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Establishment and Analysis of the Fault Tree for the Oil Transfer Pump System in CNPC Work Zone

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Abstract: The reliability of the equipment is very important for the large petrochemical industry, especially for oil pump as the core component of driving equipment. In order to reduce the loss of the enterprise brought by equipment failure, it is need to find those reasons which may lead to equipment failure and take some preventive measures as early as possible. This article analyzes the failure of the oil transfer pump system in CNPC work zone systematically, qualitatively and quantitatively, using the fault tree analysis method. Then 105 groups of minimal cut sets are found, and the probability of system failure after a certain time operation is calculated by using Weibull distribution. Combined with specific requirements of reliability, the work zone may make a scientific decision of plant maintenance cycle according to the conclusion.

Key words: fault tree; reliability; Weibull distribution; plant maintain and management

1 Introduction

Fault tree analysis (FTA) is a graphic deductive reasoning method. It is an analysis technology that by analyzing the hardware, software, environment and human factors which may possibly cause the fault of the system or system component, draws fault tree to determine the various possible combinations of the cause of the system or system component failure and their probabilities.

Fault tree analysis method puts the failure event that the system doesn´t want happen most as the top event, and then finds out all the possible and eventual reasons that cause this fault status. This method starts with qualitative analysis and quantitative analysis, can identify and evaluate the weak link of various systems, and has the characteristics of conciseness and visualization [1].

He Zheng-wen and Xu Yu analyzed the reliability of vacuum resin shot dosing equipment qualitatively and quantitatively by FTA to enhance the reliability [2]. Chen Lin constructed the fault tree of oil-well pump and found its minimal cut-sets [3]. Zheng Li and Yang Tao discussed the application of FTA in fault forecast in electric power industry [4].

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The steps of fault tree analysis method are as follows:

1) Choose the reasonable top event, the analysis boundary and range of definition of the system.

2) Build the fault tree, based on the technical data which have been collected and the help of the design operation and management personnel.

3) Simplify or modular the fault tree.

4) Qualitative analysis, find out all the minimal cut sets of the fault tree.

5) Quantitative analysis, the main task of this phase is to calculate the probability of top event.

2 The composition and working principle of oil transfer pump system

2.1 The composition of oil transfer pump

The CNPC oil station now mainly use horizontal single stage centrifugal oil pump produced by Japanese company IDP. Its main technical parameters are shown in Table 1.

Table 1 Main technical parameters of oil transfer pump

Main technical parameters	Type: horizontal single-stage centrifugal pump Transmission medium: oil Sealing form: mechanical seal Connecting forms: coupling Delivery capacity: 711 cubic meter an hour Corresponding pumping height: 70 m Revolving speed: 1485 RPM Shaft power: 161.6 kW Pump efficiency: 71% NPSH: 3.4 m Manufacturer: Japan IDP Date of production: July 1996 Date of putting-in-service: June 1997

Oil transfer pump system is composed of pump body, motor and block valve; the pump body is mainly composed of the pump case, the shaft system, and mechanical seal parts, etc. Main components and functions are as follows:

1) Pump case

There are two kinds of pump cases: axial split and radial split. The shells of most single pump are volute, their pump cavity are spiral which is used to collect liquid from the impeller and lead to diffusion tube to the pump discharge. The pump case bears all the work pressure and the heat load of the liquid.

2) Impeller

The impeller is the only power component. The pump acts on the fluid through the impeller.

3) Sealing ring

The role of the sealing ring is to prevent the internal leakage and external leakage of the pump, the sealing ring made of wear-resistant materials, sets on before and after impeller cover plate and the pump shell, and can be replaced after being worn out.

4) Axis and bearing

The pump axis connects the impeller and coupling. According to the size of the pump, one can choose rolling bearing or sliding bearing.

5) Shaft seal (mechanical seal)

There are two kinds of shaft seal: mechanical seal and packing seal. The shaft seal of oil transfer pump in the work zone of oil station is mechanical seal.

2.2 Working principle of the oil transfer pump

When the motor drives the pump shaft and the impeller rotates, the liquid on the one hand, with the impeller for circular motion, on the one hand, under the action of centrifugal force, the impeller center to the peripheral thrown, liquid can get the pressure from the impeller and speed. When the liquid flows through the volute to drainage, some can speed will be transformed into static pressure can. Throw in the liquid from the impeller, the impeller center of low pressure area, and inhaled liquid surface pressure form pressure difference, so the liquid being inhaled, and is discharged at a certain pressure.

3 The establishment of the fault tree of the oil transfer pump system

First of all, analyze the function, structure, principle, failure state, failure factors and their influence of each component, and thoroughly understand and identify a top event that don´t want it happen most; and find out all the possible direct causes of all events at various levels, and by using the symbol of the fault tree to show all kinds of events and the logic relationship, until analyzing all bottom event [1]. Specific steps include the following aspects:

1) Confirm and to be familiar with the system

Through investigating the working condition of the oil transfer pump system, learning from the related technical personnel and looking up information, the performance, running condition, operation situation and all kinds of important parameters of the oil transfer pump are understood, then its fault information and other relevant data of the system lave collected and analyzed.

2) Confirm the top event of the fault tree

According to the principle of determining the top events of fault tree analysis, we make the event – "the failure of oil transfer pump" that affects the system´s normal operation most as the top event of the system´s fault tree.

3) Build the fault tree

After determining the top event of the fault tree, according to the building principle, build the fault tree by using a top-down deductive method from the top event, then find the cause of the top event, finally tessellate the event to the degree that can´t distinguish. Various events are associated with proper logic gate, form an inverted tree diagram. The fault tree is built as shown in Figure 1 to Figure 9. Table 2 is a list of the top event, middle events and bottom events of the fault tree, which contains 62 middle events and 111 bottom events [5].

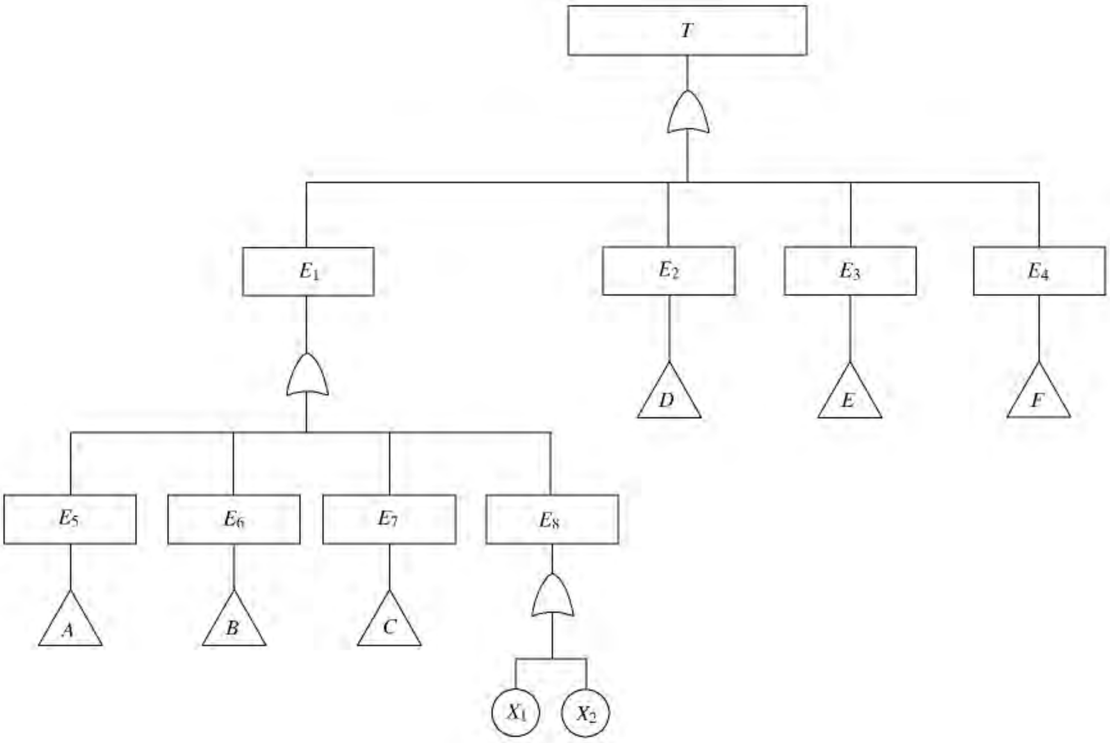

Figure 1 The oil transfer pump system fault tree Ⅰ

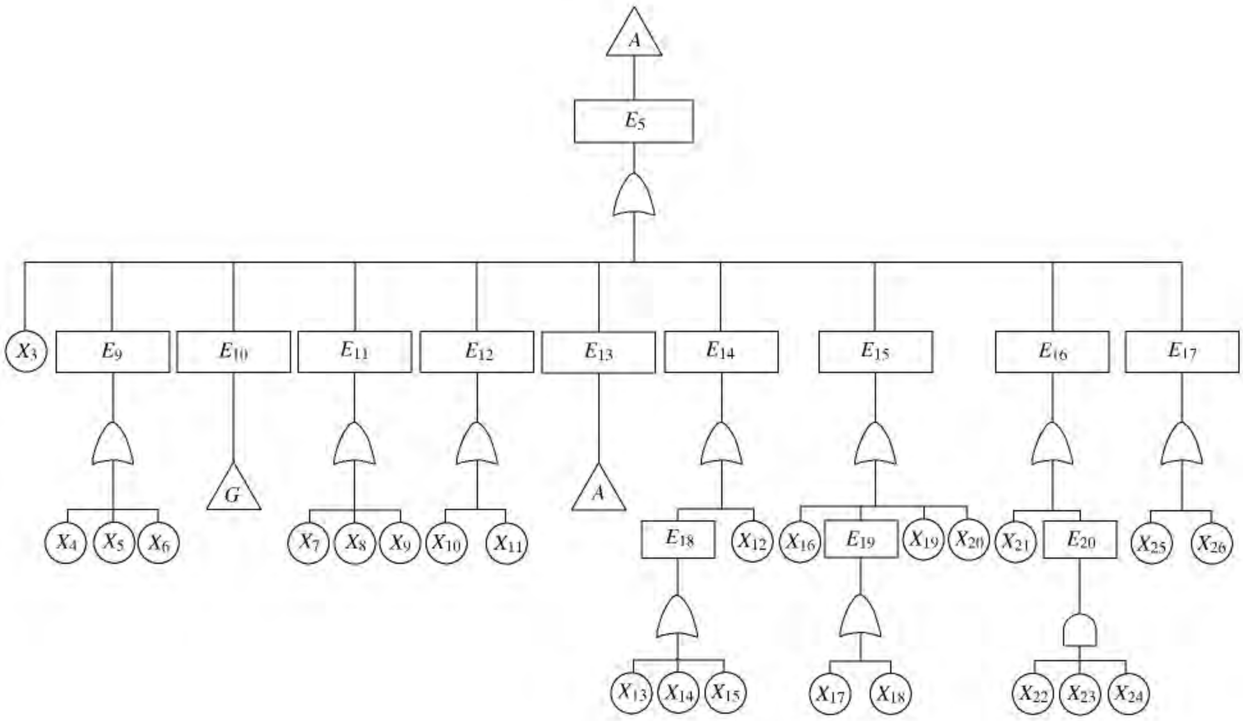

Figure 2 The oil transfer pump system fault tree Ⅱ

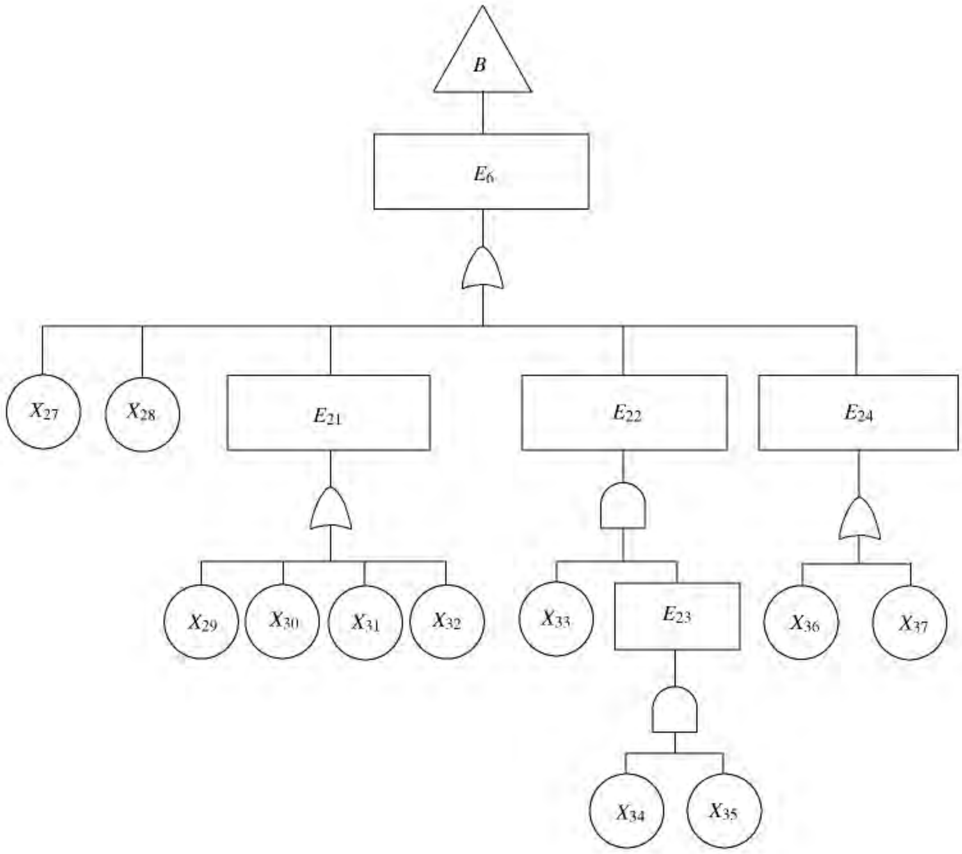

Figure 3 The oil transfer pump system fault tree Ⅲ

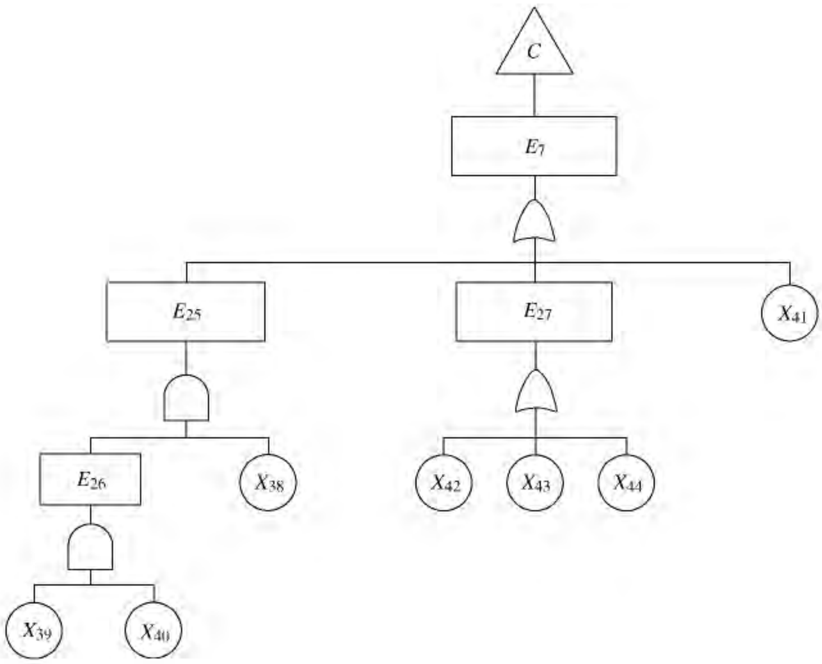

Figure 4 The oil transfer pump system fault tree Ⅳ

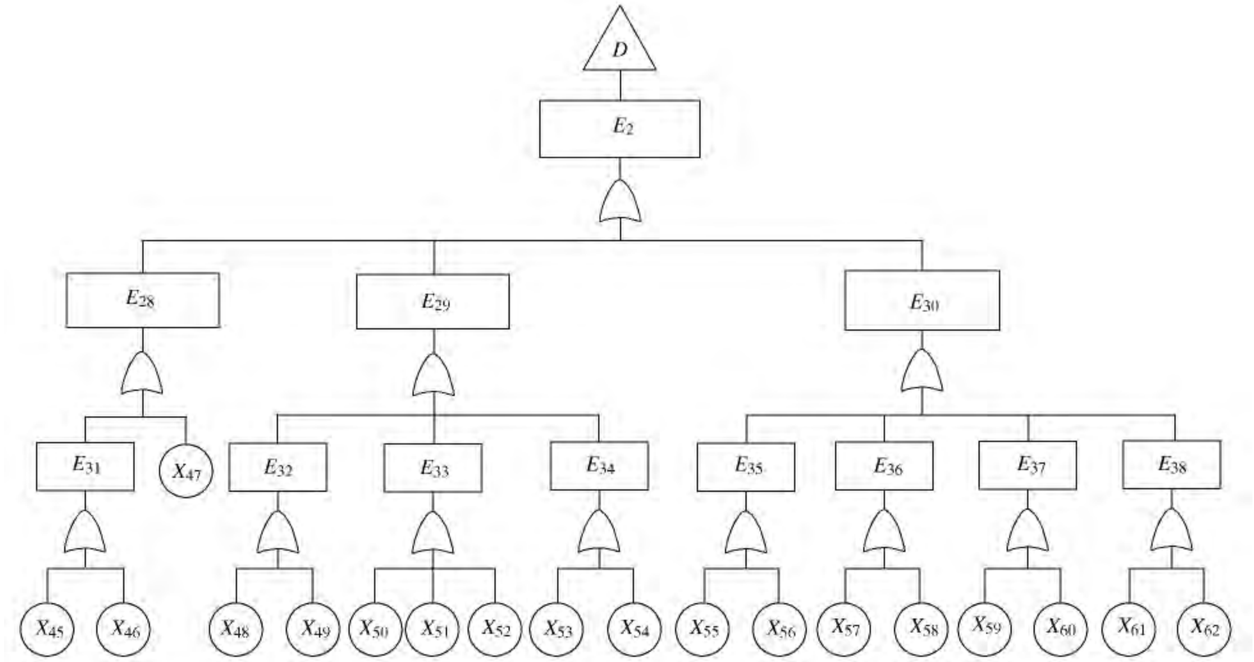

Figure 5 The oil transfer pump system fault tree Ⅴ

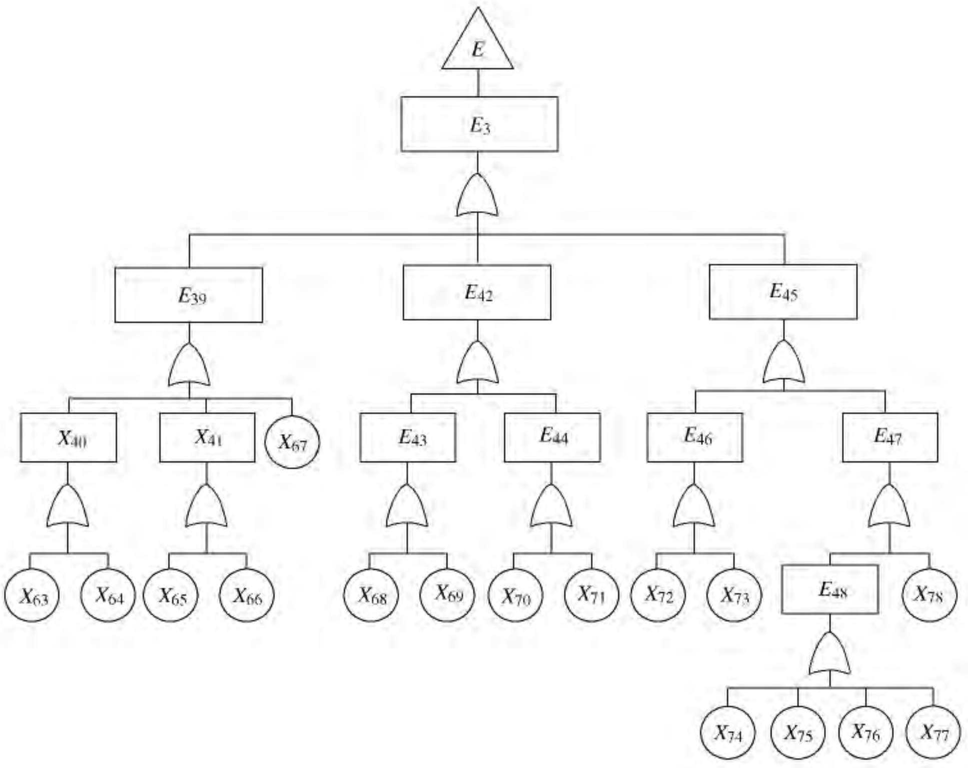

Figure 6 The oil transfer pump system fault tree Ⅵ

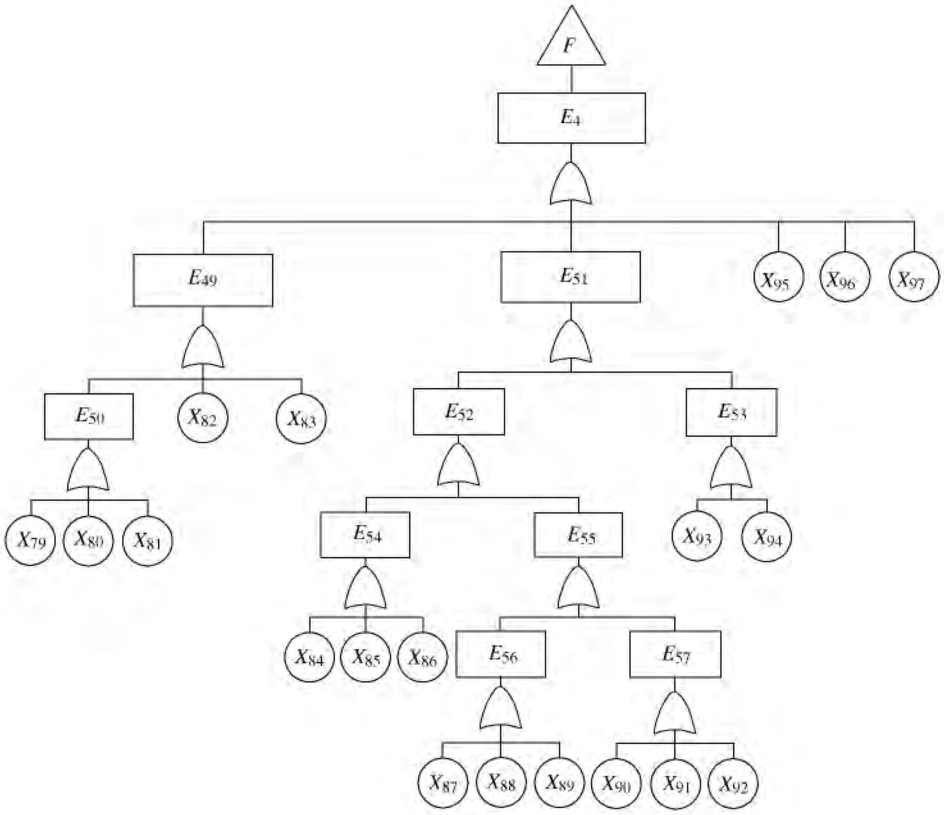

Figure 7 The oil transfer pump system fault tree Ⅶ

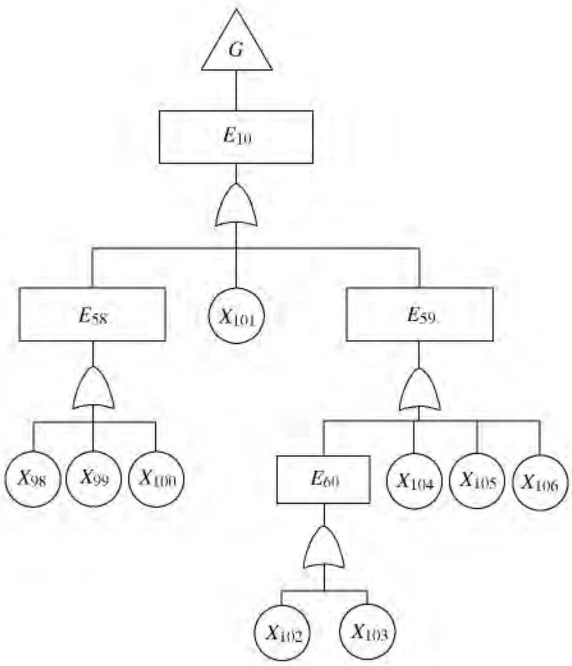

Figure 8 The oil transfer pump system fault tree Ⅷ

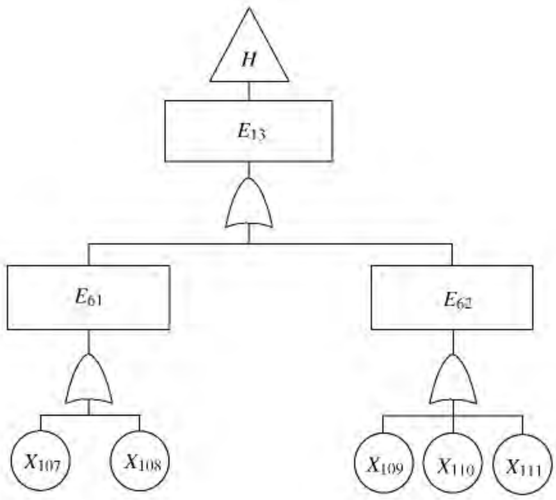

Figure 9 The oil transfer pump system fault tree Ⅸ

The letter *T* in figures above represents the top event of the fault tree, *E* represents the middle events of the fault tree, *X* represents the bottom events of the fault tree, the event descriptions are shown in Table 2.

Table 2 Oil transfer pump system fault description table

Code	Description	Code	Description
T	Oil transfer pump system failure	E_1	Pump body failure
E_2	Axis system failure	E_3	Motor failure
E_4	Valve failure	E_5	Mechanical seal failure
E_6	Impeller fault	E_7	Pump case fault
E_8	Pump choma failure	E_9	Sealing ring failure
E_{10}	Seal leakage	E_{11}	Sealing surface failure
E_{12}	Carbon ring failure	E_{13}	O-ring failure
E_{14}	Movement compensation ring failure	E_{15}	Message loop plane wear failure
E_{16}	Spring failure	E_{17}	Lubrication oil failure
E_{18}	Dirt or crystal	E_{19}	Assembly problems
E_{20}	Spring break	E_{21}	Blade failure
E_{22}	Impeller corrosion cracking	E_{23}	Stress corrosion
E_{24}	Impeller ring failure	E_{25}	Pump case corrosion cracking
E_{26}	Stress corrosion	E_{27}	The temperature of pump case is too high
E_{28}	Axis failure	E_{29}	Coupling failure
E_{30}	Bearing failure	E_{31}	Axis fracture
E_{32}	Coupling fracture	E_{33}	Coupling looseness
E_{34}	Coupling stuck	E_{35}	Bearing wear
E_{36}	Plastic deformation	E_{37}	Bearing corrosion
E_{38}	Bearing fracture	E_{39}	Stator failure
E_{40}	Iron core fault	E_{41}	Winding fault

Continued

Code	Description	Code	Description
E_{42}	Rotor failure	E_{43}	Iron core fault
E_{44}	Winding fault	E_{45}	Power failure
E_{46}	Switch unclosed	E_{47}	Failure after switch closed
E_{48}	Fuse disconnect	E_{49}	Valve stuck
E_{50}	Wrong operation	E_{51}	Valve leakage
E_{52}	Valve fracture	E_{53}	Connecting bolts leakage
E_{54}	The capacity of valve bearing is low	E_{55}	Corrosion cracking
$E_{56}6$	External corrosion	E_{57}	Internal corrosion
E_{58}	O-rings leakage	E_{59}	The contact surface of sealing is damaged or erosion
E_{60}	Axle sleeve failure	E_{61}	O-ring overheating
E_{62}	O-ring extrusion	X_1	Pump ring eccentric wear
X_2	Radial clearance largen	X_3	Throttling orifice clogged
X_4	Sealing ring aging	X_5	Sealing ring deformation
X_6	Sealing ring damaged	X_7	Sealing surface deformation
X_8	Large particle plugging sealing surface	X_9	Small particles embedded sealing surface
X_{10}	Carbon ring erosion	X_{11}	Carbon ring edge breakage
X_{12}	Movement compensation ring aging	X_{13}	Seal cavity temperature decreased
X_{14}	Liquid crystal	X_{15}	Cooling water scaling
X_{16}	Medium containing particles	X_{17}	Pump cover is not flat when installation
X_{18}	Rubber parts damaged when installation	X_{19}	Dry grinding damage caused by no medium operation
X_{20}	Cavitation	X_{21}	Spring relaxation

Continued

Code	Description	Code	Description
X_{22}	Spring corrosion	X_{23}	Stress
X_{24}	Medium corrosion	X_{25}	Poor lubricating oil cleanliness
X_{26}	Lubricating oil viscosity changed	X_{27}	Impeller cover thinning
X_{28}	Pin key fracture	X_{29}	Blade fatigued failure
X_{30}	Blade corrosion cracking	X_{31}	Blade plastic deformation
X_{32}	Blade micro vibration failure	X_{33}	Poor material properties
X_{34}	Tensile stress	X_{35}	Media corrosive
$X\,36$	Lmpeller ring eccentric wear	X_{37}	Radial clearance largen
X_{38}	Poor material properties	X_{39}	Tensile stress
X_{40}	Medium corrosion	X_{41}	Bolt failure
X_{42}	Pump and pipeline is not completely empty or full	X_{43}	Not reach the minimum absorbed dose
X_{44}	Not correct alignment	X_{45}	Axle sleeve damaged
X_{46}	Axis fatigued	X_{47}	Coaxiality of axis largen caused by vibration
X_{48}	Bolt fallen off	X_{49}	Coupling fatigued
X_{50}	Bolt looseness	X_{51}	Shock pads wear
X_{52}	Elastic conical looseness	X_{53}	Lubricating oil is not enough
X_{54}	Lubricating oil contains impurities	X_{55}	Existence of abrasive
X_{56}	Bad lubrication	X_{57}	Heavy load
X_{58}	Hard foreign matter dropped in	X_{59}	Cause by lubricating oil

Continued

Code	Description	Code	Description
X_{60}	Relative motion of the ferrule in the journal	X_{61}	Heavy load
X_{62}	Fatigued	X_{63}	Iron core deformation
X_{64}	Iron core looseness	X_{65}	Winding interphase short circuit
X_{66}	Winding wiring error	X_{67}	Engine base bolt looseness
X_{68}	Iron core deformation	X_{69}	Iron core looseness
X_{70}	Winding interphase short circuit	X_{71}	Winding wiring error
X_{72}	Take for mistake	X_{73}	Switch failure
X_{74}	Power line short circuit	X_{75}	Stator winding short circuit
X_{76}	Stator winding connection error	X_{77}	The section of fuse is too small
X_{78}	Junction box fault	X_{79}	Not according to the operating instruction
X_{80}	Not operating by professional	X_{81}	No measures to prevent error
X_{82}	Valve rod corrosion	X_{83}	Actuating device damaged
X_{84}	The valve type is unreasonable	X_{85}	Working pressure is more than design pressure
X_{86}	Poor mechanical properties of the valve material	X_{87}	Poor atmospheric condition
X_{88}	The paint of valve does not reach the standard	X_{89}	The valve material is not resistant to corrosion
X_{90}	The valve material is not resistant to corrosion	X_{91}	Corrosion failure
X_{92}	Substances helped corrosive within the oil	X_{93}	Connecting bolt failure
X_{94}	Sealing ring failure	X_{95}	Internal leakage
X_{96}	Out leakage	X_{97}	Valve screen plugging
X_{98}	Rotating ring leakage	X_{99}	Static ring leakage

Continued

Code	Description	Code	Description
X_{100}	End cover leakage	X_{101}	Friction pair end cover leakage
X_{102}	Axle sleeve wear	X_{103}	Axle sleeve blister
X_{104}	Flange erosion	X_{105}	Rotating ring damaged
X_{106}	The end face of annular seal space corrosion	X_{107}	Beyond the O-ring′s maximum temperature limit
X_{108}	Local overheating	X_{109}	Extrusion or deformation caused by stress
X_{110}	Wrong installation program	X_{111}	High operating pressure and temperature

4 The fault tree analysis of oil transfer pump system

4.1 The structural function of the fault tree of oil transfer pump system

The fault tree is connected by the "and" and "intersection" logical relationships which form its all bottom events. In order to make qualitative analysis and quantitative calculation for the fault tree conveniently, the mathematical expressions of the fault tree must be given which means the structural function. Set $\varphi(x)$ as the structural function of mathematical expression of the fault tree.

Then the structural function of the fault tree made by "and" is:

$$\varphi(x) = \prod_{i=1}^{n} X_i \qquad (1)$$

The $\prod$ in Formula (1) means multiplication, it is like a parallel system, whose engineering significance is that only when all components fail, the system will fail, and the system will normal as long as there is a component within is normal.

Then the structural function of the fault tree made by "or" is:

$$\varphi(x) = \coprod_{i=1}^{n} X_i = 1 - \prod_{i=1}^{n} (1 - X_i) \qquad (2)$$

Formula (2) shows that the fault tree of "or" is like a series system, the fault tree combined with "or" consists of several independent events. Its engineering significance is: as long as there is one component fails, the system will fail, and the system will be in normal state only when all components are normal.

4.2 The qualitative analysis of the fault tree of oil transfer pump system

Through the study of the qualitative analysis of fault tree, the minimum cut set of the fault tree can be found out. The so-called minimal cut set, is the minimal set of all possible bottom events that will cause the top event[6]. This article uses the descending algorithm to look for the minimum cut set of the fault tree of oil transfer pump system, solving steps are shown in Table 3.

Table 3 Solving steps of descending algorithm to find minimal cut sets

Code of solving steps							The minimal cut sets
1	2	3	4	5	6	7	
T	E_1	E_5	X_3	X_3	X_3	X_3	X_1
	E_2	E_6	E_9	X_4	X_4	X_4	X_2
	E_3	E_7	E_{10}	X_5	X_5	X_5	X_3
	E_4	E_8	E_{11}	X_6	X_6	X_6	X_4
		E_{28}	E_{12}	E_{58}	X_{98}	X_{98}	X_5
		E_{29}	E_{13}	X_{101}	X_{99}	X_{99}	X_6
		E_{30}	E_{14}	E_{59}	X_{100}	X_{100}	X_7
		E_{39}	E_{15}	X_7	X_{101}	X_{101}	X_8
		E_{42}	E_{16}	X_8	E_{60}	X_{102}	X_9
		E_{45}	E_{17}	X_9	X_{104}	X_{103}	X_{10}
		E_{49}	X_{27}	X_{10}	X_{105}	X_{104}	X_{11}
		E_{51}	X_{28}	X_{11}	X_{106}	X_{105}	X_{12}
		X_{95}	E_{21}	E_{61}	X_7	X_{106}	X_{13}
		X_{96}	E_{22}	E_{62}	X_8	X_7	X_{14}
		X_{97}	E_{24}	E_{18}	X_9	X_8	X_{15}
			E_{25}	X_{12}	X_{10}	X_9	X_{16}
			E_{27}	X_{16}	X_{11}	X_{10}	X_{17}
			X_{41}	E_{19}	X_{107}	X_{11}	X_{18}
			X_1	X_{19}	X_{108}	X_{107}	X_{19}
			X_2	X_{20}	X_{109}	X_{108}	X_{20}
			E_{31}	X_{21}	X_{110}	X_{109}	X_{21}
			X_{47}	E_{20}	X_{111}	X_{110}	$X_{22}X_{23}X_{24}$

Continued

Code of solving steps							The minimal cut sets
1	2	3	4	5	6	7	
			E_{32}	X_{25}	X_{13}	X_{111}	X_{25}
			E_{33}	X_{26}	X_{14}	X_{13}	X_{26}
			E_{34}	X_{27}	X_{15}	X_{14}	X_{27}
			E_{35}	X_{28}	X_{12}	X_{15}	X_{28}
			E_{36}	X_{29}	X_{16}	X_{12}	X_{29}
			E_{37}	X_{30}	X_{17}	X_{16}	X_{30}
			E_{38}	X_{31}	X_{18}	X_{17}	X_{31}
			E_{40}	X_{32}	X_{19}	X_{18}	X_{32}
			E_{41}	$X_{33}E_{23}$	X_{20}	X_{19}	$X_{33}X_{34}X_{35}$
			X_{67}	X_{36}	X_{21}	X_{20}	X_{36}
			E_{43}	X_{37}	$X_{22}X_{23}X_{24}$	X_{21}	X_{37}
			E_{44}	$E_{26}X_{38}$	X_{25}	$X_{22}X_{23}X_{24}$	$X_{38}X_{39}X_{40}$
			E_{46}	X_{42}	X_{26}	X_{25}	X_{41}
			E_{47}	X_{43}	X_{27}	X_{26}	X_{42}
			E_{50}	X_{44}	X_{28}	X_{27}	X_{43}
			X_{82}	X_{41}	X_{29}	X_{28}	X_{44}
			X_{83}	X_{1}	X_{30}	X_{29}	X_{45}
			E_{52}	X_{2}	X_{31}	X_{30}	X_{46}
			E_{53}	X_{45}	X_{32}	X_{31}	X_{47}
			X_{95}	X_{46}	$X_{33}X_{34}X_{35}$	X_{32}	X_{48}
			X_{96}	X_{47}	X_{36}	$X_{33}X_{34}X_{35}$	X_{49}
			X_{97}	X_{48}	X_{37}	X_{36}	X_{50}

Continued 2

Code of solving steps							The minimal cut sets
1	2	3	4	5	6	7	
				X_{49}	$X_{38}X_{39}X_{40}$	X_{37}	X_{51}
				X_{50}	X_{42}	$X_{38}X_{39}X_{40}$	X_{52}
				X_{51}	X_{43}	X_{42}	X_{53}
				X_{52}	X_{44}	X_{43}	X_{54}
				X_{53}	X_{41}	X_{44}	X_{55}
				X_{54}	X_{1}	X_{41}	X_{56}
				X_{55}	X_{2}	X_{1}	X_{57}
				X_{56}	X_{45}	X_{2}	X_{58}
				X_{57}	X_{46}	X_{45}	X_{59}
				X_{58}	X_{47}	X_{46}	X_{60}
				X_{59}	X_{48}	X_{47}	X_{61}
				X_{60}	X_{49}	X_{48}	X_{62}
				X_{61}	X_{50}	X_{49}	X_{63}
				X_{62}	X_{51}	X_{50}	X_{64}
				X_{63}	X_{52}	X_{51}	X_{65}
				X_{64}	X_{53}	X_{52}	X_{66}
				X_{65}	X_{54}	X_{53}	X_{67}
				X_{66}	X_{55}	X_{54}	X_{68}
				X_{67}	X_{56}	X_{55}	X_{69}
				X_{68}	X_{57}	X_{56}	X_{70}
				X_{69}	X_{58}	X_{57}	X_{71}
				X_{70}	X_{59}	X_{58}	X_{72}

Continued

Code of solving steps							The minimal cut sets
1	2	3	4	5	6	7	
				X_{71}	X_{60}	X_{59}	X_{73}
				X_{72}	X_{61}	X_{60}	X_{74}
				X_{73}	X_{62}	X_{61}	X_{75}
				E_{48}	X_{63}	X_{62}	X_{76}
				X_{78}	X_{64}	X_{63}	X_{77}
				X_{79}	X_{65}	X_{64}	X_{78}
				X_{80}	X_{66}	X_{65}	X_{79}
				X_{81}	X_{67}	X_{66}	X_{80}
				X_{82}	X_{68}	X_{67}	X_{81}
				X_{83}	X_{69}	X_{68}	X_{82}
				E_{54}	X_{70}	X_{69}	X_{83}
				E_{55}	X_{71}	X_{70}	X_{84}
				X_{93}	X_{72}	X_{71}	X_{85}
				X_{94}	X_{73}	X_{72}	X_{86}
				X_{95}	X_{74}	X_{73}	X_{87}
				X_{96}	X_{75}	X_{74}	X_{88}
				X_{97}	X_{76}	X_{75}	X_{89}
					X_{77}	X_{76}	X_{90}
					X_{78}	X_{77}	X_{91}
					X_{79}	X_{78}	X_{92}
					X_{80}	X_{79}	X_{93}
					X_{81}	X_{80}	X_{94}

Continued

Code of solving steps							The minimal cut sets
1	2	3	4	5	6	7	
					X_{82}	X_{81}	X_{95}
					X_{83}	X_{82}	X_{96}
					X_{84}	X_{83}	X_{97}
					X_{85}	X_{84}	X_{98}
					X_{86}	X_{85}	X_{99}
					E_{56}	X_{86}	X_{100}
					E_{57}	X_{87}	X_{101}
					X_{93}	X_{88}	X_{102}
					X_{94}	X_{89}	X_{103}
					X_{95}	X_{90}	X_{104}
					X_{96}	X_{91}	X_{105}
					X_{97}	X_{92}	X_{106}
						X_{93}	X_{107}
						X_{94}	X_{108}
						X_{95}	X_{109}
						X_{96}	X_{110}
						X_{97}	X_{111}

Finally the minimal cut sets of the fault tree are as follows.

$\{X_1\}$, $\{X_2\}$, $\{X_3\}$, $\{X_4\}$, $\{X_5\}$, $\{X_6\}$, $\{X_7\}$, $\{X_8\}$, $\{X_9\}$, $\{X_{10}\}$, $\{X_{11}\}$, $\{X_{12}\}$, $\{X_{13}\}$, $\{X_{14}\}$, $\{X_{15}\}$, $\{X_{16}\}$, $\{X_{17}\}$, $\{X_{18}\}$, $\{X_{19}\}$, $\{X_{20}\}$, $\{X_{21}\}$, $\{X_{22}, X_{23}, X_{24}\}$, $\{X_{25}\}$, $\{X_{26}\}$, $\{X_{27}\}$, $\{X_{28}\}$, $\{X_{29}\}$, $\{X_{30}\}$, $\{X_{31}\}$, $\{X_{32}\}$, $\{X_{33}, X_{34}, X_{35}\}$, $\{X_{36}\}$, $\{X_{37}\}$, $\{X_{38}, X_{39}, X_{40}\}$, $\{X_{41}\}$, $\{X_{42}\}$, $\{X_{42}\}$, $\{X_{43}\}$, $\{X_{44}\}$, $\{X_{45}\}$, $\{X_{46}\}$, $\{X_{47}\}$, $\{X_{48}\}$, $\{X_{49}\}$, $\{X_{50}\}$, $\{X_{51}\}$, $\{X_{52}\}$, $\{X_{53}\}$, $\{X_{54}\}$, $\{X_{55}\}$, $\{X_{56}\}$, $\{X_{57}\}$, $\{X_{58}\}$, $\{X_{59}\}$, $\{X_{60}\}$, $\{X_{61}\}$, $\{X_{62}\}$, $\{X_{63}\}$, $\{X_{64}\}$, $\{X_{65}\}$, $\{X_{66}\}$, $\{X_{67}\}$, $\{X_{68}\}$, $\{X_{69}\}$, $\{X_{70}\}$, $\{X_{71}\}$, $\{X_{72}\}$, $\{X_{73}\}$, $\{X_{74}\}$, $\{X_{75}\}$, $\{X_{76}\}$, $\{X_{77}\}$, $\{X_{78}\}$, $\{X_{79}\}$, $\{X_{80}\}$, $\{X_{81}\}$, $\{X_{82}\}$, $\{X_{83}\}$, $\{X_{84}\}$, $\{X_{85}\}$, $\{X_{86}\}$, $\{X_{87}\}$, $\{X_{88}\}$, $\{X_{89}\}$, $\{X_{90}\}$, $\{X_{91}\}$, $\{X_{92}\}$, $\{X_{93}\}$, $\{X_{94}\}$, $\{X_{95}\}$, $\{X_{96}\}$, $\{X_{97}\}$, $\{X_{98}\}$, $\{X_{99}\}$,

$\{X_{100}\}$, $\{X_{101}\}$, $\{X_{102}\}$, $\{X_{103}\}$, $\{X_{104}\}$, $\{X_{105}\}$, $\{X_{106}\}$, $\{X_{107}\}$, $\{X_{108}\}$, $\{X_{109}\}$, $\{X_{110}\}$, $\{X_{111}\}$

There are a total of 105 sets. Among which there are 102 first-order minimal cut sets and 3 third-order minimal cut sets.

According to the results of minimal cut sets, the fault tree of oil transfer pump system can be simplified. The result is shown in Figure 10.

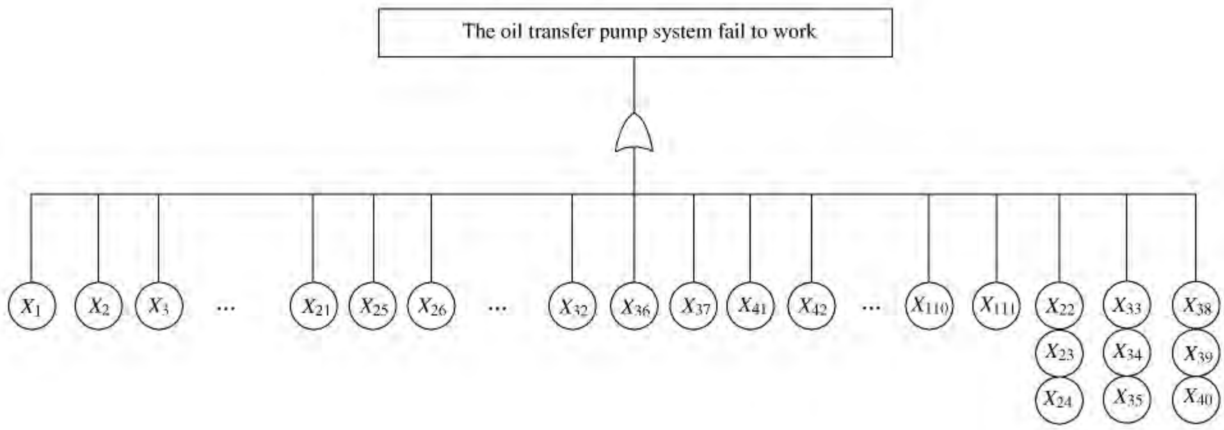

Figure 10 The simplified fault tree of oil transfer pump system

4.3 The quantitative analysis of the fault tree of oil transfer pump system

The purpose of the quantitative analysis of the fault tree is to calculate the occurring probability of the top event, which is based on the probability of bottom events. If the relevant information and records are complete and the probability of bottom events is known, the probability of top event can be obtained.

Set the minimal cut sets of the fault tree as $K_1, K_2, \cdots, K_n$, the probability of bottom events X_i is $P(x_i)$ ($i = 1, 2, \cdots, n$, $n = 111$), then the probability of top event T is:

$$P(T) = \sum_{i=1}^{n} P(K_i) - \sum_{i<j=2}^{n} P(K_i K_j) + \cdots + (-1)^{n-1} P(K_1 K_2 \cdots K_n) \qquad (3)$$

Generally, the probability of bottom events is very small, so the paper can only take $P(T) = \sum_{i=1}^{n} P(K_i)$ in engineering calculation. In this case:

$$P(T) = \sum_{i=1}^{21} P(X_i) + \sum_{i=25}^{32} P(X_i) + \sum_{i=36}^{37} P(X_i) + \sum_{i=41}^{111} P(X_i) + \{1 - \prod_{i=22}^{24} [1 - P(X_i)]\} + \{1 - \prod_{i=33}^{35} [1 - P(X_i)]\} + \{1 - \prod_{i=38}^{40} [1 - P(X_i)]\} \qquad (4)$$

In practice, the working zone does not have enough complete information and records that can obtain all the probability of bottom events, there is only part of the equipment maintenance record. So the paper chooses several components that have a great influence on oil pump system according to the failure frequency, the damage degree of the system and the difficulty of detection, and calculates its failure probability by using Weibull distribution, then calculates the probability of top event. The key components include electrical machine, valve, mechanical seal, impeller, pump case, mouth ring of pump body, shaft, shaft coupling and bearing.

This is equivalent to taking the failure of key components that chosen as a new bottom events, then the fault tree of oil transfer pump system can be further simplified as:

In order to calculate conveniently, the paper takes the mechanical seal which is an important part of the pump body as an example.

4.3.1 The calculation of the probability of the failure mode based on the double parameter Weibull distribution

When mechanical equipment is in its service life, failure rate is associated with using age. Failure rate function is a function that changes over time, so its failure rate is different as equipment in different life. The curve in Figure 12 reflects the failure distribution of the whole equipment period, including early failure period, accidental failure period and wear failure period. It is called bathtub curve because its whole shape is like a bathtub [7].

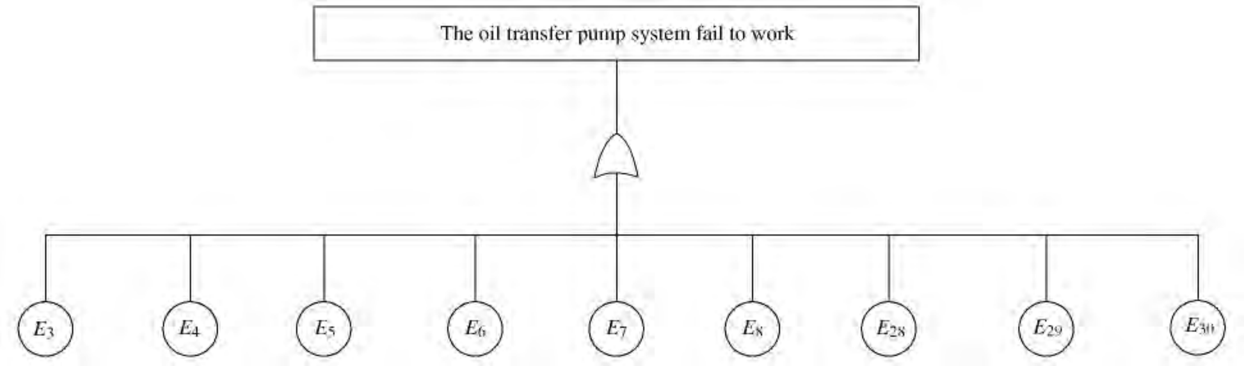

Figure 11 The further simplified fault tree of oil transfer pump system

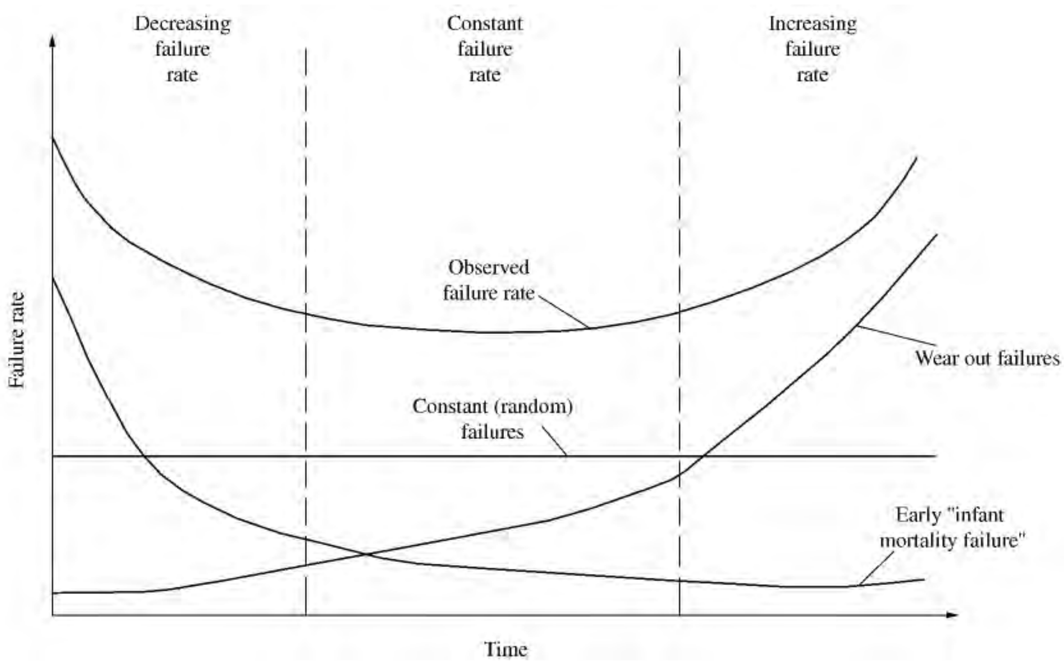

Figure 12 Bathtub curve

In recent years, Weibull distribution is the most widely used mode in the reliability analysis of equipment life, which can describe the whole bathtub curve. Using Weibull distribution, the failure rate of the equipment $\lambda(t)$ can be described more exactly, and more accurate data for the probability of bottom events in the fault tree can be provided, so the failure probability of top event calculated is more accurate[8]. Among them, the double parameter Weibull distribution is widely used in the data analysis of mechanical equipment life.

1) Weibull distribution of double parameters[9]

The failure distribution function of double parameters Weibull distribution is:

$$F(t) = 1 - \exp[-(t/\eta)^{\beta}] \quad (5)$$

Failure density function is:

$$f(t) = (\beta/\eta)(t/\eta)^{\beta-1}\exp[-(t/\eta)^{\beta}] \quad (6)$$

Reliability function is:

$$R(t) = 1 - F(t) = \exp[-(t/\eta)^{\beta}] \quad (7)$$

In these functions, t represents the life of component; β represents the shape parameter; η represents the scale parameter.

2) The parameter estimation of Weibull distribution

Combined with general international Weibull parameters of the mechanical equipment, the paper gives out the Weibull parameters of every mechanical and electrical part that involved in the bottom events of oil transfer pump system in Table 4.

Table 4 The parameters of Weibull distribution of oil transfer pump system components

Item		Value of β			Value of η		
		The Weibull shape factor			The Weibull characteristic life/h		
		Low	Typical	High	Low	Typical	High
Pump body	Mechanical seal device	0.8	1.4	4	3 000	25 000	50 000
	Impeller	0.5	2.5	6	125 000	150 000	1 400 000
	Pump case	0.5	1.8	3	20 000	50 000	300 000
	Collar of pump body	0.5	1.1	4	10 000	50 000	90 000
Shaft system	Shaft of pump	0.8	1.2	3	50 000	50 000	300 000
	Coupling	0.8	2	6	25 000	75 000	333 000
	Bearing	0.7	1	3	10 000	50 000	143 000
Electric motors	DC motor	0.5	1.2	3	100	50 000	100 000
Valve	Actuated valve	0.5	1	2	14 000	100 000	333 000

The distribution of the commonly used parameters of double parameters Weibull distribution in Table 4 is a range. Aimed at the operating condition and the service life of equipment of the oil transfer pump system in CNPC work zone, this article selects typical values of the parameters as the parameter estimates of the various components.

According to Table 4, two parameters of the mechanical seal can be confirmed, then the reliability distribution model of mechanical seal is obtained as follows.

$$F(t) = 1 - \exp[-(t/25\ 000)^{1.4}] \quad (8)$$

The reliability function

$$R(t) = \exp[-(t/25\ 000)^{1.4}] \quad (9)$$

According to the model above, the failure probability of mechanical seal system in CNPC oil station can be obtained when the oil transfer pump runs 2 000 hours.

$$q_{E_5}(2\ 000) = 1 - \exp[-(2\ 000/25\ 000)^{1.4}] = 0.028\ 7$$

In the same way, we can calculate the failure rate of other key components that run 2000 hours by using the data in Table 4.

$$q_{E_6}(2\ 000) = 0.000\ 02$$

$$q_{E_{29}}(2\ 000) = 0.000\ 71$$

$$q_{E_7}(2\ 000) = 0.003\ 04$$

$$q_{E_{30}}(2\ 000) = 0.039\ 21$$

$$q_{E_8}(2\ 000) = 0.028\ 57$$

$$q_{E_3}(2\ 000) = 0.020\ 79$$

$$q_{E_{28}}(2\ 000) = 0.020\ 79$$

$$q_{E_4}(2\ 000) = 0.019\ 80$$

4.3.2 The calculation of probability of top event

For a given fault tree, if its structural function and the probability of bottom events are known, then the probability of the top event of the fault tree can be calculated.

According to the structural function of oil transfer pump system, the probability of summation and product of the event are as follows.

The probability of summation is

$$q\left|\sum_{i=1}^{n} X_i\right| = 1 - \prod_{i=1}^{n}(1 - q_i) \quad (10)$$

The probability of product

$$q\left|\sum_{i=1}^{n} X_i\right| = \prod_{i=1}^{n} q_i \quad (11)$$

According to the Formula (10) and Formula (11), the failure probability of the fault tree can be obtained when it runs 2 000 hours.

$$g = 1 - [(1 - q_{E_3})(1 - q_{E_4})(1 - q_{E_5})(1 - q_{E_6})(1 - q_{E_7})(1 - q_{E_8})(1 - q_{E_{28}})(1 - q_{E_{29}})(1 - q_{E_{30}})] = 0.151\ 17$$

In the same way, the reliability function of the top event of the fault tree of oil transfer pump system can be obtained.

$$R(t) = 1 - F(t) = 1 - g \quad (12)$$

4.3.3 The importance analysis of the fault tree of oil transfer pump system

1) Probability importance

Probability importance refers to the change degree of the system´s unreliability that caused by the change of component i, its computational formula is shown in (13).

$$I_g(i) = \frac{\partial g(q)}{\partial(q_i)} \quad (13)$$

According to the Formula (13), all the formula of probability importance of bottom events of the simplified fault tree in Figure 11 can be obtained.

$$I_g(E_3) = (1-q_{E_4})\cdot(1-q_{E_5})\cdot(1-q_{E_6})\cdot(1-q_{E_7})\cdot(1-q_{E_8})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{29}})\cdot(1-q_{E_{30}})$$
$$I_g(E_4) = (1-q_{E_3})\cdot(1-q_{E_5})\cdot(1-q_{E_6})\cdot(1-q_{E_7})\cdot(1-q_{E_8})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{29}})\cdot(1-q_{E_{30}})$$
$$I_g(E_5) = (1-q_{E_3})\cdot(1-q_{E_4})\cdot(1-q_{E_6})\cdot(1-q_{E_7})\cdot(1-q_{E_8})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{29}})\cdot(1-q_{E_{30}})$$
$$I_g(E_6) = (1-q_{E_3})\cdot(1-q_{E_4})\cdot(1-q_{E_5})\cdot(1-q_{E_7})\cdot(1-q_{E_8})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{29}})\cdot(1-q_{E_{30}})$$
$$I_g(E_7) = (1-q_{E_3})\cdot(1-q_{E_4})\cdot(1-q_{E_5})\cdot(1-q_{E_6})\cdot(1-q_{E_8})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{29}})\cdot(1-q_{E_{30}})$$
$$I_g(E_8) = (1-q_{E_3})\cdot(1-q_{E_4})\cdot(1-q_{E_5})\cdot(1-q_{E_6})\cdot(1-q_{E_7})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{29}})\cdot(1-q_{E_{30}})$$
$$I_g(E_{28}) = (1-q_{E_3})\cdot(1-q_{E_4})\cdot(1-q_{E_5})\cdot(1-q_{E_6})\cdot(1-q_{E_7})\cdot(1-q_{E_8})\cdot(1-q_{E_{29}})\cdot(1-q_{E_{30}})$$
$$I_g(E_{29}) = (1-q_{E_3})\cdot(1-q_{E_4})\cdot(1-q_{E_5})\cdot(1-q_{E_6})\cdot(1-q_{E_7})\cdot(1-q_{E_8})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{30}})$$
$$I_g(E_{30}) = (1-q_{E_3})\cdot(1-q_{E_4})\cdot(1-q_{E_5})\cdot(1-q_{E_6})\cdot(1-q_{E_7})\cdot(1-q_{E_8})\cdot(1-q_{E_{28}})\cdot(1-q_{E_{29}})$$

The probability importance of every bottom event of the fault tree of oil transfer pump system at $t = 2\ 000$ h are as follows.

$$I_g(E_3) = 0.866\ 85,\quad I_g(E_4) = 0.865\ 98$$
$$I_g(E_5) = 0.873\ 91,\quad I_g(E_6) = 0.848\ 86$$
$$I_g(E_7) = 0.851\ 42,\quad I_g(E_8) = 0.873\ 79$$
$$I_g(E_{28}) = 0.866\ 85,\quad I_g(E_{29}) = 0.849\ 43$$
$$I_g(E_{30}) = 0.883\ 47$$

2) Key importance

Key importance refers to the change rate of the system's fault probability that caused by the change of failure rate of component i, its computational formula is shown in (14).

$$I_c(i) = \frac{\partial \ln g(q)}{\partial \ln(q_i)} = \frac{\partial g}{g} / \frac{\partial q_i}{q_i} = \frac{q_i}{g} I_g(i) \quad (14)$$

Using the formula (14), the formula of key importance of bottom events can be obtained as follows.

$$I_c(E_3) = \frac{q_{E_3}}{g} I_g(E_3),\ I_c(E_4) = \frac{q_{E_4}}{g} I_g(E_4)$$
$$I_c(E_5) = \frac{q_{E_5}}{g} I_g(E_5),\ I_c(E_6) = \frac{q_{E_6}}{g} I_g(E_6)$$
$$I_c(E_7) = \frac{q_{E_7}}{g} I_g(E_7),\ I_c(E_8) = \frac{q_{E_8}}{g} I_g(E_8)$$
$$I_c(E_{28}) = \frac{q_{E_{28}}}{g} I_g(E_{28}),\ I_c(E_{29}) = \frac{q_{E_{29}}}{g} I_g(E_{29})$$
$$I_c(E_{30}) = \frac{q_{E_{30}}}{g} I_g(E_{30})$$

The key importance of every bottom event of the fault tree of oil transfer pump system at $t = 2\ 000$ hours are as follows:

$$I_c(E_3) = 0.119\ 22,\quad I_c(E_4) = 0.113\ 42$$
$$I_c(E_5) = 0.165\ 91,\quad I_c(E_6) = 0.000\ 11$$
$$I_c(E_7) = 0.017\ 12,\quad I_c(E_8) = 0.165\ 14$$
$$I_g(E_{28}) = 0.119\ 22,\quad I_c(E_{29}) = 0.003\ 99$$
$$I_c(E_{30}) = 0.229\ 15$$

5 Conclusion

1) The fault tree of oil transfer pump system can help the workers in the working zone be more clear about the logical relationship between the faults, then they could find out the reason quicker when failure occurred.

2) When the working zone is maintaining equipment, workers should increase the maintenance frequency of key components, in order to prevent the failure of oil transfer pump system caused by components' failure.

3) According to the results of quantitative analysis of the fault tree, calculate the availability of system further, then make relevant preventive maintenance

decisions on the basis of system target. For example, it can be made maintenance strategy with the goal of maximizing the system availability, introduced the variable of maintenance cost and made maintenance strategy with the goal of minimizing the summation of using cost and maintenance cost.

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