CHAPTER 4

FUZZY FAULT TREE ANALYSIS FOR DIAGNOSIS OF CANNULA FAULT IN POWER TRANSFORMER

4.1 INTRODUCTION

In the earlier two chapters of this thesis we worked on fuzzy schemes for fault detection and reliability evaluation of any system, in general. Present chapter extends our study for the development of a fuzzy scheme for fault tree analysis of any general system. The functioning of the developed fuzzy scheme is demonstrated for diagnosis of cannula fault in power transformers.

The involvement of a very large number of variables and their multiple interrelations make the design of a power transformer very complicated. This complicacy in design of a power system and variations in operating conditions cause uncertain and random occurrence of faults. Fault Tree Analysis (FTA) has been proved to be a very effective tool to predict probability of hazard, caused by a sequence and combinations of faults and failure events. A fault tree is a pictorial representation of various combinations of faults leading to hazard. In this analysis, first of all the hazard is explored and then the events causing this hazard are located. In conventional FTA the basic events are assigned a crisp number. However, there are various crucial and complex systems of great importance that impart vague characteristics. Due to the complexity of such systems and their vague nature, it is very difficult to obtain an adequate inference about the failure of these systems.
With the availability of the concept of fuzzy sets given by Zadeh [68] in 1965, Tanaka et al. [47] used fuzzy set theory to replace a crisp number by fuzzy number for better estimation of failure possibility of top event. Singer [23] presented fuzzy set theoretic approach to fault tree analysis. Chen [88] used arithmetic of fuzzy numbers to evaluate system reliability. Yang [106] constructed a fuzzy approach to fault diagnosis which is used in fuzzy fault tree analysis to represent knowledge of the causal relationships in the process operation and control system. This method was applied successfully to a nitric acid cooler process plant. Fuzzy set theoretic approach for estimating failure rate parameters was developed by Pandey and Tyagi [19] which provided comprehensive results in estimation of variety of parameter involving human judgment, vague operating conditions, etc. Pandey et al. [21] further developed a technique that proved successful in other area of knowledge, fuzzy reasoning and in the evaluation and assessment of equipment failure modes etc. Since a very limited statistics is normally available about the power transformer failure, thus it is unrealistic to obtain the probability of basic events up to a required accuracy by using probability distribution. Therefore, in this present chapter probabilistic considerations of basic events are replaced with possibilities.

The failure of power may interrupt various important operations and make a huge damage to the economy of any nation. Power transformer is one of the important electricity equipment used in power networks. Thus the fault diagnosis and its maintenance in power transformer is the utmost priority of power supply enterprises. Chen and Tiejun [9] investigated the fuzzy fault tree in the machinery equipment fault diagnosis. In his theory they used fuzzy mathematics to deal with the uncertainty incurred in the failure probability of basic events. Tong Wu et al [99] also introduced a method for fault diagnosis of power
transformer. In their work, they used the analysis method to process the probability of faults without statistical data and developed a method for different mode probability data conversing to triangular fuzzy numbers.

Accurate failure statistics is crucial requirement for reliability estimation in power transformer failure. In a situation where failure data may not be obtained accurately due to various reasons, it is more practical to employ linguistic terms to express data value for failure of a particular event. Since a power transformer may be installed under different operating conditions, it is impractical to assign a single fuzzy number to the failure possibility of the basic events in fault tree analysis. To overcome this problem, we have categorized the operating conditions of a power transformer as “Worst Case Condition”, “Conducive Environment” and “Highly Conducive Environment” for a power transformer to work. By “Worst Case Condition” we mean a situation that rarely occurs that is the state of emergency. “Conducive Environment” is a normal state where most of the transformers are installed. Highly Conducive environment is a very special and conducive environment created artificially to keep transformer cool and working for a very long time. Using the linguistic terminology given by different experts for the failure of power transformer working under different operating conditions, each basic event is assigned several fuzzy numbers. In our work in this chapter, we have also proposed a very precise and realistic approach based on PERT method to get a single fuzzy number for each basic event. Our approach uses fuzzy numbers and generalizes the PERT method to evaluate the failure possibility of each basic event to enable us to give more realistic estimates of failure possibility of basic events.
4.2 FAULT TREE ANALYSIS

Fault Tree Analysis (FTA) developed by U.S. Air force in 1962 is extensively used as a top to down approach of finding the causes of an undesired result (Hazard). The undesired result is repeatedly connected into subset of possible causes until no further division is possible or necessary. The resulting interconnections from the root causes to the final undesired event form a “fault tree”. A fault tree is a graphical model of pathways within a system that can lead to a foreseeable, undesirable loss event. The pathways interconnect contributory events and conditions using standard logic symbols. In Fig. 4.1 we see that it includes two types of event and two types of logical symbols (gates). The rectangle defines an intermediate or top event that is the output of a logic gate. The circle indicates a basic event that is a primary failure of a system element. The symbol “+” stands for an OR gate and the symbol “.” stands for an AND gate. The “OR” gate produces output if any input exists. And the “AND” gate produces output if all inputs coexist. The top event of the fault tree given in Fig. 4.1 can be expressed as:

\[ T = A_1 \cup A_2 = X_1 \cap X_2 \cup X_3 \cup X_4 \]

Fault tree analysis consists of two major parts, construction and evaluation. Here we are mainly concerned with the fuzzy evaluation of the failure possibility of the top events in a fault tree. Let \( p_{X_i} \) be the failure probability of event \( X_i \), then the failure probability of the top event \( T \) can be given as:

\[ p_T = 1 - \left( 1 - p_{X_1} \right) \left( 1 - p_{X_2} \right) \left( 1 - p_{X_3} \right) \left( 1 - p_{X_4} \right). \]
In conventional fault tree analysis, the inherent uncertainties in the probabilities of basic events are not accounted for, in the calculation of top event probability. Thus it is often very difficult to estimate precise failure rates of basic events. In such cases, it is therefore unrealistic to assume a crisp number for different basic events. Tanaka et al. [47] used fuzzy sets to replace crisp numbers by fuzzy numbers for better estimation of possibility of the hazard. So, if $\tilde{p}_{E_i}$ is the failure possibility of the basic event $E_i$, then the Boolean expression for fault tree shown in Fig. 4.1 may be given as

$$\tilde{p}_T = 1 - (1 - \tilde{p}_{E_1}\tilde{p}_{E_2})(1 - \tilde{p}_{E_3})(1 - \tilde{p}_{E_4})$$

4.3 TRIANGULAR FUZZY NUMBERS AND THEIR ARITHMETIC

(a) **Triangular Fuzzy Number:** A fuzzy number $\tilde{A}$ is termed as triangular fuzzy number if the membership function of fuzzy number $A$ is given as follows
In our study, we will use a triplet \((a_1, a_2, a_3)\) to denote a triangular fuzzy number.

(b) Operations on triangular fuzzy numbers: The addition of triangular fuzzy number

\[ A = (a_1, a_2, a_3) \text{ and } B = (b_1, b_2, b_3) \text{ is defined as:} \]

\[ A + B = a_1 + b_1, a_2 + b_2, a_3 + b_3 \]

Thus the addition of two triangular fuzzy numbers is again a triangular fuzzy number.

Similarly subtraction of two triangular fuzzy numbers is also a triangular fuzzy number and it can be given by the following expression:

\[ A - B = a_1 - b_1, a_2 - b_2, a_3 - b_3 \]

The multiplication of two fuzzy numbers \(A = (a_1, a_2, a_3)\) and \(B = (b_1, b_2, b_3)\) denoted as \(A \times B\) can be defined as:

\[
\mu_{A \times B}(x) = \begin{cases} 
\frac{x - a_1}{a_2 - a_1} & \text{if } a_1 \leq x \leq a_2 \\
\frac{a_3 - x}{a_3 - a_2} & \text{if } a_2 \leq x \leq a_3 \\
0 & \text{otherwise}
\end{cases}
\]

where \(T_1 = (a_2 - a_1)(b_2 - b_1)\), \(T_2 = a_3(a_2 - a_1) + b_2(b_2 - b_1)\), \(U_1 = (a_2 - a_1)(b_2 - b_1)\), \(U_2 = b_3(a_2 - a_1) + a_3(b_2 - b_1)\),

\[ D_1 = \frac{T_2}{2T_1}, \ D_2 = \frac{U_2}{2U_1}, \ P = a_1b_1, \ Q = a_2b_2, \ R = a_3b_3. \]

It is evident that the resulting fuzzy number \(A \times B\) is not a triangular fuzzy number. But in most of the cases, computation with resulting fuzzy numbers becomes very tedious. Thus it is necessary to avoid the second and higher degree terms to make them...
computationally convenient and therefore the product of two fuzzy numbers is reduced to a triangular fuzzy number \((P, Q, R)\) or \((a_1b_1, a_2b_2, a_3b_3)\).

4.4 POSSIBILITY THEORY

The possibility theory formulated by Zadeh [71] in term of fuzzy set, was an attempt to give a mathematical representation of linguistic uncertainty, that is the uncertainty associated with imprecise and vague information. In contrast to the objective character of the probability theory, the possibility theory provides tools for the modeling of ‘subjective probabilities’. It is based upon the concept of the possibility distribution. There is a direct connection between possibility and fuzzy sets.

Let \(X\) denote a variable, taking values from a universal set \(R\) and let us consider the expression \(X = x, \ x \in R\) which is used to describe the fact that the value of \(X\) is \(x\). Now consider a fuzzy set \(F\) on \(R\) that expresses an elastic constraint on values to be assigned to \(X\). Then for a particular value \(x \in R\), \(F(x)\) gives the degree of compatibility of \(x\) with the concept described by \(F\). Also for a given proposition ‘\(X\) is \(F\)’, based upon fuzzy set \(F\), it will be more realistic to interpret \(F(x)\) as the degree of possibility that \(X = x\). So for a given fuzzy set \(F\) on \(R\) and the proposition “\(X\) is \(F\)”, the possibility \(r_F(x)\) of \(X = x\) for each \(x \in R\) is numerically equal to the degree \(F(x)\) to which \(x\) belongs to \(F\), that is,

\[
r_F(x) = F(x) \text{ for all } x \in R
\]

The function \(r_F : X \to [0, 1]\) defined by the equation given above is clearly a possibility distribution function on \(R\). For a given \(r_F\), the associated possibility measure \((Pos F)\) is defined for all \(A \subseteq P(X)\) by the equation

\[
Pos_F(A) = \sup_{x \in A} r_F(x)
\]
4.5 FUZZY OPERATORS

Using algebraic operations on fuzzy numbers (triangular or trapezoidal), we can obtain fuzzy operators corresponding to Boolean operators “AND”, “OR” etc. Let \( \tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n \) are the possibility functions of the basic events \( i=1, 2 \ldots n \). Then fuzzy “AND” and “OR” operators denoted by ANF and ORF respectively, can be defined as:

\[
\tilde{p}_y = \text{ANF}(\tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n) = \prod_{i=1}^{n} \tilde{p}_i,
\]

where \( \prod \) denotes the fuzzy multiplication.

Further let \( \tilde{p}_i \)'s are represented by triangular fuzzy numbers, that is, \( \tilde{p}_i = (a_{i1}, a_{i2}, a_{i3}) \), where \( i=1, 2 \ldots n \). Then

\[
\tilde{p}_y = \text{ANF}(\tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n) = (\prod_{i=1}^{n} a_{i1}, \prod_{i=1}^{n} a_{i2}, \prod_{i=1}^{n} a_{i3}),
\]

\[= (a_{y1}, a_{y2}, a_{y3}), \text{ say}\]

\[
\tilde{p}_y = \text{ORF}(\tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n) = 1 - \prod_{i=1}^{n} 1 - \tilde{p}_i = 1 - \prod_{i=1}^{n} (1 - (a_{i1}, a_{i2}, a_{i3}))
\]

\[= (1 - \prod_{i=1}^{n} (1 - a_{i1}), 1 - \prod_{i=1}^{n} (1 - a_{i2}), 1 - \prod_{i=1}^{n} (1 - a_{i3})), = \tilde{p}_y
\]

\[= (a_{y1}, a_{y2}, a_{y3}), \text{ say}\]

4.6 PROPOSED ALGORITHM TO EVALUATE FAILURE POSSIBILITY OF BASIC EVENTS

In the proposed algorithm, fuzzy numbers are used instead of crisp numbers to represent failure probability of occurrence of each basic event in fault tree analysis. For the sake of simplicity, triangular fuzzy numbers are used to define the failure possibility of the
basic events. Since a triangular fuzzy number is capable to capture the impreciseness of experts’ assessments, the vagueness of unreliable data is easy to compute.

**Step 1:** First identify an undesirable top event (Hazard), intermediate events and the basic events leading to top event by exploring history concerned with the failure of that event. Further connect these events using logical gates “AND” and “OR” to get the pictorial representation of occurrence of top event.

**Step 2:** Since the basic events follow different statistical properties of sampled data collected for a particular event, so the data for the occurrence of the basic events must be collected by different experts, which in the present case is three, say A, B and C. Further the observations be taken under the prescribed category of operating conditions, classified as “Worst –Case Conditions”, “Conducive Environment and “Highly Conducive Environment” respectively.

**Step 3:** Using sampled data collected by the experts A, B and C the possibility of occurrence of basic events are assigned different fuzzy numbers.

**Step 4:** It is a well known fact that mostly a system is operated under “Conducive Environment”. So it is assumed that the data collected for the failure of a basic event follows a skewed beta distribution. Thus a PERT method based technique is used to find a single fuzzy number to the failure possibility of a basic event. If \( p_a(E_i), \hat{p}_c(E_i) \) and \( \hat{p}_h(E_i) \) are fuzzy numbers assigned to a basic event \( E_i \) by Expert A, B and C taking observations in “Worst Case Condition”, “Conducive Environment” and “Highly Conducive Environment” respectively, then the failure possibility of the basic event \( E_i \) may be given as

\[
\hat{p}(E_i) = \frac{\hat{p}_a(E_i) + 4\hat{p}_c(E_i) + \hat{p}_h(E_i)}{6}
\]

90
Step 5:- The fuzzy number thus obtained for different basic events are used to compute failure possibility of top event.

4.7 FUZZY IMPORTANCE INDEX (FII)

To improve reliability of a system, it is always better to improve the reliability of basic events, which have greater importance instead of the events with less importance. Therefore, in fault tree analysis, ranking of basic events as per their importance play a vital role. Let $p_{\text{r}}$ be the failure possibility of top event and $\tilde{p}_{\text{r}}$ denote the failure possibility of the occurrence of top event, if the basic event $E_i$ does not happen. In other words we can say $p_{\text{r}}$ be the failure possibility of top event, when failure possibility of basic event $E_i$ is a crisp number (0, 0, 0). The distance of $\tilde{p}_{\text{r}}$ from $p_{\text{r}}$ will determine the importance of a basic event $E_i$. A basic event $E_i$ will be of greater importance than the other basic event $E_j$, if the distance between $\tilde{p}_{\text{r}}$ and $p_{\text{r}}$ is greater than that of $\tilde{p}_{\text{r}}$ and $p_{\text{r}}$. The distance between two fuzzy numbers may be obtained by using Hamming or Euclidean distance. The fuzzy importance of each basic event may be quantified as Fuzzy Importance Index (FII).

$$\text{FII} (E_i) = \text{Distance of } \tilde{p}_{\text{r}} \text{ from } p_{\text{r}}$$

If the failure possibilities of the basic events are triangular fuzzy numbers, then the failure possibility of top event will also be a triangular fuzzy numbers. Here we denote $\tilde{p}_{\text{r}}$ and $p_{\text{r}}$ by the triplets $(l, m, u)$ and $(l', m', u')$ respectively. Thus the FII $(E_i)$ for a basic event $E_i$ may be defined as follows:

$$\text{FII} (E_i) = \text{ED}(\tilde{p}_{\text{r}}, p_{\text{r}}) = \sqrt{(l - l')^2 + (m - m')^2 + (u - u')^2}$$
Thus for basic events \( E_i \) and \( E_j \), if \( \text{FII}(E_i) > \text{FII}(E_j) \) then the precipitation of basic event \( E_i \) will be more sensitive than that of event \( E_j \) to improve system reliability. Using this method we can rank the basic events in accordance with their importance index and improve the reliability of the system by preventing the failure of a component of greater importance.

4.8 FAILURE POSSIBILITY OF CANNULA FAULT IN POWER TRANSFORMER

(a) Fault Tree Analysis of Cannula Fault:

The fault tree of Cannula Fault in power transformer is taken as an analytical example to explain the proposed algorithm of fault diagnosis process. The fault tree of Cannula fault in power transformer is shown in Fig. 4.2.

We use following codes’ for basic and intermediate events of power transformer.

**Top event** \( T \): Cannula Fault;

**Intermediate Events:**

\( M_1 \) : Cannula Overheating; \hspace{1cm} \( M_2 \) : Inside Discharging;

\( M_3 \) : Outer Insulated Flashover; \hspace{1cm} \( M_4 \) : Deterioration of Insulation;

\( M_5 \) : High Contact Resistance; \hspace{1cm} \( M_6 \) : Abnormal Overvoltage;
Fig. 4.2: Fault Tree of Cannula Fault

Basic Events:

$E_1$: Over loading; $E_2$: Natural Aging;

$E_3$: Insulated Damping; $E_4$: Connector Loosening;

$E_5$: Interface Oxygenating; $E_6$: Nicerless Encapsulation;

$E_7$: Outer Short Circuit; $E_8$: Copper Pole Contact Cable;
$E_9$ : Nicerless Dipping; $E_{10}$ : Unshielded & imperfect grounding;

$E_{11}$ : Structure unreasonable; $E_{12}$ : Lightning Conductor Failure;

$E_{13}$ : Near Lightning Spot; $E_{14}$ : High Energy Lightning;

$E_{15}$ : Annimal; $E_{16}$ : Dumping Flashover Murry;

$E_{17}$ : Overvoltage by Human Error; $E_{18}$ : Human Error Fault;

The Boolean expression corresponding to this fault tree can be given as below.

\[ T = M_1 \cup E_{18} \cup M_2 \cup M_3, \quad M_1 = E_1 \cup M_4 \cup E_6 \cup E_7 \cup M_5 \cup E_8 \]

\[ M_2 = E_9 \cup E_3 \cup E_{10} \cup E_8, \quad M_3 = E_{11} \cup M_6 \cup E_{16} \cup E_{11}, \]

\[ M_4 = E_9 \cup E_3, \quad M_5 = E_4 \cup E_5, \quad M_6 = E_{17} \cup M_{13} \cup E_{12} \cup E_{14} \]

According to the data from [99], the accurate probability value of basic events in fault tree with statistical data is fuzzified and listed in Table 4.1.

**Table 4.1: Fuzzy Numbers for Failure Possibility of Basic Events**

<table>
<thead>
<tr>
<th>Basic Event</th>
<th>Expert A (About .06)</th>
<th>Expert B (About .09)</th>
<th>Expert C (About .11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>0.035</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>E2</td>
<td>0.04</td>
<td>0.065</td>
<td>0.085</td>
</tr>
<tr>
<td>E3</td>
<td>0.06</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>E4</td>
<td>0.04</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>E5</td>
<td>0.04</td>
<td>0.064</td>
<td>0.09</td>
</tr>
<tr>
<td>E6</td>
<td>0.04</td>
<td>0.07</td>
<td>0.13</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>0.14</td>
<td>0.17</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>0.11</td>
<td>0.15</td>
<td>0.18</td>
<td>0.14</td>
</tr>
<tr>
<td>0.14</td>
<td>0.17</td>
<td>0.20</td>
<td>0.175</td>
</tr>
<tr>
<td>0.13</td>
<td>0.16</td>
<td>0.11</td>
<td>0.22</td>
</tr>
<tr>
<td>0.15</td>
<td>0.18</td>
<td>0.24</td>
<td>0.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.045</td>
<td>0.08</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>0.07</td>
<td>0.11</td>
<td>0.15</td>
<td>0.095</td>
</tr>
<tr>
<td>0.11</td>
<td>0.14</td>
<td>0.16</td>
<td>0.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.035</td>
<td>0.065</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>0.07</td>
<td>0.10</td>
<td>0.14</td>
<td>0.095</td>
</tr>
<tr>
<td>0.11</td>
<td>0.14</td>
<td>0.17</td>
<td>0.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.035</td>
<td>0.06</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>0.09</td>
<td>0.10</td>
<td>0.14</td>
<td>0.075</td>
</tr>
<tr>
<td>0.11</td>
<td>0.14</td>
<td>0.17</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.135</td>
<td>0.16</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>0.20</td>
<td>0.20</td>
<td>0.24</td>
<td>0.195</td>
</tr>
<tr>
<td>0.23</td>
<td>0.23</td>
<td>0.265</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
<td>0.045</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>0.07</td>
<td>0.07</td>
<td>0.10</td>
<td>0.065</td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
<td>0.04</td>
<td>0.07</td>
<td>0.035</td>
</tr>
<tr>
<td>0.04</td>
<td>0.06</td>
<td>0.09</td>
<td>0.055</td>
</tr>
<tr>
<td>0.07</td>
<td>0.08</td>
<td>0.12</td>
<td>0.085</td>
</tr>
<tr>
<td>0.11</td>
<td>0.11</td>
<td>0.12</td>
<td>0.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic Event E14</th>
<th>Expert A (About .05)</th>
<th>Expert B (About .08)</th>
<th>Expert C (About .11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>0.05</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>0.08</td>
<td>0.08</td>
<td>0.12</td>
<td>0.075</td>
</tr>
<tr>
<td>0.11</td>
<td>0.11</td>
<td>0.14</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.040</td>
<td>0.065</td>
<td>0.085</td>
<td>0.07</td>
</tr>
<tr>
<td>0.07</td>
<td>0.10</td>
<td>0.14</td>
<td>0.095</td>
</tr>
<tr>
<td>0.10</td>
<td>0.14</td>
<td>0.17</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>0.175</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>0.20</td>
<td>0.20</td>
<td>0.235</td>
<td>0.20</td>
</tr>
<tr>
<td>0.24</td>
<td>0.24</td>
<td>0.28</td>
<td>0.24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.075</td>
<td>0.11</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>0.14</td>
<td>0.14</td>
<td>0.17</td>
<td>0.175</td>
</tr>
<tr>
<td>0.18</td>
<td>0.18</td>
<td>0.22</td>
<td>0.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.24</td>
<td>0.28</td>
<td>0.24</td>
</tr>
<tr>
<td>0.28</td>
<td>0.28</td>
<td>0.315</td>
<td>0.29</td>
</tr>
<tr>
<td>0.33</td>
<td>0.33</td>
<td>0.37</td>
<td>0.37</td>
</tr>
</tbody>
</table>
These events may be expressed with following membership functions:

\[ \mu_{E_1}(x) = \begin{cases} 
\frac{x-0.035}{0.025} & \text{if } 0.035 \leq x \leq 0.06 \\
\frac{0.08-x}{0.02} & \text{if } 0.06 \leq x \leq 0.08 \\
\frac{0.12-x}{0.03} & \text{if } 0.09 \leq x \leq 0.12 
\end{cases} \]

\[ \mu_{E_2}(x) = \begin{cases} 
\frac{x-0.075}{0.035} & \text{if } 0.075 \leq x \leq 0.11 \\
\frac{0.14-x}{0.03} & \text{if } 0.11 \leq x \leq 0.14 
\end{cases} \]

\[ \mu_{E_3}(x) = \begin{cases} 
\frac{x-0.04}{0.025} & \text{if } 0.04 \leq x \leq 0.065 \\
\frac{0.14-x}{0.02} & \text{if } 0.065 \leq x \leq 0.85 \\
\frac{0.12-x}{0.03} & \text{if } 0.09 \leq x \leq 0.12 \\
\frac{x-0.06}{0.04} & \text{if } 0.06 \leq x \leq 0.10 \\
\frac{0.13-x}{0.03} & \text{if } 0.10 \leq x \leq 0.13 
\end{cases} \]

Fig. 4.3: Failure possibility of event E_1
Fig. 4.4: Failure Possibility of Event $E_2$

\[
\mu_{E_2}(x) = \begin{cases} 
\frac{x-0.06}{0.02} & \text{if } 0.06 \leq x \leq 0.08 \\
0.11-x & \text{if } 0.08 \leq x \leq 0.11 \\
0.02 & \text{if } x > 0.11 
\end{cases}
\]

\[
\mu_{E_2}(x) = \begin{cases} 
\frac{x-0.09}{0.03} & \text{if } 0.09 \leq x \leq 0.12 \\
0.16-x & \text{if } 0.12 \leq x \leq 0.16 \\
0.02 & \text{if } x > 0.16 
\end{cases}
\]

Fig. 4.5: Failure possibility of event $E_3$

\[
\mu_{E_3}(x) = \begin{cases} 
\frac{x-0.04}{0.03} & \text{if } 0.04 \leq x \leq 0.07 \\
0.10-x & \text{if } 0.07 \leq x \leq 0.10 \\
0.02 & \text{if } x > 0.10 
\end{cases}
\]

\[
\mu_{E_3}(x) = \begin{cases} 
\frac{x-0.07}{0.03} & \text{if } 0.07 \leq x \leq 0.10 \\
0.14-x & \text{if } 0.10 \leq x \leq 0.14 \\
0.02 & \text{if } x > 0.14 
\end{cases}
\]
\[
\mu_e(x) = \begin{cases} 
  x - 0.085 & \text{if } 0.08 \leq x \leq 0.13 \\
  0.045 & \\
  0.16 - x & \text{if } 0.13 \leq x \leq 0.16 
\end{cases}
\]

Fig. 4.6: Failure Possibility of event \(E_4\)

\[
\mu_e(x) = \begin{cases} 
  x - 0.04 & \text{if } 0.04 \leq x \leq 0.064 \\
  0.024 & \\
  0.09 - x & \text{if } 0.064 \leq x \leq 0.09 \\
  0.026 & \\
  0.13 - x & \text{if } 0.94 \leq x \leq 0.13 \\
  0.036 & \\
\end{cases}, \quad \mu_e(x) = \begin{cases} 
  x - 0.07 & \text{if } 0.07 \leq x \leq 0.094 \\
  0.024 & \\
  0.13 - x & \text{if } 0.94 \leq x \leq 0.13 \\
  0.036 & \\
\end{cases}
\]

Fig. 4.7: Failure Possibility of event \(E_5\)

About .07
About .10
About .13

About .064
About .094
About .11
\[ \mu_{e_6}(x) = \begin{cases} \frac{x - 0.095}{0.035} & \text{if } 0.095 \leq x \leq 0.13 \\ \frac{0.16 - x}{0.03} & \text{if } 0.13 \leq x \leq 0.16 \end{cases}, \quad \mu_{e_6}(x) = \begin{cases} \frac{x - 0.11}{0.04} & \text{if } 0.11 \leq x \leq 0.15 \\ \frac{0.18 - x}{0.03} & \text{if } 0.15 \leq x \leq 0.18 \end{cases} \]

\[ \mu_{e_6}(x) = \begin{cases} \frac{x - 0.14}{0.03} & \text{if } 0.14 \leq x \leq 0.17 \\ \frac{0.20 - x}{0.03} & \text{if } 0.17 \leq x \leq 0.20 \end{cases} \]
Fig. 4.9: Failure Possibility of event $E_7$

\[
\mu_{E_7}(x) = \begin{cases} 
  x - 0.045 & \text{if } 0.045 \leq x \leq 0.08 \\
  0.035 & \text{if } 0.08 \leq x \leq 0.11 \\
  0.11 - x & \text{if } 0.11 \leq x \leq 0.15 
\end{cases} , \quad \mu_{E_8}(x) = \begin{cases} 
  x - 0.07 & \text{if } 0.07 \leq x \leq 0.11 \\
  0.04 & \text{if } 0.11 \leq x \leq 0.15 
\end{cases}
\]

Fig. 4.10: Failure Possibility of event $E_8$

\[
\mu_{E_8}(x) = \begin{cases} 
  x - 0.035 & \text{if } 0.035 \leq x \leq 0.065 \\
  0.03 & \text{if } 0.065 \leq x \leq 0.08 \\
  0.08 - x & \text{if } 0.08 \leq x \leq 0.10 \\
  0.015 & \text{if } 0.10 \leq x \leq 0.14 
\end{cases} , \quad \mu_{E_9}(x) = \begin{cases} 
  x - 0.07 & \text{if } 0.07 \leq x \leq 0.10 \\
  0.04 & \text{if } 0.10 \leq x \leq 0.14 
\end{cases}
\]
\[
\mu_\text{E}(x) = \begin{cases} 
  x - 0.095 & \text{if } 0.095 \leq x \leq 0.14 \\
  0.045 & \\
  0.17 - x & \text{if } 0.14 \leq x \leq 0.17 \\
  0.03 &
\end{cases}
\]

Fig. 4.11: Failure Possibility of event E_9

\[
\mu_\text{E}_9(x) = \begin{cases} 
  x - 0.035 & \text{if } 0.035 \leq x \leq 0.06 \\
  0.025 & \\
  0.08 - x & \text{if } 0.06 \leq x \leq 0.08 \\
  0.02 &
\end{cases}
\]

\[
\mu_\text{E}_{10}(x) = \begin{cases} 
  x - 0.075 & \text{if } 0.075 \leq x \leq 0.11 \\
  0.035 & \\
  0.14 - x & \text{if } 0.11 \leq x \leq 0.14 \\
  0.03 &
\end{cases}
\]

Fig. 4.12: Failure Possibility of event E_{10}
\[ \mu_{e_{11}}(x) = \begin{cases} 
\frac{x-0.135}{0.025} & \text{if } 0.135 \leq x \leq 0.16 \\
0.20-x & \text{if } 0.16 \leq x \leq 0.20 \\
\frac{x-0.195}{0.035} & \text{if } 0.195 \leq x \leq 0.23 \\
0.265-x & \text{if } 0.23 \leq x \leq 0.265 \\
\end{cases}, \quad \mu_{e_{12}}(x) = \begin{cases} 
\frac{x-0.16}{0.04} & \text{if } 0.16 \leq x \leq 0.20 \\
0.24-x & \text{if } 0.20 \leq x \leq 0.24 \\
\end{cases} \]

\[ \mu_{e_{21}}(x) = \begin{cases} 
\frac{x-0.015}{0.030} & \text{if } 0.015 \leq x \leq 0.045 \\
0.07-x & \text{if } 0.045 \leq x \leq 0.07 \\
\frac{x-0.065}{0.03} & \text{if } 0.065 \leq x \leq 0.095 \\
0.13-x & \text{if } 0.095 \leq x \leq 0.13 \\
\end{cases}, \quad \mu_{e_{22}}(x) = \begin{cases} 
\frac{x-0.04}{0.03} & \text{if } 0.04 \leq x \leq 0.07 \\
0.10-x & \text{if } 0.07 \leq x \leq 0.10 \\
\end{cases} \]

Fig. 4.13: Failure Possibility of event $E_{11}$
\[ \mu_{E_{12}}(x) = \begin{cases} \frac{x-0.015}{0.025} & \text{if } 0.015 \leq x \leq 0.04 \\ 0.07-x & \text{if } 0.04 \leq x \leq 0.07 \\ \frac{0.07-x}{0.03} & \text{if } 0.07 \leq x \leq 0.1 \end{cases} \]

\[ \mu_{E_{13}}(x) = \begin{cases} \frac{x-0.025}{0.025} & \text{if } 0.025 \leq x \leq 0.05 \\ 0.08-x & \text{if } 0.05 \leq x \leq 0.08 \\ \frac{0.08-x}{0.03} & \text{if } 0.08 \leq x \leq 0.1 \end{cases} \]

Fig. 4.14: Failure Possibility of event E_{12}

Fig. 4.15: Failure Possibility of event E_{13}
\[ \mu_{E_{14}}(x) = \begin{cases} 
\frac{x - 0.075}{0.035} & \text{if } 0.075 \leq x \leq 0.11 \\
\frac{0.14 - x}{0.03} & \text{if } 0.11 \leq x \leq 0.14 
\end{cases} \]

\[ \mu_{E_{15}}(x) = \begin{cases} 
\frac{x - 0.040}{0.025} & \text{if } 0.040 \leq x \leq 0.065 \\
\frac{0.085 - x}{0.02} & \text{if } 0.065 \leq x \leq 0.085 \\
\frac{x - 0.095}{0.045} & \text{if } 0.095 \leq x \leq 0.14 \\
\frac{0.17 - x}{0.03} & \text{if } 0.14 \leq x \leq 0.17 
\end{cases} \]

Fig. 4.16: Failure Possibility of event \( E_{14} \)

Fig. 4.17: Failure Possibility of event \( E_{15} \)
\[ \mu_{e_{16}}(x) = \begin{cases} x - 0.14 & \text{if } 0.14 \leq x \leq 0.175 \\ 0.035 & \end{cases}, \quad \mu_{e_{16}}(x) = \begin{cases} x - 0.17 & \text{if } 0.17 \leq x \leq 0.20 \\ 0.03 & \end{cases} \]

\[ \mu_{e_{17}}(x) = \begin{cases} x - 0.20 & \text{if } 0.20 \leq x \leq 0.24 \\ 0.04 & \end{cases}, \quad \mu_{e_{17}}(x) = \begin{cases} x - 0.235 & \text{if } 0.20 \leq x \leq 0.235 \\ 0.035 & \end{cases} \]

\[ \mu_{e_{18}}(x) = \begin{cases} x - 0.075 & \text{if } 0.075 \leq x \leq 0.11 \\ 0.035 & \end{cases}, \quad \mu_{e_{18}}(x) = \begin{cases} x - 0.10 & \text{if } 0.10 \leq x \leq 0.14 \\ 0.04 & \end{cases} \]

\[ \mu_{e_{18}}(x) = \begin{cases} x - 0.145 & \text{if } 0.145 \leq x \leq 0.18 \\ 0.035 & \end{cases}, \quad \mu_{e_{18}}(x) = \begin{cases} x - 0.17 & \text{if } 0.14 \leq x \leq 0.17 \\ 0.03 & \end{cases} \]

\[ \mu_{e_{18}}(x) = \begin{cases} x - 0.22 & \text{if } 0.18 \leq x \leq 0.22 \\ 0.04 & \end{cases} \]

Fig. 4.18: Failure Possibility of event $E_{16}$
On employing the propose technique to evaluate the best fuzzy number for failure possibility of each basic event assigned by all three experts to each basic event we obtain a unique fuzzy number for each basic event. Fuzzy numbers thus obtained for each basic event are listed in table 4.2.
Table 4.2: Fuzzy Numbers Approximated for Failure Possibility of Basic Events

<table>
<thead>
<tr>
<th>Basic Event E1</th>
<th>Basic Event E7</th>
<th>Basic Event E13</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.065</td>
<td>0.088</td>
<td>0.117</td>
</tr>
<tr>
<td>0.166</td>
<td>0.198</td>
<td>0.235</td>
</tr>
<tr>
<td>0.035</td>
<td>0.061</td>
<td>0.092</td>
</tr>
<tr>
<td>Basic Event E2</td>
<td>Basic Event E8</td>
<td>Basic Event E14</td>
</tr>
<tr>
<td>0.06</td>
<td>0.088</td>
<td>0.116</td>
</tr>
<tr>
<td>0.07</td>
<td>0.108</td>
<td>0.145</td>
</tr>
<tr>
<td>0.05</td>
<td>0.08</td>
<td>0.117</td>
</tr>
<tr>
<td>Basic Event E3</td>
<td>Basic Event E9</td>
<td>Basic Event E15</td>
</tr>
<tr>
<td>0.087</td>
<td>0.118</td>
<td>0.155</td>
</tr>
<tr>
<td>0.065</td>
<td>0.101</td>
<td>0.13</td>
</tr>
<tr>
<td>0.069</td>
<td>0.101</td>
<td>0.136</td>
</tr>
<tr>
<td>Basic Event E4</td>
<td>Basic Event E10</td>
<td>Basic Event E16</td>
</tr>
<tr>
<td>0.068</td>
<td>0.1</td>
<td>0.137</td>
</tr>
<tr>
<td>0.065</td>
<td>0.088</td>
<td>0.137</td>
</tr>
<tr>
<td>0.17</td>
<td>0.203</td>
<td>0.237</td>
</tr>
<tr>
<td>Basic Event E5</td>
<td>Basic Event E11</td>
<td>Basic Event E17</td>
</tr>
<tr>
<td>0.066</td>
<td>0.092</td>
<td>0.125</td>
</tr>
<tr>
<td>0.162</td>
<td>0.198</td>
<td>0.238</td>
</tr>
<tr>
<td>0.102</td>
<td>0.142</td>
<td>0.173</td>
</tr>
<tr>
<td>Basic Event E6</td>
<td>Basic Event E12</td>
<td>Basic Event E18</td>
</tr>
<tr>
<td>0.113</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>0.04</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>0.242</td>
<td>0.282</td>
<td>0.318</td>
</tr>
</tbody>
</table>

The approximated Fuzzy numbers listed in Table 4.2 to represent the failure possibility of the basic events are defined by the following expressions and shown in Fig. 4.21:

\[
\mu_e(x) = \begin{cases} 
\frac{x - 0.065}{0.023}, & \text{if } 0.065 \leq x \leq 0.088 \\
\frac{0.117 - x}{0.029}, & \text{if } 0.088 \leq x \leq 0.117 
\end{cases}, \quad \mu_e(x) = \begin{cases} 
\frac{x - 0.06}{0.028}, & \text{if } 0.060 \leq x \leq 0.088 \\
\frac{0.116 - x}{0.028}, & \text{if } 0.088 \leq x \leq 0.116 
\end{cases}
\]

\[
\mu_e(x) = \begin{cases} 
\frac{x - 0.087}{0.031}, & \text{if } 0.087 \leq x \leq 0.118 \\
\frac{0.155 - x}{0.037}, & \text{if } 0.118 \leq x \leq 0.155 
\end{cases}, \quad \mu_e(x) = \begin{cases} 
\frac{x - 0.068}{0.032}, & \text{if } 0.068 \leq x \leq 0.100 \\
\frac{0.137 - x}{0.037}, & \text{if } 0.100 \leq x \leq 0.137 
\end{cases}
\]

\[
\mu_e(x) = \begin{cases} 
\frac{x - 0.066}{0.026}, & \text{if } 0.066 \leq x \leq 0.092 \\
\frac{0.125 - x}{0.033}, & \text{if } 0.092 \leq x \leq 0.125 
\end{cases}, \quad \mu_e(x) = \begin{cases} 
\frac{x - 0.113}{0.037}, & \text{if } 0.113 \leq x \leq 0.150 \\
\frac{0.180 - x}{0.030}, & \text{if } 0.150 \leq x \leq 0.180 
\end{cases}
\]

\[
\mu_e(x) = \begin{cases} 
\frac{x - 0.166}{0.032}, & \text{if } 0.166 \leq x \leq 0.198 \\
\frac{0.235 - x}{0.037}, & \text{if } 0.198 \leq x \leq 0.235 
\end{cases}, \quad \mu_e(x) = \begin{cases} 
\frac{x - 0.070}{0.043}, & \text{if } 0.065 \leq x \leq 0.108 \\
\frac{0.145 - x}{0.037}, & \text{if } 0.108 \leq x \leq 0.145 
\end{cases}
\]
\[ \mu_e(x) = \begin{cases} \frac{x-0.065}{0.036} & \text{if } 0.065 \leq x \leq 0.101 \\ \frac{0.130-x}{0.029} & \text{if } 0.101 \leq x \leq 0.130 \end{cases} \]

\[ \mu_e(x) = \begin{cases} \frac{x-0.065}{0.023} & \text{if } 0.065 \leq x \leq 0.088 \\ \frac{0.117-x}{0.029} & \text{if } 0.088 \leq x \leq 0.117 \end{cases} \]

\[ \mu_e(x) = \begin{cases} \frac{x-0.035}{0.025} & \text{if } 0.035 \leq x \leq 0.061 \\ \frac{0.092-x}{0.031} & \text{if } 0.061 \leq x \leq 0.092 \end{cases} \]

\[ \mu_e(x) = \begin{cases} \frac{x-0.050}{0.030} & \text{if } 0.050 \leq x \leq 0.080 \\ \frac{0.117-x}{0.037} & \text{if } 0.080 \leq x \leq 0.117 \end{cases} \]

\[ \mu_e(x) = \begin{cases} \frac{x-0.069}{0.032} & \text{if } 0.069 \leq x \leq 0.101 \\ \frac{0.136-x}{0.035} & \text{if } 0.101 \leq x \leq 0.136 \end{cases} \]

\[ \mu_e(x) = \begin{cases} \frac{x-0.170}{0.033} & \text{if } 0.170 \leq x \leq 0.203 \\ \frac{0.237-x}{0.034} & \text{if } 0.203 \leq x \leq 0.237 \end{cases} \]

\[ \mu_e(x) = \begin{cases} \frac{x-0.102}{0.040} & \text{if } 0.102 \leq x \leq 0.142 \\ \frac{0.173-x}{0.031} & \text{if } 0.142 \leq x \leq 0.173 \end{cases} \]

\[ \mu_e(x) = \begin{cases} \frac{x-0.242}{0.040} & \text{if } 0.242 \leq x \leq 0.282 \\ \frac{0.282-x}{0.036} & \text{if } 0.282 \leq x \leq 0.318 \end{cases} \]

Fig. 4.21: Failure Possibilities of Basic Events
Using fuzzy operators and triangular fuzzy number approximated to be the possibilities of each basic event, we calculate the possibility of top event. The possibility of top event is resulted as a triangular fuzzy number \((0.862, 0.933, 0.970)\) expressed as follows and shown in Fig. 4.22.

\[
\mu_x(x) = \begin{cases} 
\frac{x - 0.862}{0.071} & \text{if } 0.862 \leq x \leq 0.933 \\
\frac{0.970 - x}{0.037} & \text{if } 0.933 \leq x \leq 0.970
\end{cases}
\]

Fig. 4.22: Failure Possibility of Cannula Fault

(b) Fuzzy Importance Index of Basic Events in Cannula Fault Diagnosis:

To illustrate proposed method of Fuzzy Importance Index (FII), we implement it to the Fault Tree Analysis of Cannula Fault in power transformer. The failure possibility of top event calculated herein is \((0.862, 0.933, 0.970)\) and denoted as \((l, m, u)\). We use \(P_{E_i}\) to denote the failure possibility of top event, when basic event \(E_i\) does not happen. To calculate failure possibility \(P_{E_i}(l', m', n')\) the failure possibility for basic event \(E_i\) is assigned a triangular fuzzy number \((0, 0, 0)\) i.e. a crisp number zero. The failure possibility \((l', m', n')\) of top event for each basic event \(E_i\) is listed in Table 4.3.
Table 4.3: Possibility of top event when basic event \( E_i \) does not happen

<table>
<thead>
<tr>
<th>Basic Event ((E_i))</th>
<th>Possibility of top event when basic event ( E_i ) does not happen ((P_{T_i}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_1)</td>
<td>((0.852, 0.927, 0.966))</td>
</tr>
<tr>
<td>(E_2)</td>
<td>((0.852, 0.927, 0.966))</td>
</tr>
<tr>
<td>(E_3)</td>
<td>((0.834, 0.914, 0.958))</td>
</tr>
<tr>
<td>(E_4)</td>
<td>((0.852, 0.926, 0.966))</td>
</tr>
<tr>
<td>(E_5)</td>
<td>((0.852, 0.926, 0.966))</td>
</tr>
<tr>
<td>(E_6)</td>
<td>((0.844, 0.921, 0.964))</td>
</tr>
<tr>
<td>(E_7)</td>
<td>((0.834, 0.917, 0.961))</td>
</tr>
<tr>
<td>(E_8)</td>
<td>((0.840, 0.916, 0.959))</td>
</tr>
<tr>
<td>(E_9)</td>
<td>((0.852, 0.926, 0.966))</td>
</tr>
<tr>
<td>(E_{10})</td>
<td>((0.852, 0.927, 0.966))</td>
</tr>
<tr>
<td>(E_{11})</td>
<td>((0.835, 0.917, 0.961))</td>
</tr>
<tr>
<td>(E_{12})</td>
<td>((0.856, 0.928, 0.967))</td>
</tr>
<tr>
<td>(E_{13})</td>
<td>((0.857, 0.929, 0.967))</td>
</tr>
<tr>
<td>(E_{14})</td>
<td>((0.854, 0.927, 0.966))</td>
</tr>
<tr>
<td>(E_{15})</td>
<td>((0.851, 0.926, 0.966))</td>
</tr>
<tr>
<td>(E_{16})</td>
<td>((0.833, 0.916, 0.961))</td>
</tr>
<tr>
<td>(E_{17})</td>
<td>((0.846, 0.922, 0.964))</td>
</tr>
<tr>
<td>(E_{18})</td>
<td>((0.817, 0.907, 0.957))</td>
</tr>
</tbody>
</table>

The fuzzy importance index for each basic event \( E_i \), obtained by using the following expression is listed in Table 4.4 and shown in Fig. 4.23.

\[
\text{FII}(i) = \sqrt{(l - \cdot \cdot \cdot + \cdot \cdot \cdot - \cdot \cdot \cdot + \cdot \cdot \cdot - w)^2}
\]
Table 4.4: Fuzzy Importance of Basic Events

<table>
<thead>
<tr>
<th>Basic Event ($E_i$)</th>
<th>Fuzzy Importance Index (FII)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{13}$</td>
<td>0.005</td>
</tr>
<tr>
<td>$E_{12}$</td>
<td>0.006</td>
</tr>
<tr>
<td>$E_{14}$</td>
<td>0.008</td>
</tr>
<tr>
<td>$E_1$</td>
<td>0.010</td>
</tr>
<tr>
<td>$E_2$</td>
<td>0.010</td>
</tr>
<tr>
<td>$E_4$</td>
<td>0.010</td>
</tr>
<tr>
<td>$E_5$</td>
<td>0.010</td>
</tr>
<tr>
<td>$E_9$</td>
<td>0.010</td>
</tr>
<tr>
<td>$E_{10}$</td>
<td>0.010</td>
</tr>
<tr>
<td>$E_{15}$</td>
<td>0.011</td>
</tr>
<tr>
<td>$E_{17}$</td>
<td>0.017</td>
</tr>
<tr>
<td>$E_6$</td>
<td>0.019</td>
</tr>
<tr>
<td>$E_8$</td>
<td>0.026</td>
</tr>
<tr>
<td>$E_{11}$</td>
<td>0.029</td>
</tr>
<tr>
<td>$E_7$</td>
<td>0.030</td>
</tr>
<tr>
<td>$E_{16}$</td>
<td>0.031</td>
</tr>
<tr>
<td>$E_3$</td>
<td>0.032</td>
</tr>
<tr>
<td>$E_{18}$</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Fig. 4.23: Fuzzy Importance Index of basic events (FII)
4.9 DISCUSSION AND CONCLUSIONS

In the present chapter we have introduced a novel approach to approximate the failure possibility of basic events, if more than one fuzzy number was assigned to a particular basic event by different experts. The possibilities of basic events were considered to be triangular fuzzy numbers. Three fuzzy numbers were assigned to each basic event by three Experts A, B and C. These experts collected data for failure of each component in three different operating conditions “Worst Case Conditions”, “Conducive Environment” and “Highly Conducive Environment”. Unlike previous techniques, here we deliberated over the operating conditions rigorously and assessed the weightage of each of them. Taking view of this, we generalized the PERT method for fuzzy numbers to obtain the best choice of fuzzy number to a basic event. The proposed method is observed to be very pragmatic and preclude of failure possibility for basic events.

Further since, all basic events do not contribute equally in failure of a system that is, in the occurrence of top event, so it is important to assess the importance of each basic event. We have, in our work, employed a very effective and computationally easy technique to obtain fuzzy important index. The implementation of proposed methods is demonstrated through the diagnosis of cannula fault in power transformer. We classified eighteen basic events, which lead to the occurrence of top event. We finally reached to the conclusion that the reliability of cannula and hence of Power Transformer may be improved by preventing occurrence of basic event $E_{18}$. 

112