Advanced risk analysis of systems endangered by ESD

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Abstract. Evaluation of industrial processes to determine risk of fire or explosion caused by electrostatic discharge (ESD) is even nowadays qualitative in most cases. Although qualitative analysis significantly helps to make an industrial process safer, it is based on the survey of the process and strongly subjective, depending on the estimation of an expert. Fault tree analysis is a traditional method to quantify the risk; it helps to select optimal protection. However, determination of top event, secondary events and basic events of the fault tree is difficult, especially the quantification of the probabilities of the basic events. In several cases no statistical information is available for most of the events. Using fuzzy membership functions instead of simple numbers for the quantification of probabilities makes it possible to take this uncertainty into consideration. Fuzzy logic based fault tree analysis of chemical processes were made to determine the effect of basic events on the probability of the top event (explosion or fire) and its reliability.

1. Introduction
Several processes in pharmaceutical industry are endangered by electrostatic discharge. Transportation of dust, pouring ingredients into vessels, packing and unpacking are typical processes where charge separation occurs [1]. When the accumulated charge results in an electrostatic discharge of certain energy, solvent vapors or other inflammable gaseous mixtures can produce fire or explosion. Different measures are introduced to avoid charge accumulation, mainly by providing one or more appropriate grounding path. Therefore strict regulations exist about the conductance of clothes, gloves, shoes, packaging materials etc. to ensure low enough grounding resistance.

However there is a wide range in the selection of such clothing, several types of industrial floor exists, therefore it is useful to determine, which one is critical and which one is moderately important to ensure safety. That makes it necessary to quantify the change of risk at different combination of safety measures. For this purpose application of fault tree analysis was selected.

2. Advanced fault tree analysis
Fault tree is not a new method; it is used in many different fields. For the first step, an event tree has to be created, which is a map to our „top event” (in our case to fire or explosion) containing the logical connection between the events that lead to the top event. At the bottom of the fault tree basic events can be found, these are not decomposed to further events.
With a slight change we can modify the event tree into a fault tree. This modification means, that we order to each event it’s probability of occurrence. The advantage of the fault tree is, that it shows, how the probability of the basic events affects the probability of the top event.

It is difficult to specify the probability of the basic events is many cases, because not enough statistical information available for its value. Introducing fuzzy-logic, fault tree can be transformed into fuzzy fault tree [2,3], which orders a so called membership function to each event. It’s range of the function is between zero and one, it signifies how close is a given probability to the estimated one. Most simple type of the membership functions is a triangle. Its value $\mu(x)$ is 0 at $x=x_{\text{min}}$ and $x=x_{\text{max}}$, while $\mu(x)=1$ at $x=x_{\text{core}}$. (Naturally, $x$ is a probability value in the [0,1] interval.)

Obviously in the „fuzzy fault tree” classical logical operations (and, or etc.) are replaced by fuzzy operations (FAND, FOR, etc.). Thus the resultant probability for the top event arises a membership function. This gives more information than the probability value belongs to the apex, because difference $x_{\text{min}}-x_{\text{max}}$ shows how confident we are with the probability vale assigned to the top event, so how we can trust the calculated value.

In the practice we can use this the following way. Presume that we are measuring a physical value, e.g. humidity, and in the function of time we record the measuring values. With these results we can determine what the probability value is, that the examined quantity is under a given limit during a certain operation. If we do the measurement with expensive instrument of great accuracy, difference $x_{\text{min}}-x_{\text{max}}$ will be low. Using a cheap, low accuracy instrument, the situation is just the inverse, the bottom of the membership function is extended, showing that we are uncertain with the result.

Finally, observing the membership function of the top event, it can be determined, how it is influenced by the selection of the instrument. If the influence is significant, than it is worth to choose beside the more expensive instrument and if not, than the less expensive instrument is satisfying.

3. Application of advanced fault tree analysis on an industrial process

Advanced fault tree analysis was used for the examination of a process of a pharmaceutical company [4,5]. The examined process consists of different phases of work. Each phase was examined separately and a fuzzy membership function for the probability of top event was determined. To obtain the resultant risk of the total process, membership functions of probabilities were weighted and added. This paper is focused on such a manufacturing phase, in which powder is poured into a mixer containing solvent with inflammable vapor. Powder is stored in paper bags; the mixer is opened during the pouring in. Event tree for this process can be constructed according to the following way. Top event (fire or explosion) occurs when inflammable atmosphere (appropriate mixture of air and solvent) and ignition source are present at the same time. Formation of electrostatic discharge requires a spark gap and charge accumulation that increases potential difference above its breakdown voltage. Such a dangerous charge accumulation occurs when grounding resistance is not low enough at a given arrangement and charge separation intensity.

Using the notation of the simplified model in Figure 1., the steady state voltage on resistor $R_d$ is $U=I_dR_d$, it must be lower than the breakdown voltage $U_{\text{br}}$ of the spark gap to avoid ESD. To keep $U$ below $U_{\text{br}}$, it is necessary to reduce current $I_d$ or resistor $R_d$. First one is usually depends on the speed of filling in and the properties of the applied powder. Second one is the resultant value of different grounding paths, typically the surface resistance of objects (influenced by the relative humidity) and the resistance of clothes, gloves, shoes, etc. Important part of the grounding path is the resistance of the floor. Energy of the discharge is influenced by the breakdown voltage and the capacitance of the arrangement, $W=0.5CU_{\text{br}}^2$.

Figure 1. Simplified model for charge accumulation and discharge. $I_{ch}$: charging current, $R_d$: grounding resistance, $C$: capacitance of the examined arrangement.
Regarding the limited space of the paper, a strongly simplified version of the event tree is represented in Table 1. (In the detailed version more than fifty events exist for one operation.) As it can be seen, there are 10 basic events; a probability value or membership function has to be assigned to these events.

**Table 1. Strongly simplified event tree of the process**

| No. | Event                                      | Relation | Events involved in the relation |
|-----|--------------------------------------------|----------|---------------------------------|
| 1   | Fire, explosion                            | And      | 2, 3                            |
| 2   | Inflammable atmosphere                      | Basic    |                                 |
| 3   | ESD of appropriate energy                   | And      | 4, 5                            |
| 4   | Breakdown voltage exceeded                  | And      | 6, 7                            |
| 5   | Spark gap exists                            | Basic    |                                 |
| 6   | Charge accumulation                         | And      | 8, 9                            |
| 7   | C is high enough                            | Basic    |                                 |
| 8   | High grounding resistance                   | And      | 10, 11                          |
| 9   | High charging current                       | Or       | 12, 13                          |
| 10  | Low relative humidity                       | Basic    |                                 |
| 11  | High resistance current path                | Or       | 14, 15                          |
| 12  | High speed of filling                       | Basic    |                                 |
| 13  | Charging of human body                      | Basic    |                                 |
| 14  | Improper glows and clothes                  | And      | 16, 17                          |
| 15  | Improper shoes or floor                     | Or       | 18, 19                          |
| 16  | Gloves made of insulating material          | Basic    |                                 |
| 17  | Clothes made of insulating material         | Basic    |                                 |
| 18  | High grounding resistance of floor          | Basic    |                                 |
| 19  | Improper shoes                             | Basic    |                                 |

4. Case study

Using the existing event tree it is possible to analyze different cases determining the probability values or membership functions of the events.

Presence of inflammable atmosphere is supposed to be continuous, hence the solvent vapor concentration inside the mixer is above the critical limit, outside it is below that, so opening the mixer results in a critical concentration value somewhere near the opening. Existence of spark gap is also supposed to be continuous, as well as the energy stored in the capacitor is practically always enough to ignite the solvent vapor, therefore their probability was selected 1.

Relative humidity can be set to a constant value by air conditioning, or it can change during the process. In the first case fault of the air conditioning system can cause dry air, in the second case it can occur by chance. For the case study 0.3 was selected.

There are two main cases, when gloves, clothes and shoes can be improper (too high resistance). First one is, when the material is not proper because of improper manufacturing or the aging of the material, or because of the contamination. Second one, that workers uses different gloves, clothes and shoes than it is required. Based on laboratory measurement of samples and the examination of working practices, 0.02 and 0.03 were selected. Material properties and effect of contamination plays an important role in the grounding resistance of the floor. On site measurements made from time to time helps to identify the probability of high resistance. For the case study 0.007 was applied.

Among charging processes, pouring in of powder is supposed to occur more often than the charging of human body due to walking on carrying the components. The assigned values are 0.85 in the first and 0.4 in the second case. If we want to use fuzzy fault tree, membership functions have to be used instead of probability values. The triangular functions can be seen in Table 2. (Case1).
Table 2. Results of analyzed cases

| No. | Case1     | Case2     | Case3     |
|-----|-----------|-----------|-----------|
| 1   | 0.0022    | 0.0033    | 0.0027    |
| 2   | 1.0000    | 1.0000    | 1.0000    |
| 3   | 0.0022    | 0.0033    | 0.0027    |
| 4   | 1.0000    | 1.0000    | 1.0000    |
| 5   | 0.0022    | 0.0033    | 0.0027    |
| 6   | 1.0000    | 1.0000    | 1.0000    |
| 7   | 0.0028    | 0.0042    | 0.0034    |
| 8   | 0.7900    | 0.7900    | 0.7900    |
| 9   | 0.2000    | 0.2000    | 0.2000    |
| 10  | 0.0142    | 0.0211    | 0.0171    |
| 11  | 0.7000    | 0.7000    | 0.7000    |
| 12  | 0.3000    | 0.3000    | 0.3000    |
| 13  | 0.0002    | 0.0002    | 0.0002    |
| 14  | 0.0140    | 0.0209    | 0.0169    |
| 15  | 0.0100    | 0.0100    | 0.0100    |
| 16  | 0.0200    | 0.0200    | 0.0200    |
| 17  | 0.0040    | 0.0040    | 0.0040    |
| 18  | 0.0100    | 0.0100    | 0.0100    |
| 19  | 0.0070    | 0.0070    | 0.0070    |

Case 2. represents that situation, when the probability, that floor can have high resistance is doubled, but the difference between $x_{\text{max}}$ and $x_{\text{min}}$ is unchanged. The calculation result shows, that increasing the probability of the insulating floor, a significant change in the probability of the top event can be observed.

Case 3. shows that situation, when difference between $x_{\text{max}}$ and $x_{\text{min}}$ is also increased, indicating, that probability value assigned to this basic event is now more uncertain than it was in the previous case. It can be observed, that this change arises in the membership function of the top event.

5. Conclusion
Application of advanced fault tree analysis for a given industrial process is a useful tool to find a cost-effective solution for the decrease of risk arising from electrostatic discharge.

References
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