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Quantification of Risk Reduction Due to the Installation of Different Lightning Protection Solutions for Large Atmospheric Storage Tanks

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In the past decades the impact of natural events in industrial plants have triggered a number of technological accidents. Accidents may be followed by the release of relevant quantities of hazardous substances, with relevant consequences for the population and for the environment. Technological accidents triggered by natural events are very common in the industrial facilities, although only recently their specificity was recognized and they are now indicated as Natech (natural-technological) events. In particular, lightning strikes are a recognized hazard that causes the loss of large quantities of product and compromise the safety for chemical and oil industries. Past accident analysis evidenced that the most vulnerable installations to lightning strike are oil tank terminals of oil refineries. Since there is general agreement that a total protection from lighting hazard is impossible, quantitative risk assessment is needed to assess the possibility of technological accidents caused by lightning strike. The aim of the present study was the development of a dedicated methodology for the quantitative assessment of risk due to technological accidents triggered by lightning strikes in chemical and process industries. In particular the accidental scenarios have been identified and the frequencies for every scenario have been calculated. The method developed was applied to assess the risk reduction that can be achieved by the installation of air terminals to protect storage tanks in lightning prone zones. Different solutions are compared in order to select the best protection system for different storage tanks and lay-outs.

1. Introduction

Technological accidents triggered by natural events in process industries can have serious consequences on the industrial sites and on the surroundings. They were analysed by Rasmussen (1995) that examined the several databases reporting past industrial accidents. The study indicates that 1-5% of past industrial accidents have natural events as causative factors. Past accident analysis evidences that lightning triggered loss of containment accidents often result in severe consequences, also due to the high ignition probability of flammable substances in these scenarios (82% of accidents analyzed ended in severe fires (Renni et al., 2010)).
Both, the historical analysis of past accidents (Renni et al., 2010) and new born dedicated methodology for NaTech risk assessment (Antonioni et al., 2009) agree that the plant items more vulnerable to lightning impact are storage tanks. The study by Argyropoulos et al. (2012) confirms that lightning is a major accident initiator and evidences the necessity of an effective lightning protection system for hydrocarbon storage tank parks.
Fires are the most probable accident scenario caused lightning strikes on storage tanks (Renni et al., 2010). Moreover, the resulting fire may, eventually, involve other equipment units starting a devastating accident escalation process to nearby equipment units (Landucci et al., 2009). Thus, advanced risk

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management methods are required to minimize the occurrence of such “Domino events” in industrial fire-prone zones (e.g. Tugnoli et al. 2012), in particular for those areas that experience the lightning threat.
Lightning hazard has been addressed also within the more general framework of NaTech hazard (Cozzani, 2010). Specific contributions focused on providing tools for the inclusion of NaTech-related threats in risk assessment practice (Landucci et al.,2012).
The large number of lightning accidents recorded in the accident databases evidence a weakness in the protective measures proposed in industrial standards and codes (API RP 545, 2009; OISD GDN 180, 1999). In particular only qualitative or semi-quantitative risk assessment can be provided for lightning triggered accidents on storage tanks. As a result, the protection measures proposed for the storage tanks are applied at all the tanks with only minor differences, depending on the site location and position of the tanks in the industrial lay-out. There is general agreement that such ordinary protection systems are not able to protect a process item from the effects of a direct lightning strike (Galván Diego, 2010; Carpenter, 1996). In order to verify the effectiveness of the lightning protection measures, a brief review of standards for lightning protection adopted in refineries has been also carried out in this study.
In a previous study (Necci et al, 2013a), a Monte Carlo model was developed for the assessment of lightning capture frequency on storage tanks. The model was applied to the analysis of the effect of specific protection barriers on lightning impact frequency. In order to protect critical equipment units or storage tanks from the lightning hazard, several typologies of specific lightning protection systems can be adopted. In this study, the reduction of the capture frequency due to the installation of different typologies external lightning protection systems (ELSP) was assessed.

2. Codes and standards on lightning protection for storage tank parks

2.1 Introductory remarks

API RP 545 (2009) is the dedicated standard on lighting protection for storage tanks and substitutes the previous indications provided by API RP 2003 (2008). Two potential threats are identified for installations containing flammable substances: threat from a direct lightning strike, when the flash hits the target equipment, and threat from indirect lightning strike, when the flash hits the ground (or another structure) in the vicinity of the tank. In both events, the lightning current (or a portion of it) flows through the tank. Any discontinuities in the current paths may result in arcing across the gaps that may ignite the flammable atmosphere eventually present in the storage tank.
For this reason, the document lists several objectives to achieve, in order to protect the storage tank from the lightning threat. In particular, External Floating Roof Tanks (EFRT) should meet specific design requirement for the installation of shunts, seals and bypass conductors. These protective devices, together with specific indications about operational planning have the aim of avoiding ignition of flammable material, by minimizing spark generation probability, as a consequence of a lightning strike, and by preventing the formation of flammable-air mixture at the rim-seal.
The Indian “Oil Industry Safety Directorate (OISD)” provides its specific standard on the task of lightning protection for storage tanks (OISD GDN 180, 1999), on the basis of national (BIS IS-2309, 1989) and international standards (NFPA 780, 1997) for the lightning protection of structures. It is similar in contents to the API RP 545, but it includes a section for the protection of the tank from the threat of direct lightning strikes by the use of dedicated air terminals. However, there is general agreement among the different standards that total protection from the lightning hazard in storage tank areas is only a final goal, due to the stochastic behaviour of lightning strikes. Thus, the design of lightning protection systems should be joined to a dedicated method for risk analysis(API RP 545, 2009, CEI EN 62305, 2006).

2.2 Grounding and bonding

API RP 545 (2009) does not include specific requirement concerning the grounding of the structure since the metal body of the storage tank provides adequate grounding itself.
Bonding is a specific requirement for External Floating Roof Tanks (EFRT). In order to significantly reduce potential differences between the different parts of the tank, an electrical connection is provided among all the components. This measure creates a “safe” path for the lightning current to the ground. An adequate bonding is achieved by the installation of shunts and bypass conductors between the storage tank body and the floating roof (API RP 545, 2009). Furthermore, any gauge or guide pole components or assemblies that penetrate the tank floating roof shall be electrically insulated from the tank floating roof.
Even if these measures are capable to completely protect the tank from the ignition threat due to indirect strike currents, the analysis of past accidents demonstrate that in case of direct lightning impact, bonding can slightly reduce the probability of ignition of flammable atmosphere, but does not ensure the prevention of incendiary sparks (OISD GDN 180, 1999). However, since the probability of indirect strikes is much

higher than the probability of direct strike on the storage tank (up to 1000 times larger (Carpenter, 1996), bonding is considered a mandatory requirement for the design and installation of atmospheric storage tanks.

2.3 External lightning protection system (ELPS)

The OISD GDN 180 (1999) describes a methodology for the design of external lightning protection systems for storage tank parks. A lightning protection system (Conventional Air Terminal System) consists of the following three basic components:

a) Air terminal: capable of drawing the lightning discharge to it in preference to vulnerable parts of the protected structure.

b) Down conductor: provide a safe low-impedance path to the ground.

c) Earth connection: provides safe discharge of lightning current into the soil

Different air terminal provides different protection to the respect of direct strikes to the storage tank. The solutions proposed by OISD 180 are discussed in the following.

2.4 Lightning rods

The design of lightning rods (OISD GDN 180, 1999) is performed by the application of the “rolling sphere method” (Cooray and Becerra, 2010), used to define the minimum number of rods per tank that shall be installed. Rods are designed to attract a stroke and divert the resulting current via a preferred path (the down conductor) to earth. They are reasonably effective in performing these functions. However, air terminals can cause fires by attracting the strike, since the design assume to place the air terminal in close proximity to the flammables (top of tank body). The closer the stroke channel is to the flammables, the higher the related effects (bound charge and earth currents), and the greater the risk of a fire initiating arc. Thus, even if they are capable of reducing the dangerous effect of lightning strikes on storage tanks, i.e. neglecting the direct damage to the tank shell (Necci et al., 2013b), they also increase the chances of lightning hitting the tank (Carpenter, 1996).

2.5 Lightning protection masts

Their mechanism is similar to the lightning rods. Air terminals are supported by tall masts, placed at some distance from the tank (6 m in order to avoid side flashes (OISD GDN 180, 1999)) (Figure 1-a). The number of lightning masts that shall be applied is obtained by the use of the “rolling sphere method” (Table 1) based on a striking distance (the rolling sphere radius) of 30m. Since this system is really capable of attracting lightning away from the equipment, they are capable to reduce significantly the probability of direct lightning strikes to the tank.

2.6 Overhead shield wire

A system of overhead earth wires placed at the top of dedicated supporting structures can be installed to protect a storage tank. The system is designed (OISD GDN 180, 1999) according to rolling sphere concept based on a striking distance of 30 m (Figure 1-b). A single earth wire with a minimum clearance of about 8 m above the highest point of the tank can protect a tank of about 6 to 8 m diameter (OISD GDN 180, 1999). For tank diameters between 8 to 30 m two parallel earth wires are used while for tank diameters between 30 to 80 m (Figure 1-b); three parallel wires are required to protect the tank.

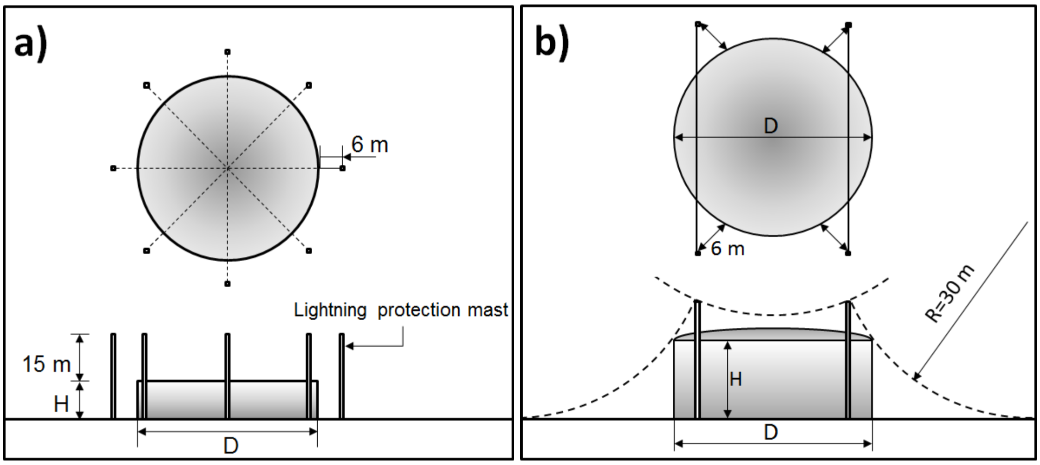

Figure 1: Air terminals for the ELPS: a) Lightning masts; b) overhead shield wire

3. Capture model

A “capture model” is needed to assess the frequency of lightning impact on a process vessel of known geometry. The model requires the geometrical features of the storage tank, i.e. height and diameter, then it calculates the lightning strike probability in the unit of time. The capture model was developed using a Monte Carlo method (Borghetti et al., 2007). The procedure is based on the generation of a large number of lightning events with the associated parameters as lightning current amplitude and stroke location coordinates x and y, intended as the point of formation of the descending step leader (Cooray and Becerra, 2010). It is assumed that the parameters of the randomly generated events follow the log-normal probability distributions (Anderson and Eriksson, 1980) for negative and positive strokes. The complete methodology for the application of the Monte Carlo model to assess the capture frequency on the basis of lightning frequencies and statistics is assessed elsewhere (Necci et al., 2013a).
Lightning flash densities are often available on the basis of historical data data (e.g. (SIRF, 2013). It is possible to obtain the value of the lightning ground flash density ($\boldsymbol{n_g}$) measured in number of flashes per year per square kilometre. The following equation provides an assessment of expected annual capture frequency for a generic unit *j* in the installation (Necci et al., 2013a):

$$f_{capture,j} = \frac{n_{captured,j}}{n_{tot}} \cdot n_g \cdot A \tag{1}$$

Where $\boldsymbol{n_{captured,j}}$ is the number of simulated lightning captured by the j-th unit, $\boldsymbol{n_{tot}}$ is the number of simulations and ***A*** is the extension of the area in which simulations are performed.
In order to express the protection that can be achieved by the use of a protection system, a non-dimensional factor, LI, has been defined. The factor indicates the mitigation effect on the expected number of lightning captured by a specific equipment in a complex lay-out, due to the presence of lightning protection systems. This index represents the ratio between the lightning capture frequency of the unit in its specific layout and the capture frequency that the same unit would have in an unprotected open flat field:

$$LI = \frac{f_{captured,j}}{f_{capture,j,solo}} \tag{2}$$

Where ***LI*** is the lightning capture frequency reduction factor and $\boldsymbol{f_{capture,j,solo}}$ is the capture frequency of equipment *j* as if it was an unprotected stand-alone item.

4. Results

In Appendix 1 of OISD GDN 180 (1999) details on the use of the rolling sphere method for the design of ELPS are shown. In particular air terminal height, number and distance from the tank are reported. Lightning mast network should overcome the maximum tank height of 15 m; it should include one mast per every 24 m of the tank perimeter; masts should be placed at a minimum distance of 6 m from the tank. A reference tank height of 12 m has been considered in the following (OISD GDN 180, 1999).

Table 1: The use of lightning protection mast network: capture frequency calculation and reduction factor

Diameter (m)	Mast Number	$f_{capture}$ (y^{-1})	$f_{capture,solo}$ (y^{-1})	LI
up to 12	3	5.44E-02	2.59E-06	4.77E-05
13-21	4	6.08E-02	3.02E-06	4.97E-05
22-32	5	6.89E-02	1.38E-05	2.01E-04
33-38	6	7.37E-02	2.33E-05	3.17E-04
39-45	7	7.91E-02	3.72E-05	4.69E-04
46-51	8	8.42E-02	5.92E-05	7.03E-04
52-57	9	8.94E-02	1.03E-04	1.16E-03
58-63	10	9.46E-02	1.56E-04	1.64E-03
64-71	11	1.02E-01	2.52E-04	2.46E-03
72-79	12	1.10E-01	4.44E-04	4.04E-03

Table 1 reports the indications provided by OISD GDN 180 for the installation of a lightning mast network around storage tank in a wide range of possible tank size It also reports the $\boldsymbol{f_{capture}}$, the $\boldsymbol{f_{capture,solo}}$ and the ***LI*** for each tank size, calculated for the largest diameter proposed in the range of applicability.

Table 2: The use of overhead shield wire network: capture frequency calculation and reduction index

Diameter (m)	Wire Number	$f_{capture}$ (y^{-1})	$f_{capture,solo}$ (y^{-1})	LI
6-8	1	9.00E-06	5.19E-02	1.73E-04
9-30	2	5.00E-06	6.74E-02	7.42E-05
31-80	3	9.40E-05	1.11E-01	8.47E-04

Table 2 reports the indications provided by OISD 180 for the installation of overhead shield wires network above a storage tank in three possible configuration, according to the tank size. It also reports the $\boldsymbol{f_{capture}}$, the $\boldsymbol{f_{capture,solo}}$ and the ***LI*** for every tank size, calculated for the largest diameter proposed in the range of applicability.

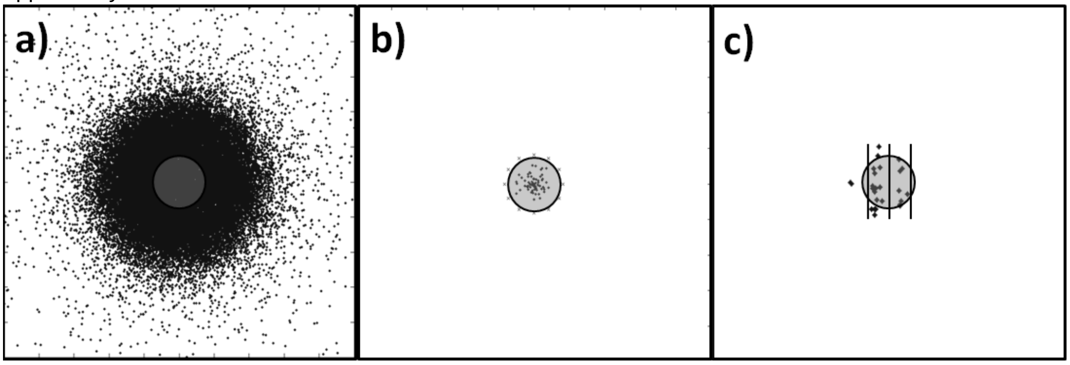

Figure 2: The use of Monte Carlo model to evaluate the protection provided by the ELPS. The location of attracted lightning on a map in three cases: a) the storage is tank unprotected; b) the storage tank is protected by lightning mast network; c) the storage tank is protected by overhead shield wires

In order to visualize the model operability, Figure 2 shows a footprint of a simple lay-out in which the Monte Carlo method has been applied. The point of formation of the descending step leader of those lightning strikes attracted by the storage tank are evidenced in dark gray, while the tank is light gray. The two different solutions are applied to protect the storage tank. Figure 2-a shows the attracted lightning for a huge tank of 79 m diameter in case the tank is unprotected; Figure 2-b the attracted lightning by the tank in the case it is protected by twelve masts (see Table 1); Figure 2-c shows the attracted lightning by the tank in the it is protected by three overhead shield wires (see Table 2). A number of 10^6 simulations were performed for each panel.

5. Conclusions

A review of different codes for lightning protection of storage tank parks has been performed. Bonding all the conductive section of the tank provides adequate protection from indirect lightning strikes. In order to protect the storage tank from direct lightning strikes, ELPS may be considered for installation. A Monte Carlo method has been used to evaluate the benefit gained by the use of different air terminal solutions. In case of the use of lightning masts the direct strike frequency reduction factor varies from $4 \cdot 10^{-3}$ to $4 \cdot 10^{-5}$. In the case ground wires are installed, reduction factor ranges between $9 \cdot 10^{-4}$ and $7 \cdot 10^{-5}$. The results demonstrate that lightning attraction frequency and thus NaTech risk induced by lightning can be reduced of many orders of magnitude by the use of dedicated ELPS. The current methodology, applied as a part of a quantitative risk analysis of lightning triggered accidents, may support the selection of the correct protection solution among all the possible, in order to reduce the risk triggered by lightning to tolerable values.

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