Risk Analysis of Oil/Gas Leakage of Subsea Production System Based on Fuzzy Fault Tree

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***Abstract*-Subsea production system, being of high value to deep water oil and gas production, has become more and more important recently. Simultaneously, issues related to its safety and reliability are hotly disputed by engineers and scholars. Based on fuzzy fault tree, risk analysis of oil and gas leakage is successfully completed. Through the construction of fault tree, qualitative analysis is conducted, obtaining minimum cut sets and cut-sets importance. Moreover, quantitative analysis, based on theory of fuzzy sets, is employed, through which failure probability, probabilistic importance and critical importance have been figured out. The above-mentioned results serve as a good reference to avoid oil and gas leakage in subsea production system.**

Keywords- Subsea Production System; Oil/Gas Leakage; Risk Analysis; Fuzzy Fault Tree Analysis; Fuzzy Set Theory

I. INTRODUCTION

Subsea system is a vital way of oil and gas production in offshore engineering, ranging from 20m to 3,000m. Some consist of a single satellite well and flowline, while others are more complex in structure, including several wells, templates, manifolds, X-Trees, pipelines, risers, PLETs, PLEMs and processing/commingling facilities etc. Subsea system, shown in Fig.1, is a mixture of a great many facilities. In the beginning, crude oil or gas is explored from wells, explicitly denoted in Fig. 2. Furthermore, it flows through X-Tree, Jumper, Manifold, PLET and PLEM etc. Finally, it is transferred to a fixed of floating facility, or directly to an onshore installation.

The environment of subsea production system is always very harsh: low temperature, high pressure, difficulties of maintenance and repair, large spreading ranges of subsea layout. Therefore, risks in subsea production system extensively exist because of complex subsea environment, third-party damage, malfunction of facilities etc. As we all know, leakage of oil and gas ranks high in the hazards of subsea production system, which will lead to an obvious production loss, bad influence to sea creatures or even some deadly disasters to humans.

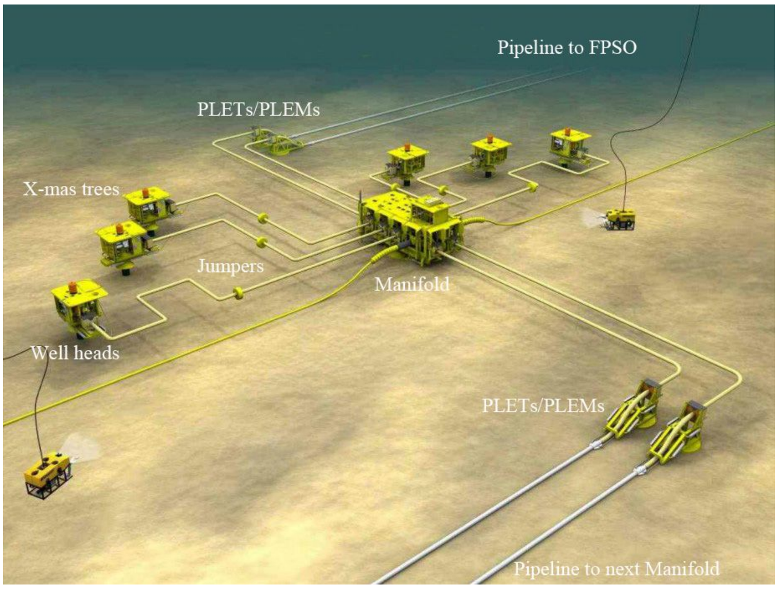

Fig. 1 Subsea production system

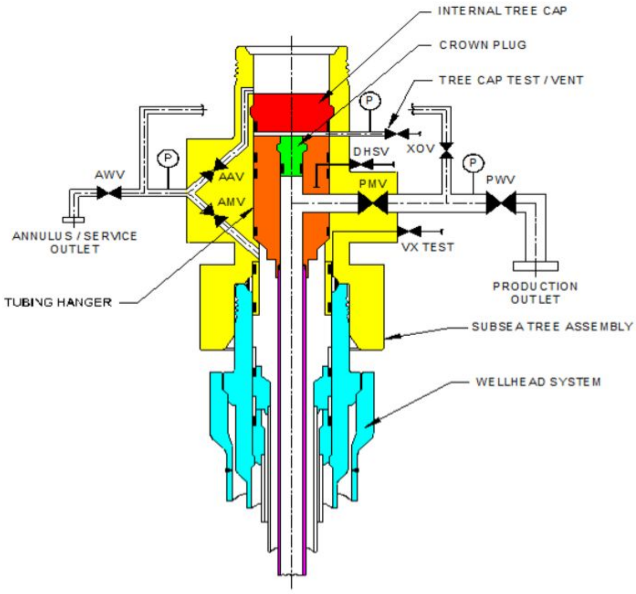

Fig. 2 Wellhead and X-Tree

However, researches related to this subject are rare. In International Student Offshore Design Competition (2005), students from Federal University of Rio de Janeiro have talked about subsea production system for gas field offshore Brazil without analyzing leakage [1], though J.P. Dejean, D. Averbuch integrated flow assurance into risk management of deep offshore field development, realizing the quantification of major risks in terms of economic consequences and optimizing a maintenance policy. But they have not provided quantitative analysis of oil and gas leakage [2]. Accordingly, it is of high value and necessity to conduct risk analysis of oil and gas leakage of subsea production system. The flow chart of this paper is shown in Fig.3.

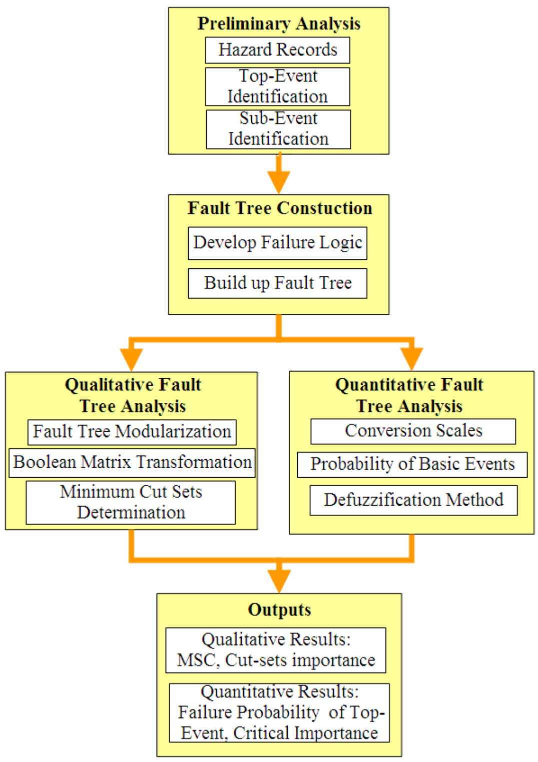

Fig. 3 Flow chart of risk analysis

II. FAULT TREE ANALYSIS OF OIL AND GAS LEAKAGE

Fault tree analysis (FTA) is a deductive method to identify the causal relationships leading to a specific system failure mode, which can be expressed in terms of combinations of component failure modes and operator actions. So, how to conduct fault tree analysis? Firstly, the top undesired event, namely top event, is identified [3, 4]. Additionally, direct causes of top event, namely middle event, are identified. And through a certain steps of deductions, the initial causes, namely basic events, are identified. Finally, fault tree is completed by a combination of events and logic gates.

A. Fault Tree Construction

In order to analyze the leakage of oil and gas in subsea production system, we choose oil and gas leakage as the top event. Its causes vary in different parts of subsea production system, including wells, X-Trees, connectors, pipelines, flowlines, jumpers, risers, manifolds, PLETs and PLEMs, etc. [5] Fault tree of leakage of subsea production system is built up through deduction, shown in Fig. 4. In addition, events, including top event, middle events and basic events, are listed in Table 1.

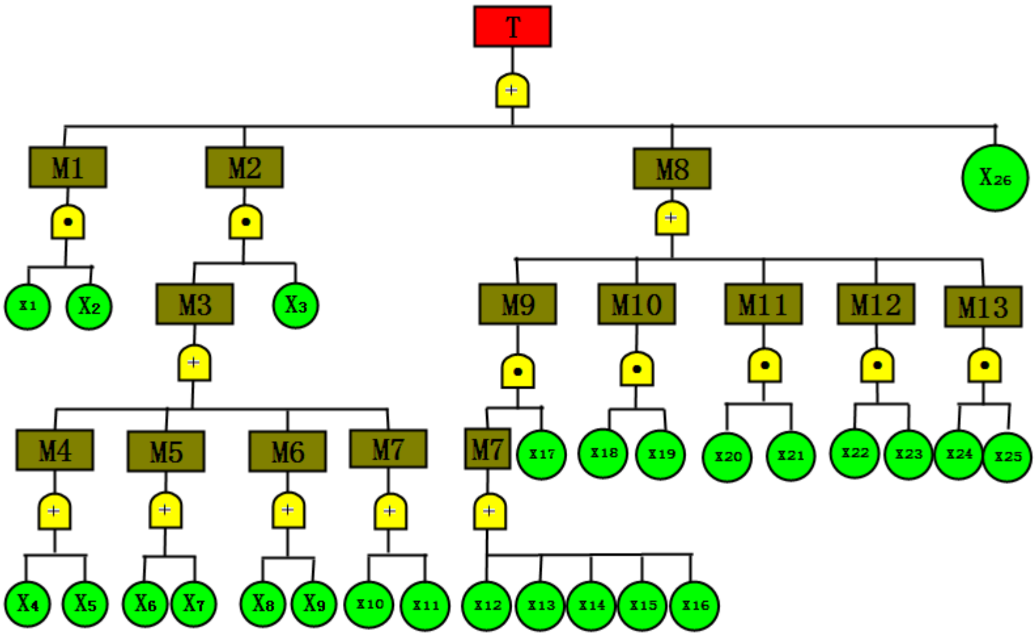

Fig. 4 Fault tree of leakage of subsea production system

TABLE 1 EVENTS LIST OF FAULT TREE

No.	Event Name	No.	Event Name
T	Leakage in subsea production system	M1	Leakage in oil/gas well
M2	leakage in pipe	M3	Defect in pipe
M4	Defect in jumper	M5	Defect in flowline
M6	Defect in pipeline	M7	Defect in riser
M8	Leakage in key facilities	M9	Leakage in connector
M10	Defect in connector	M11	Leakage in X-Tree
M12	Leakage in manifold	M13	Leakage in PLET/PLEM
X1	Over pressure in oil/gas well	X2	Failure of control of oil/gas well
X3	Puncture in jumper	X4	Rupture in jumper
X5	Puncture in flowline	X6	Rupture in flowline
X7	Puncture in pipeline	X8	Rupture in pipeline
X9	Puncture in riser	X10	Rupture in riser
X11	Failure of leakage control of pipe	X12	Defect in X-tree-wellhead connectors
X13	Defect in pipe connectors	X14	Defect in pipe-manifold connectors
X15	Defect in pipe-PLET connectors	X16	Defect in pipe- PLEM connectors
X17	Failure of leakage control of connectors	X18	Defect in X-Tree
X19	Failure of leakage control of X-Tree	X20	Defect in manifold
X21	Failure of leakage control of manifold	X22	Defect in PLET
X23	Failure of leakage control of PLET	X24	Defect in PLEM
X25	Failure of leakage control of PLEM	X26	Third-party damage

B. Qualitative Fault Tree Analysis

The purpose of qualitative fault tree analysis is to work out MCSs, which is the key step to identify the accident models, reasons and effects. Besides, cut-sets importance of each basic event can be worked out simultaneously, being of great value to help us get an overall view of leakage of subsea production system.

1) Minimum Cut Sets

By Boolean algebraic operation [6], top event can be abbreviated into standard expression shown in Eq.1.

$$\begin{aligned} T = {} & X26 + X1X2 + X3X11 + X12X17 + X18X19 + X20X21 + X22X23 \\ & X10X11 + X16X17 + X13X17 + X14X17 + X15X17 + X4X11 \\ & X24X25 + X5X11 + X7X11 + X9X11 + X6X11 + X8X11 \end{aligned} \quad \text{(Eq.1)}$$

Then, MCSs of above mentioned leakage fault tree can be easily obtained from Eq.1. The first-order MCSs include: {X26}; the second-order MCSs include:

{X1,X2},{X3,X11},{X12,X17},{X18,X19},{X6,X11},{X15,X17},{X5,X11},{X16,X17},{X22,X23},

{X24,X25},{X7,X11},{X9,X11}{X13,X17},{X10,X11},{X4,X11},{X8,X11},{X14,X17}, {X20,X21}.

As we all know, the less order of MCS is, the higher of its occurrence frequency will be. Accordingly, the first order MCS, namely third-party damage, would be considered in advance in the aspect of qualitative fault tree analysis.

2) Cut-sets Importance

Based on MSCs, cut-sets importance of every basic event can be figured out through Eq.2. Besides, they are ranked in Eq.3. Consequently, basic events with a higher cut-sets importance, for example failure of leakage control of pipe, are advised to be emphasized.

$$I_k(i) = \frac{1}{k}\sum_{r=1}^{k}\frac{1}{m_r(X_i \in E_r)}, \qquad (i = 1, 2, \cdots, n) \quad \text{(Eq.2)}$$

$$\begin{aligned} & I_K(11) > I_K(17) > I_K(26) > I_K(1) = I_K(2) = I_K(3) = I_K(4) = I_K(5) \\ & = I_K(6) = I_K(7) = I_K(8) = I_K(9) = I_K(10) = I_K(12) = I_K(13) \\ & = I_K(14) = I_K(15) = I_K(16) = I_K(18) = I_K(19) = I_K(20) \\ & = I_K(21) = I_K(22) = I_K(23) = I_K(24) = I_K(25) \end{aligned} \quad \text{(Eq.3)}$$

Where k is the number of cut sets, m_x is the number of basic events which belong to MSC Ex, n is the number of basic events, $I_k(i)$ is cut-set importance of basic event X_i.

III. QUANTITATIVE FAULT TREE ANALYSIS BASED ON FUZZY SET THEORY

The main jobs of quantitative fault tree analysis are to get the failure probability of top event and sensitivity of the basic events. Based on minimum cut sets, the failure probability of top event can be worked out through Eq.4.

In order to get the sensitivity analysis of basic events and failure probability of top event, failure probability of every basic event is needed to be worked out. Considering the lack of enough data and material for the leakage of subsea production system, fuzzy fault tree analysis [7] is employed to achieve our goal, which combines expert elicitation with fuzzy set theories.

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

$$P(X_j) = \prod_{i \in K_j} q_i \quad \text{(Eq.4)}$$

A. Failure Probability of Basic and Top Events

Expert elicitation or expert judgment, providing useful information for risk assessment and decision making, is employed to evaluate probability of basic event. Generally speaking, there are three steps [8, 9] to obtain failure probability of basic events.

Step1 Select experts

Experts selected must have at least 5 years of research experience in subsea production system. They had better work on different parts of subsea production system, such as design, installation, maintenance etc. Since these experts are different in backgrounds, so are the qualities of their assessments. Accordingly, weighting scores, considering title, experience, educational level, are introduced to represent qualities of experts. Experts' weighting scores are shown in Table 2. And weighting factors of 20 experts are listed in Table 3.

Step2 Convert linguistic terms into fuzzy numbers

Experts describe the probability of basic events with seven levels, namely 'very low', 'low', 'fairly low', 'medium', 'fairly high', 'high', 'very high'. According to offshore engineering [10, 11], a numerical approximation system is proposed to convert levels into fuzzy numbers. The conversion scales are shown in Fig. 5 and its corresponding membership functions are also given.

TABLE 2 WEIGHTING SCORES

Aspect	Classification	Score
Title	Pro., Manager	8
	Asst. Prof./manager	6
	Instructor, Supervisor	4
	Worker	1
Experience (years)	>20	9
	15~20	7
	10~15	5
	5~10	3
Educational level	Doctor	8
	Master	5
	Bachelor	3
	Junior college	2

TABLE 3 WEIGHTING FACTORS

No.	Title	Educational level	Experience	Weighting score	Weighting factor
1	Manager	Doctor	>20	25	0.0814332
2	Manager	Doctor	>20	25	0.0814332
3	Manager	Master	15~20	20	0.0651466
4	Pro.	Doctor	15~20	23	0.0749186
5	Pro.	Doctor	10~15	21	0.0684039
6	Pro.	Doctor	5~10	19	0.0618893
7	Asst. Pro.	Doctor	10~15	19	0.0618893
8	Asst. Pro.	Doctor	10~15	19	0.0618893
9	Asst. Pro.	Doctor	5~10	17	0.0553746
10	Asst. manager	Master	10~15	16	0.0521173
11	Asst. manager	Master	5~10	14	0.0456026
12	Asst. manager	Bachelor	5~10	12	0.0390879
13	Instructor	Master	10~15	14	0.0456026
14	Instructor	Bachelor	10~15	12	0.0390879
15	Supervisor	Bachelor	10~15	12	0.0390879
16	Supervisor	College	5~10	9	0.029316
17	Worker	Master	5~10	9	0.029316
18	Worker	Bachelor	5~10	7	0.0228013
19	Worker	College	10~15	8	0.0260586
20	Worker	College	5~10	6	0.019544

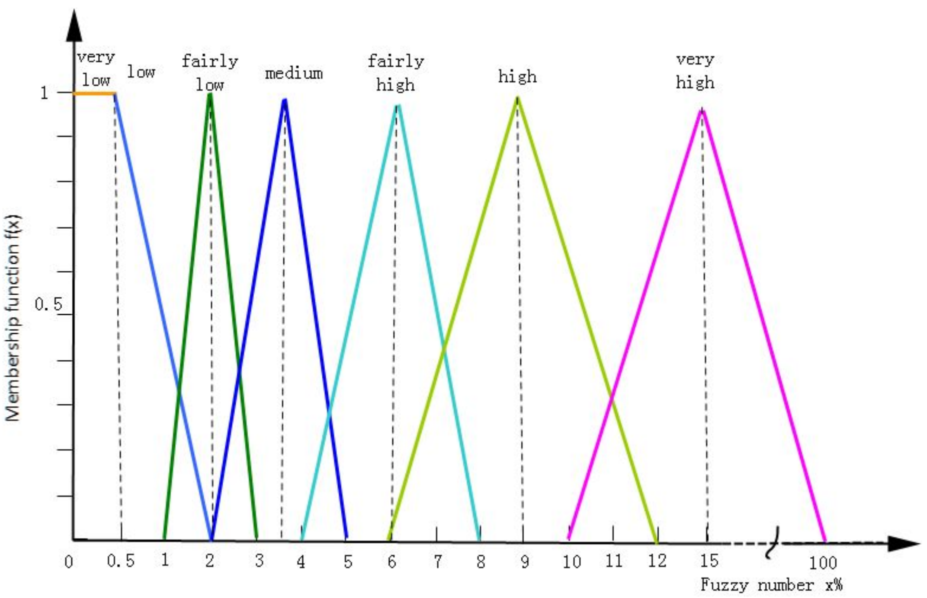

Fig. 5 Fuzzy sets representing linguistic values

Corresponding membership functions are as follows:

$$f_{VL}(x)=\begin{cases}1 & 0<x<0.005\\ 0 & otherwise\end{cases} \tag{Eq.5a}$$

$$f_{L}(x)=\begin{cases}\dfrac{0.02-x}{0.015} & 0.005<x<0.02\\ 0 & otherwise\end{cases} \tag{Eq.5b}$$

$$f_{FL}(x)=\begin{cases}\dfrac{x-0.01}{0.01} & 0.01<x\le 0.02\\ \dfrac{0.03-x}{0.01} & 0.02<x<0.03\\ 0 & otherwise\end{cases} \tag{Eq.5c}$$

$$f_{M}(x)=\begin{cases}\dfrac{x-0.02}{0.015} & 0.02<x\le 0.035\\ \dfrac{0.05-x}{0.015} & 0.035<x<0.05\\ 0 & otherwise\end{cases} \tag{Eq.5d}$$

$$f_{FH}(x)=\begin{cases}\dfrac{x-0.04}{0.02} & 0.04<x\le 0.06\\ \dfrac{0.08-x}{0.02} & 0.06<x<0.08\\ 0 & otherwise\end{cases} \tag{Eq.5f}$$

$$f_{VH}(x)=\begin{cases}0 & x<0.1\\ \dfrac{x-0.1}{0.05} & 0.1\le x\le 0.15\\ \dfrac{1-x}{0.85} & 0.15<x<1\end{cases} \tag{Eq.5g}$$

Using α-cut of corresponding membership functions, fuzzy sets of numbers could be obtained. If α-cut we got is set, medium number is chosen as the membership grade. If α-cut we got is number, its value is chosen as the membership grade. Then, fuzzy set of linguistic terms is worked out, shown in Eq.6. Here, α-cut equals to 1.

$$\tilde{A}=\frac{0.0025}{VL}+\frac{0.005}{L}+\frac{0.02}{FL}+\frac{0.035}{M}+\frac{0.06}{FH}+\frac{0.09}{H}+\frac{0.15}{VH} \tag{Eq.6}$$

Step3 Aggregate fuzzy numbers

In terms of a certain basic event, X_i, its linguistic remarks from 20 experts can be converted to fuzzy numbers through Eq.7. Taking experts' weighting factors into consideration, fuzzy numbers can be aggregated by linear opinion pool [12].

$$M_i=\sum_{j=1}^{20} w_j A_{ij}, \quad j=1,2,\cdots,n \tag{Eq.7}$$

Where, w_j is weighting factor of a certain expert j. A_{ij} is fuzzy number converted from linguistic expression given by expert j. M_i is a combination of fuzzy numbers of basic event X_i, which represents its failure probability. Therefore, failure probability of every basic event can be evaluated, listed in Table 4. Finally, the failure probability of top event would be figured out by Eq.3 and the result is 0.0177.

TABLE 4 FAILURE PROBABILITY OF BASIC EVENTS

No.	Failure Probability	No.	Failure Probability	No.	Failure Probability
X1	0.043013029	X2	0.033192182	X3	0.009511401
X4	0.009364821	X5	0.007003257	X6	0.009495114
X7	0.007760586	X8	0.010325733	X9	0.023037459
X10	0.028819218	X11	0.053762215	X12	0.019543974
X13	0.020480456	X14	0.019340391	X15	0.01745114
X16	0.018298046	X17	0.045228013	X18	0.019942997
X19	0.032043974	X20	0.020382736	X21	0.022296417
X22	0.018868078	X23	0.021359935	X24	0.018868078
X25	0.021359935	X26	0.004495114	——	——

B. Sensitivity Analysis

Probabilistic importance and critical importance can be calculated separately by Eq.8 and Eq.9 [13].

$$I_g(i) = \frac{\partial P(T)}{\partial q_i}, (i = 1, 2, \cdots, n) \quad \text{(Eq.8)}$$

$$I_g^c(i) = \frac{q_i}{P(T)} \bullet I_g(i), (i = 1, 2, \cdots, n) \quad \text{(Eq.9)}$$

Where, $P(T)$ is probability of top event, q_i is probability of basic event X_i, $I_g(i)$ is probabilistic importance of basic event X_i, $I_g^c(i)$ is critical importance of basic event X_i.

Considering the data obtained from above calculation, a comprehensive figure has been accordingly depicted (Fig. 6). Four curves are involved: Curve 1-failure probability of basic events; Curve 2-cut sets importance of basic events; Curve 3-probabilistic importance of basic events; Curve 4-critical importance of basic events.

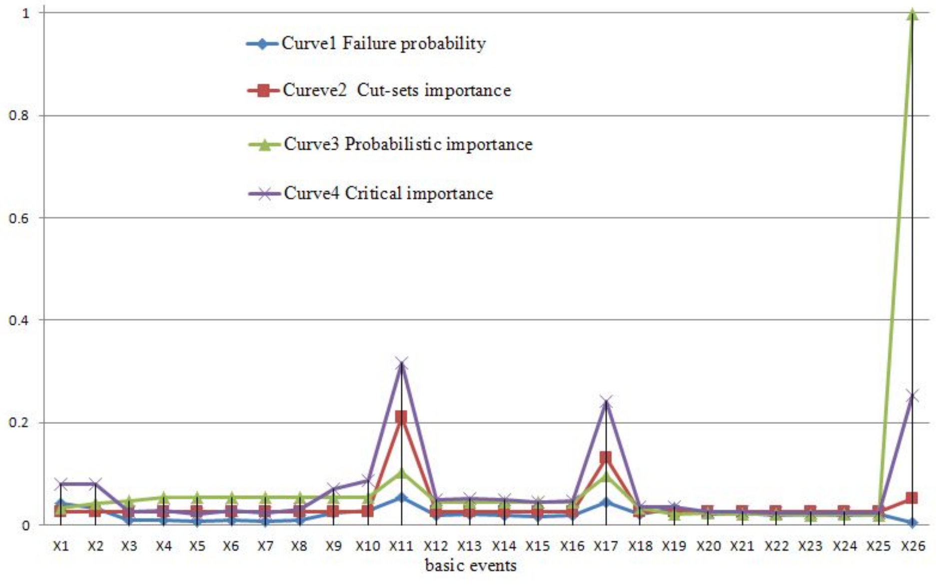

Fig. 6 Sensitivity analysis of subsea system

Accordingly, four conclusions have been drawn based on sensitivity analysis.

1) X11, X17 and X1 possess relatively high failure probabilities in subsea production system.

2) In terms of cut-sets importance curve, X11 has the highest cut-sets importance, suggesting that failure of pipe-leakage-control has the biggest influence on the leakage of subsea system in the aspect of tree structure. Moreover, cut-sets importance of X17 and X26 rank next to X11.

3) If probability of basic event, X26, has been reduced, the probability of top event will be correspondingly lessened in the highest degree according to probabilistic importance curve. Besides, the influence degree of X11 and X17 are just less than X26.

4) X11 has the highest critical importance not only because of its high sensitivity, but also biggest failure probability. Additionally, critical importance of X26 and X17 rank the second and third place.

IV. CONCLUSIONS

Risk analysis of subsea production system has been successfully completed based on fuzzy fault tree. Not only is qualitative analysis employed, but also quantitative analysis, obtaining MCSs, failure probabilities, cut-sets importance, probabilistic importance and critical importance etc. In sum, fault tree of leakage in subsea production system has been built up, and minimum cut sets are worked out through qualitative analysis, including 1 first order and 18 second order MCSs. Conclusions in this paper could be generalized as follows:

1) Considering the engineering reality of subsea production system, a numerical approximation mode has been proposed. Moreover, failure probabilities of basic events are correspondingly worded out.

2) Leakage probability of subsea production system, obtained from fuzzy fault tree analysis, is 0.0177, which is acceptable in offshore engineering.

3) Based on sensitivity analysis, relatively risky events include failure of leakage control of pipe and connectors, and third-party damage. Especially, failure of leakage control of pipe possesses the highest critical importance. As a result of this, some practicable measures are highly needed to ensure a reliable leakage control of pipe.

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