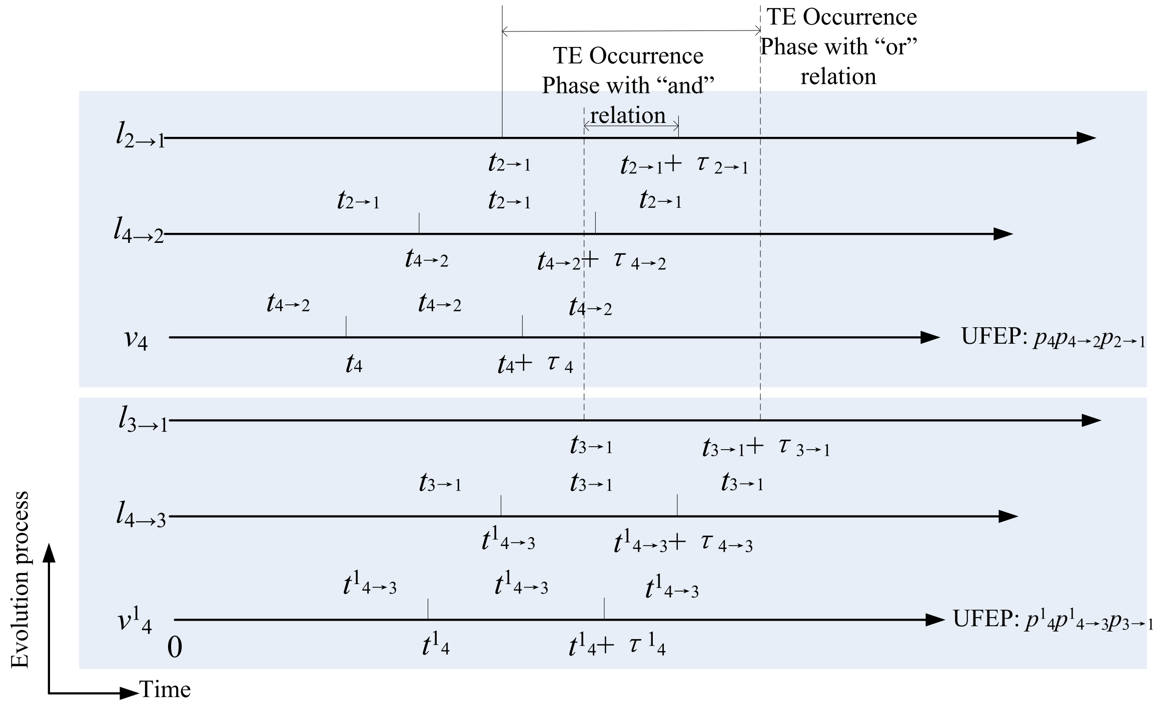


FIGURE 7. Time characteristics of the TEs in two URSFNs.

is different. Considering the time characteristics, the occurrence and duration of events and transmission are functions of time. Only when there is overlapping time, then FEP can be carried out. The logical relationships that lead to the previous connections of TE determine the occurrence time and duration of TE. The time characteristics of each

$$W_{fault}=\begin{cases}\sum\limits_{\forall N(\prod p_{v_i})}\Big(\sum\limits_{\exists N(\prod p_{v_i})}\Big(\prod\limits_{\forall v_i \text{in} e_f} p_{v_i}\prod\limits_{\forall p_{c\to r}\in e_f} p_{c\to r}\Big)\Big) & \begin{array}{l} t_f=\text{MAX}\{\forall t_{c\to f}\}\\ \tau_f=\cap\forall[t_{c\to f},t_{c\to f}+\tau_{c\to f}]\neq\varphi\end{array} \quad \begin{array}{l}\text{And Relation of UFEPs,}\\ \text{first kind}\end{array}\\ 0 & \begin{array}{l} t_f=\text{MAX}\{\forall t_{c\to f}\}\\ \tau_f=\cap\forall[t_{c\to f},t_{c\to f}+\tau_{c\to f}]=\varphi\end{array} \quad \begin{array}{l}\text{And Relation of UFEPs,}\\ \text{first kind}\end{array}\\ \sum\limits_{\forall N(\prod p_{v_i})}\Big(\sum\limits_{\exists N(\prod p_{v_i})}\Big(\prod\limits_{\forall v_i \text{in} e_f} p_{v_i}\prod\limits_{\forall p_{c\to r}\in e_f} p_{c\to r}\Big)\Big) & \begin{array}{l} t_f=\text{MIN}\{\forall t_{c\to f}\}\\ \tau_f=\cup\forall[t_{c\to f},t_{c\to f}+\tau_{c\to f}]\end{array} \quad \begin{array}{l}\text{Or Relation of UFEPs,}\\ \text{first kind}\end{array}\\ \sum\limits_{\forall N(\prod p_{v_i})}\Big(\sum\limits_{\exists N(\prod p_{v_i})}\begin{pmatrix}\prod\limits_{\forall v_i \text{in} e_f} p_{v_i}\prod\limits_{\forall p_{c\to r}\in e_f} p_{c\to r}+\\ \prod\limits_{\forall v_i^1 \text{in} e_f^1} p_{v_i^1}\prod\limits_{\forall p_{c^1\to r}\in e_f^1} p_{c^1\to r}+\\ \ldots+\prod\limits_{\forall v_i^n \text{in} e_f^n} p_{v_i^n}\prod\limits_{\forall p_{c^n\to r}\in e_f^n} p_{c^n\to r}\end{pmatrix} & \begin{array}{l} t_f=\text{MAX}\{\forall t_{c\to f}\}\\ \tau_f=\cap\forall[t_{c\to f},t_{c\to f}+\tau_{c\to f}]\neq\varphi\end{array} \quad \begin{array}{l}\text{And Relation of UFEPs,}\\ \text{Second kind}\end{array}\\ 0 & \begin{array}{l} t_f=\text{MAX}\{\forall t_{c\to f}\}\\ \tau_f=\cap\forall[t_{c\to f},t_{c\to f}+\tau_{c\to f}]=\varphi\end{array} \quad \begin{array}{l}\text{And Relation of UFEPs,}\\ \text{Second kind}\end{array}\\ \sum\limits_{\forall N(\prod p_{v_i})}\Big(\sum\limits_{\exists N(\prod p_{v_i})}\begin{pmatrix}\prod\limits_{\forall v_i \text{in} e_f} p_{v_i}\prod\limits_{\forall p_{c\to r}\in e_f} p_{c\to r}+\\ \prod\limits_{\forall v_i^1 \text{in} e_f^1} p_{v_i^1}\prod\limits_{\forall p_{c^1\to r}\in e_f^1} p_{c^1\to r}+\\ \ldots+\prod\limits_{\forall v_i^n \text{in} e_f^n} p_{v_i^n}\prod\limits_{\forall p_{c^n\to r}\in e_f^n} p_{c^n\to r}\end{pmatrix} & \begin{array}{l} t_f=\text{MIN}\{\forall t_{c\to f}\}\\ \tau_f=\cup\forall[t_{c\to f},t_{c\to f}+\tau_{c\to f}]\end{array} \quad \begin{array}{l}\text{Or Relation of UFEPs,}\\ \text{Second kind}\end{array}\end{cases} \tag{12}$$

previous connection can be obtained considering superimpose by logical relation. For Eq.(12), whether the first or the second kind of EE repetitive events, when TE occurs due to the "and" relationship of the UFEPs, t_f is the maximum value of the TE occurrence time of each UFEP. τ_f is the intersection of TE duration of each UFEP, if the intersection is empty, $W_{fault} = 0$. When TE occurs due to the "or" relationship of the UFEPs, t_f is the minimum value of the TE occurrence time of each UFEP. τ_f is the union of TE duration of each UFEP, and time τ_f may be discontinuous.

From the above discussion process, we can see that in order to prevent TE from occurring, we can take measures in the following aspects. 1) Because EE is the beginning of the FEP, EE is prevented from occurring. At the same time, the two kinds of repeatability of EE are distinguished. 2) If it cannot be prevented, the duration of EE will be shortened. 3) If it can't be shortened, we should try to delay the occurrence time of transmission and shorten the duration of transmission. The control of subsequent transmission is the same. The purpose is to make the transmission of the UFEP not overlap, and then disconnect the FEP. 4) TE can also be prevented from occurring by the logical relationship that causes TE to occur in the UFEP.

VI. INADAPTABILITY OF THE METHODS FOR DESCRIBING SFEP

For the description of SFEP, several popular methods are difficult to apply. Because they are not suitable for SFEP description, these methods can not mine fault data information in SFEP, and it is more difficult to deal with the complex structure in SFEP. The reasons why these methods are difficult to describe SFEP are discussed in detail below.

A. FORMAL CONCEPT ANALYSIS

Formal Concept Analysis (FCA) [39] is a method proposed by Wille to analyze data and extract rules from formal background. On the basis of mathematics, formal analysis can formally describe concepts, attributes and their relationships, and form concept lattices to express ontological meanings. Concept lattices can use Hasse diagrams to concisely represent generalization and instantiation among concepts. Concept lattice structure model is the core data structure of FAC.

Analyse whether FCA can be used in SFEP description. FCA corresponds and analyses objects, attributes and relationships mainly through Hasse matrix operation. Hasse matrix will remove the diagonal elements in the judgment matrix and delete some relationships by retaining the maximum path principle. After these two operations, the Hasse matrix can not represent the events, factors and their relationships in SFEP. Because SFEP does not conform to the assumption that maximum relational paths are preserved among events. In SFEP, even if CEs and REs are the same, different paths will be obtained due to different fault evolution. Therefore, the path can not be simplified according to the maximum path principle. In addition, multiple CEs may cause a RE with some logical relationships. Such as that multiple CEs must occur simultaneously to cause RE, or only one of them is required to cause RE. These logical relationships are hard to express by Hasse matrix. Therefore, it is difficult to describe SFEP using FCA method.

B. INTERPRETATIVE STRUCTURAL MODELING

Interpretative Structural Modeling Method (ISM) [40], which is a widely used analytical method in system engineering, is a structured model analysis technology. ISM obtains the reachability matrix by logical operation of adjacent matrix of digraph and decomposes it. Finally, the hierarchical representation of complex systems is obtained. It can be used for the formulation of plans for various industries, especially for the study of complex structures with multi-objective and multi-event.

In the network hierarchical digraph constructed by ISM, each event must have a definite hierarchy. This hierarchy represents the distance between CE and RE in SFEP. The farther the distance, the more complex the evolution is. For the same CE, it may participate in different evolution processes leading to RE. Therefore, a CE may exist at different levels. There are also cases where multiple CEs lead to RE in different logical relationships. Therefore, ISM is not suitable for describing SFEP.

C. SYSTEM DYNAMICS

System Dynamics(SD) [41] appeared in 1956 and was founded by Professor J.W. Forrester of MIT. Based on the close interdependence between the system behavior and the internal mechanism, it is obtained through the process of establishing and operating the mathematical model. Gradually excavate the relationship cause and result of the change form, namely the structure.

In order to study system changes with SD, the first step is to determine the evolution or cumulative period. SFEP has its own characteristics. First of all, there are many influencing factors. Because of the different influencing factors and their changes, SFEP is diverse. The same event causes multiple fault evolution paths. Multiple CEs may cause a RE to occur in different logical relationships. At present, SD theory is still not satisfied with the research of these characteristics, so SD method is not suitable for SFEP analysis.

D. SIGNED DIRECTED GRAPH

Signed Directed Graph (SDG) [42] is a qualitative technology. SDG is used to describe the causal behavior of a system under normal or abnormal conditions. According to the established causal diagram, useful information is captured and system fault analysis is realized.

SDG is a qualitative analysis method. It is difficult to quantitatively analyze the occurrence probability of SFEP events. It is difficult to analyze the variability of SFEP under the influence of multiple factors. It is also difficult to determine the RE caused by multiple CEs under different logical relationships. So SDG is not applicable.

In summary, the study of SFEP needs a unique research system. Although the SFN proposed by the author is developing and imperfect, it can basically complete the description and analysis of SEFP. Therefore, SFN has obvious advantages over other methods in describing SFEP, especially in describing and analyzing complex SFEP.

VII. CONCLUSION

1) The significance of unidirectional rings in SFN is given. It is considered that RS is the superposition of FEPs. Each cycle produces a certain amount of TEP, and all the previous cycles of this cycle are his conditional events. The concepts of RS and ordered relation are defined and their physical meanings are discussed. Three basic network representations of RS and their symbolic meanings are given. The transformation method of URSFN and SFT is reconstructed, and the equivalence symbols are defined, including the equivalence event and equivalence connection. Their properties and functions are explained. According to the logic of events in SFT transformed, the TEP calculations are related with three kinds of RS.

2) The meaning of AEIFEP is discussed. AEIFEP and GFEP are two limit states for fault initiation objects. The fault initiators in former are the objects of EEs and PEs and that of latter is only the objects of EEs. The two methods of GFEP and AIFEP are used to calculate the TEP, and the two limit states of occurrence probability are obtained. The minimum value is calculated in GFEP, and the maximum value is calculated in AEIFEP, so any possible TEP is between the two. The TEP of AEIFEP is the sum of TEPs calculated with EEs and PEs as the EEs of these TEPs. The equations and conditions are given.

3) The repeatability of events is studied and the definition is given. There are two kinds of repeatability: one is that the same EE occurs in two routes, they occor at the same time; the second is that similar events occur at different times or multiple similar events occur together, although of the same nature, they are regarded as different events. These two kinds of repetitive events have different effects on TEP, so the calculation methods are also different. The time characteristics of events, namely, the time characteristics of FEP, are studied. The time characteristics of evolution experience are expressed by the occurrence time and duration of the events and transitions. Study the overlap of the occurrence time and duration of the events and transitive connections, then we get the TEP calculation method under different ''and, or'' relations and two kinds of repetitive events. According to the repeatability and timeliness, some measures to prevent TE are given.

4) Increased comparison with Formal Concept Analysis, Interpretative Structural Modeling Method, System Dynamics and Signed Directed Graph. The reasons why they are not suitable for SFEP research are explained.

This research is the third stage of space fault tree theory. Space fault network is an abstract structure, which is mined from the actual fault evolution process. This structure has a wider adaptability, and provides an effective theory and method for research on the system fault evolution process in the future intelligent and large data environment.

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