Lightning Protection of High-Risk Installations: Petrochemical Plants

Arturo Galván Diego

Abstract Petrochemical plants are outdoor facilities that hold and produce vast quantities of chemicals. Critical stages of production deal with toxic, flammable and explosive substances. The petrochemicals industry sources raw materials from refining and gas-processing and converts these raw materials into valuable products using a variety of chemical process technologies. Historically the industry evolved out of technological innovation in the developed industrialised economies. Until the last quarter of the twentieth century production of petrochemicals was concentrated in Western Europe, the United States and Japan. Over the last few decades, however, production in areas with competitively priced feedstocks has increased dramatically. New production capacity has been built in the Middle East and Asia, and lightning strikes can be a major hazard.

Keywords Fire hazard · Galvanic effect · Bound charge · Shielding failure · Spark and lightning protection

Lightning can be responsible for damage of two types in any modern plant: one, the destruction resulting from a direct stroke, and the other, the impairment of equipment due to surges in the electric/electronic system, caused either by direct strokes to power lines at some distance from the plant, or by electrostatically induced voltages [1]. When a chemical plant gets hit directly by lightning in critical stages of production, what usually follows are explosions, process upsets, power outages, and potential injuries to personnel, and both direct and indirect lightning strikes can be a major hazard. All lightning protection standards stress that no single lightning protection measure can get rid of lightning strikes 100%, but it is possible to reduce the likelihood of damage from lightning strikes applying suitable measures combined.

There are three main reasons why to implement lightning protection measures in petrochemical installations, in order of importance.

1. Protect people (staff).

A. Galván Diego (✉)
National Institute of Electricity and Clean Energy (INEEL), Cuernavaca, Mexico
e-mail: agalvan@ineel.mx

C. Gomes (ed.), *Lightning*, Lecture Notes in Electrical Engineering 780,
https://doi.org/10.1007/978-981-16-3440-6_6

2. Prevents damage to systems.
3. Prevents damage to structures and buildings.

The philosophy of lightning protection is, according to author's experiences and standards criteria, as follow:

1. Avoid or get rid of lightning hit upon tall metallic structures by lightning protection terminals. The taller a structure is, the higher the chance it will be struck by lightning.
2. Conduct safely the lightning current to ground. This measure should get rid of the voltage drop due to the inductance of the lightning conductor.
3. Apply equipotential bonding measures in each particular system joined with the general grounding grid. This measure will avoid dangerous potential differences.
4. Apply comprehensive provisions of equipment and electrical system grounding, like those recommended in local or relevant standards, such as IEC and NEC. This provides safe working conditions for personnel.
5. Implement local grounding grids connected to a general grounding grid in order to ensure equipotential surfaces and low ground resistance.
6. Install surge protection system for electrical and electronic systems. This measure will guarantee trouble-free operation of complex electrical and electronic systems without consequential damage.

The complexity of petrochemical plants is due to the diversity of systems involved in the operation of the plant, that deserve properly lightning protection measures:

1. Process installations, with tall process metallic towers, metallic chimneys and flare stacks, process containers/vessels.
2. Oil storage tanks farm.
3. Power substations.
4. Distribution lines.
5. Structures and buildings.
6. Low voltage system.
7. Telecommunication Systems and control rooms.

This chapter is devoted to analyze and recommend measures in order to reduce damage from lightning direct hit and indirect lightning effects in all areas of petrochemical installations, according to the six lightning protection points and the seven types of systems referred above.

1 Direct Lightning Protection

In order to implement a measure for direct lightning protection, the designer has to decide into three valid options [2–4].

1. Self protection.
2. Non-isolated protection.

3. Isolated protection.

For self-protection, lightning stepped leader is allowed to intercept with the structure, thus total lightning current will be injected into the metal structure. The first return stroke of negative lightning strikes, the commonest among cloud-to-ground flashes, has impulse currents with a peak value, Ip, of 30 kA on average, a peak current derivative, (di/dt), of 30 kA/μs on average and continuing current of several hundred of amperes and times of 0.5 s. Thus, interception of lightning leader and consequent passage of impulse current may generate highly localized hotspots, large potential gradients, and mechanical stresses in the material due to the flow of fast varying currents. In such situation, strong walls are essential to prevent puncturing at the point of strike, joule heating close to flammable materials and mechanical collapse due to magnetic forces. Not only real failures but even the sense of the risk of failure may strongly influence the smooth operation of the system [2]. Figure 1 depicts this protection scheme.

For non-isolated protection, lightning stepped leader is allowed to intercept with the air terminal bonded to the structure, thus total lightning current will be injected into the metal structure, but hotspot is put away from the metal structure of the structure to the tip of the air terminal. Effects by the current passage on the metal structure of the tank are similar to those given for self-protection scheme. Figure 2 depicts this protection scheme.

For isolated protection, isolated metal masts (with overhead grounded networks in some cases) are installed to protect the structure (process container, oil tank or small buildings). These conductors are installed with a minimum separation, S, from the structure to be protected to avoid arcing between structure and mast in the event of lightning strike to the mast. The minimum separation is calculated by the pertinent

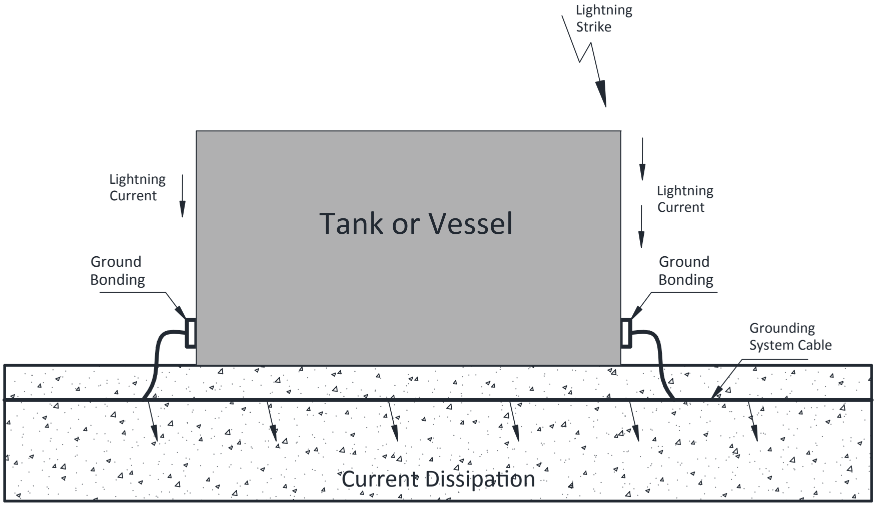


Fig. 1 Self-protection criterion for lightning protection for structures in petrochemical plants

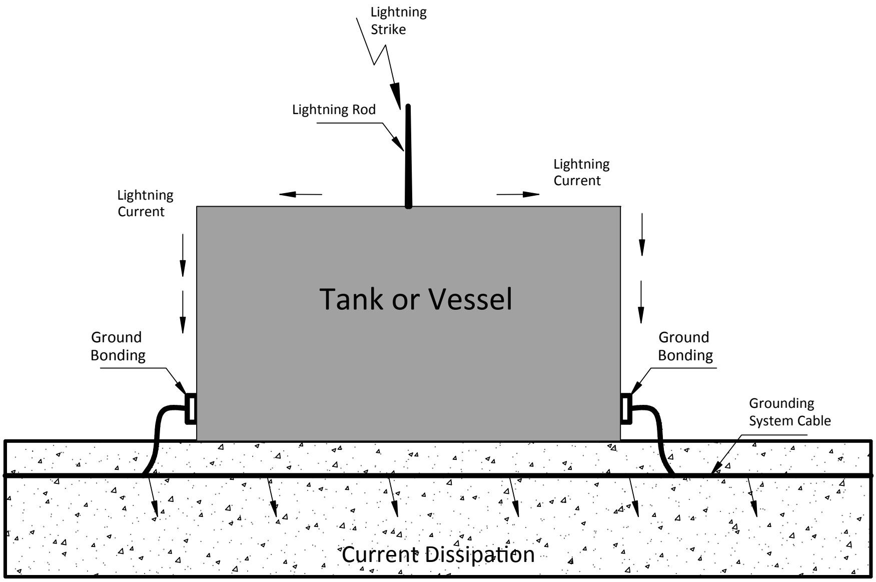


Fig. 2 Non-isolated criterion for lightning protection for structures in petrochemical plants

equation given in [3]. The masts will act both as the air-termination and the down conductor, and in the case of a metallic grid over the tip of the structure will act as the air-termination system. A suitable grounding system should be installed at the earth-termination of the mast in order to disperse the lightning current readily into the soil masses, see Section IV. The structure walls and the mast should be electrically bonded at the ground level to avoid surface arcing. Such isolated LPS will prevent the development of hotspots in the structure walls and also ensure that there will be no significant current flow in the structure walls. However, due to the rapidly varying current along the mast in the event of a lightning will induce certain voltage in the structure walls which will in turn drives current to ground. It is whorthly mentioning that this current will be much smaller than the current injected by direct lightning strikes. Lightning bulk current is managed by air terminals and metallic structure is exposed only to induction voltages and currents. This scheme can be termed "shielding", as employed in lightning protection of transmission lines, and the level of protection (and the number of air terminations or masts) will depend on the accepted current to generate shielding failure. Figure 3 depicts this protection scheme.

Contrary to some believes, Isolated and Non-Isolated systems made of air terminals increases the probability that a strike will occur in the proximity of the installation, but a properly designed system can offer substantial damage avoidance protection for many structures. Conversely, an improperly designed system can aggravate lightning-related problems [2, 5].

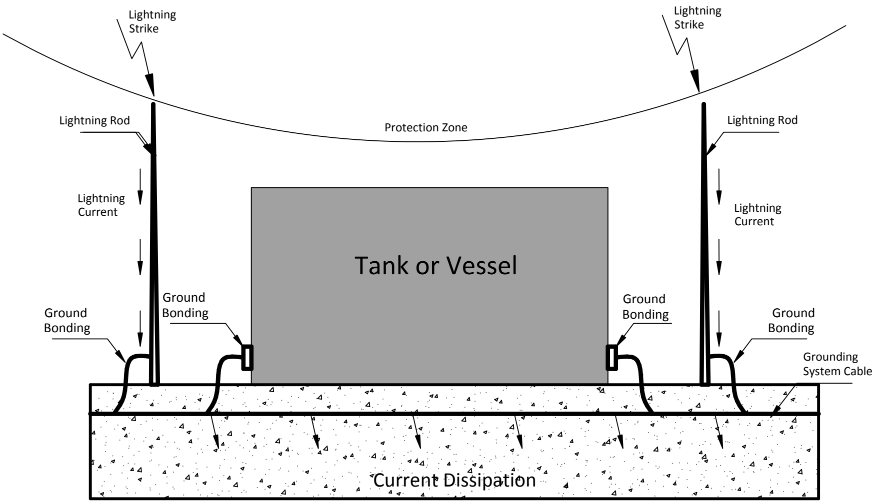


Fig. 3 Isolated criterion for lightning protection for structures in petrochemical plants

1.1 *High Metallic Structures*

For very tall structures (like destilling towers or flare stacks) or very wide structures (like oil-fuel tanks with big diameters), isolated protection is an impractical measure to adopt. For structures like cracking containers, process tanks and blending containers, isolated protection is more suitable to be adopted, and for buildings non-isolated protection should be adopted [2].

It is probable that some of the higher grounded steel structures, do receive occasional lightning strokes with no appreciable damage to itself. They maybe considered as self-protected against lightning strokes. Such high structures create a zone of protection about their bases [1] (Fig. 4).

For the case of destilling towers, the minimum thickness walls are greater than 6 mm. So, a direct lightning hit theoretically would not produce puncture, but the local hot-spot with an ignition hazard possibility should be evaluated according to local lightning current performance (density, rate of rise of current, charge and long tail current). In this case, non-isolated protection scheme could be a suitable protection measure.

Metal chimneys and flare stacks need no protection against lightning other than that afforded by their construction, provided they are properly grounded. Metal flare stacks are usually remotely located from process areas and rarely fall within a zone of protection from other structures. In such stacks, it is also desirable that metal guy wires and cables be grounded at their lower ends. Guy wires attached to steel anchor rods set in the earth may be considered as sufficiently well grounded. Guy wires set in concrete or attached to buildings or nonconducting supports should be provided with additional grounding facilities. Vent stacks situated at the top of process

Fig. 4 Petrochemical plant inherently selfprotecting for tall structures. Non-isolated protection are normally applied in order to divert the striking point from metal structure to be protected. Adapted from Tompson [6]

structures can usually be considered as adequately grounded through the vessel or supporting structural steel. Special precautions must be taken with chimneys and stacks of nonconducting materials such as brick, tile, concrete, or similar material liable to damage by lightning.

It is customary practice to install air terminals (lightning rods) uniformly about the top rim of the stack at intervals not greater than 8 ft. The air terminals should be connected together by means of a metal ring or band forming a loop about 2 ft below the top of the chimney. The air terminals must then be connected to ground by at least two down conductors installed on opposite sides of the stack. Where stacks have a metal lining, the lining should be connected to the air terminals at its upper end and grounded at the bottom. Reinforced concrete stacks should be treated as above, but in addition, the reinforcing metal should be electrically connected together and bonded to the down conductors on the outside of the stack at the top and bottom of the concrete [1, 7]. A typical arrangement of air terminals on a stack is shown in Fig. 5.

1.2 Oil Storage Tanks or Vessels

IEC Standard [3] establishes that the material of metallic pipes and tanks can be considered itself as air termination (natural components) if thickness meets the value

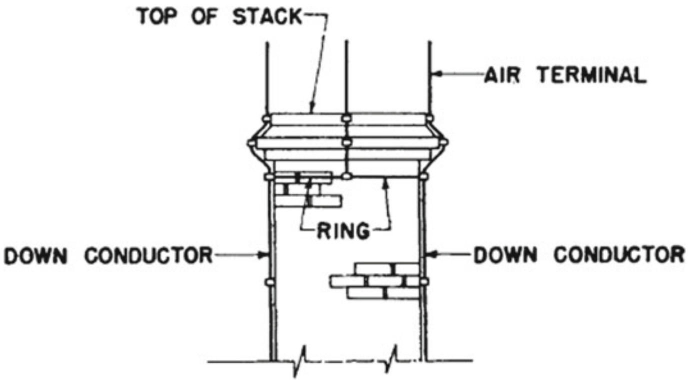


Fig. 5 Non-isolated air terminal arrangement for a stack [1, 7]

Table 1 Risk conditions of lightning-related hotspot on the metal structure

Scheme	Hotspot at structure metal	Bulk lightning current at structure metal
Self-protection	High	High
Non-isolated	Low	High
Isolated	Low	Low

of 4.8 mm for steel (lesser than 3/16″ required by [8] and [9]) and the temperature rise of the inner surface at the point of strike does not constitute a danger.

Table 1 shows the risk conditions for each protection scheme. For self-protection scheme, where the risk of hotspot is very high, it is important to take steps to reduce damage as the result of a lightning strike, side-flash or corona discharge.

In 2009, a study on lightning effects on above-ground storage tanks was carried out [10], especially in terms on puncturing effects when stainless and ferrous steel were exposed to a long duration lightning current. Results of this study indicated that for a 5 mm thick samples, with both 100 C and 400 C (that is, 200 A or 800 A in 0.5 s) the molten pool volumes were 64 mm^3 for 100 A and 400 mm^3 for 400 A. None of the samples in this case were punctured. However, there was a depth of penetration of the molten pool: 2.1–2.5 mm for 100 C and 3.5 mm—3.7 mm for 400 C. According to [10], a threat of 200 C is considered as an adequately severe level against which protection is required in the event of lightning direct strikes. Testing concludes that for 200 C steel can be punctured at 2.5 mm thickness, but at 3.5 mm there is no possibility of puncture. It is then clear that there is no possibility of a 3/16″ (4.8 mm) steel shell being punctured, and with a safety margin of at least 1 mm to allow for reduction in thickness due to corrosion.

As it is shown in Fig. 6 [10], when lightning arc attaches to any part of the tank (or structure), a certain amount of erosion of the metal will occur on the metallic surface, causing hot-spots on the back of thicker metal sheets (inner surface becomes

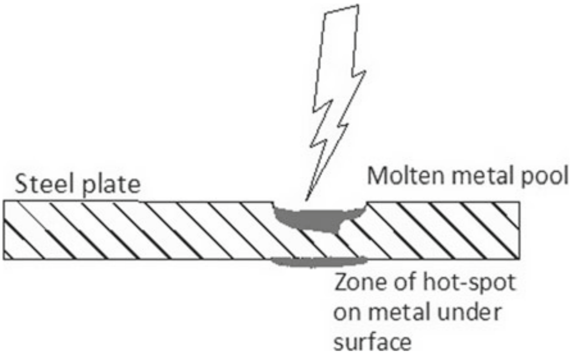


Fig. 6 Effects at the arc attachment point over and under the steel plate surface [10]

quite warm). It is recognized that even if puncture does not occur, the local hot-spot could itself pose an ignition hazard.

All lightning protection measures given above rely on the strict fulfillment of the operational conditions, material thickness and reliable bonding. If some of them are not fulfilled (change in operation conditions, erosion of material, and corrosion in bonding connections), the risk of fire and explosion due to a lightning current can rise to unaccepted levels. For example, the oil industry in some countries establishes a replacement criterion of steel sheets of oil storage tanks when thickness is reduced up to 100 mils (2.54 mm), which represents a good parameter for mechanical integrity of the tank [2]. However, such criterion could not be sufficient for preventing metal puncturing or the development of hotspots. The proposal is upsizing the replacement thickness for better safety, to a value of 3.5 mm, which can be considered as a suitable thickness for lightning protection.

According to Denov and Zoro [11], for areas of very high lightning activity (200 thunderstorm days/year) and long tail lightning, like in Indonesia, 4.8 mm thickness of wall metallic structure of an oil storage tank could become insufficient for lightning self-protection. In such a case, the recommended thickness of steel plate should be greater than 7.1 mm, and if corrosion is of concern, the minimum thickness should be at least 10 mm. Certainly, this lightning protection measure increase considerably the cost of the oil storage tank or vessel.

Properly grounded steel vessels and tanks are essentially self-protecting or maybe considered protected if located in a zone of protection as defined above. Certain definite precautions should be observed, however, in the protection of the vessel and its contents. The following procedures are of value in this respect [1–4]:

1. Flammable liquids and gases should be stored in all metal structures, essentially gastight.
2. Vapor or gas openings to the atmosphere should be protected against the entrance of flame.
3. Positive metallic contact of piping to vessels to eliminate spark gaps at points where there may be an escape or an accumulation of flammable vapors must be assured.

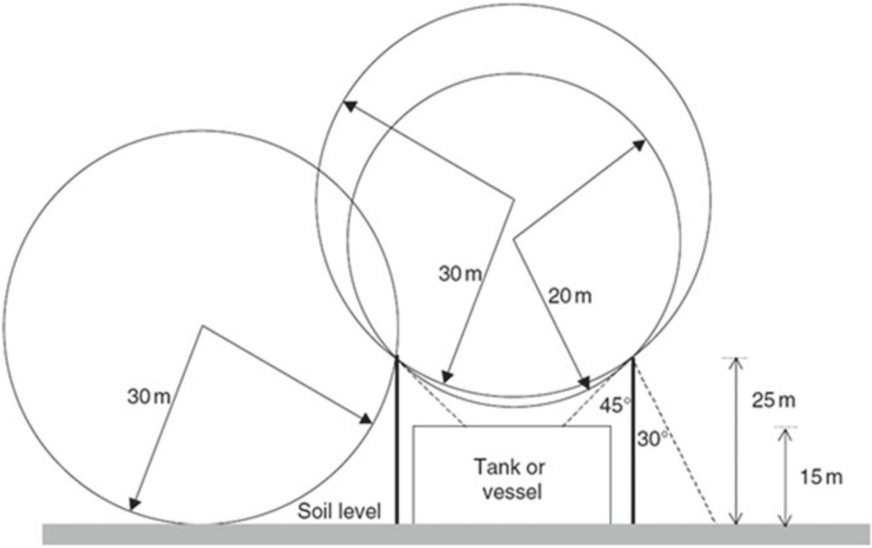


Fig. 7 Direct lightning protection pf storage tanks and vessels, according to [3, 4, 8]

4. In extreme cases, it may be necessary to establish zones of protection through the use of grounded masts and overhead grounded networks of wires or other similar provisions making up a protective cage. In addition, it is recommended that all parts of steel tanks be in metallic contact as provided by riveted and caulked or welded construction and that all fixtures be in intimate electrical contact or bonded. It should be noted that steel tanks with wooden or other nonmetallic roofs have a relatively poor record of safety.

According to [3, 4], the rolling sphere method is suitable for positioning air terminals in all cases, including structures with risk of fire and explosions, and protection zone of levels I and II (20 and 30 m of rolling sphere's radii), are recommended to be used in [4] and [8] respectively, as shown in Fig. 7.

1.3 Power Substations

According to IEEE recommendation [12], there are two methods of direct lightning protection (shielding) of substations: (a) classical empirical methods—fixed angles and empirical curves, and (b) electrogeometrical method. For fixed angle protection, the angle decreases as the height of the air terminal (including ground wires and lightning masts) increases in order to maintain a low failure rate. Using the rolling sphere method, the equivalent angle of protection should be 45° for air terminals up to 15 m height, 30° from 15 to 25 m height and 20° from 25 to 50 m height.

For the electrogeometrical model application, following shielding concepts should be considered:

1. Electrogeometrical model is based on return stroke current.
2. The strike distance is related to the return stroke current.
3. Minimum return stroke current of 2 kA is recommended for voltages below 115 kV.
4. Allowable return stroke current for shielding failure is related to the (a) basic insulation level (BIL) of the bus insulators or the negative polarity impulse critical flashover (CFO), and (b) the surge impedance of the station bus.
5. Decrease the allowable return stroke current by 2 when a direct hit upon an equipment or open point in the high bus conductor are concerned.
6. Reduced BIL equipment is not protected by a design based on return stroke current, therefore it should be protected by surge arresters.
7. Shield spacing becomes quite close at voltages of 69 kV and below.
8. Rolling sphere method is a simplified electrogeometrical model, considering that the striking distance to the ground, a mast or a wire is the same.

1.4 Overhead Lines

Many plants are connected to overhead power lines operating either at utilization voltages or at higher potentials; such a distribution system invites lightning strikes. A high degree of protection for such lines can be achieved by the installation of lightning arresters on the line side of substations fed from overhead lines and at the terminus of an overhead line. Further protection for more extensive overhead systems may be obtained by the use of the overhead ground wire system. This method of shielding live conductors on pole lines has been very successfully employed through the years; its effectiveness, however, depends upon several factors. Ground resistance must be low. The installation must be so designed that the live conductors are not only widely spaced from the ground conductor but, for maximum protection, they must be within a shielded area below the ground wire [1].

According to IEEE recommendation [13], a shielding angle (as shown by Fig. 8) of 45° or less is recommended so that most lightning flashes will terminate on the grounding wire rather than on the phase conductors, being valid for lines less tan 15 m tall with conductor spacing less than 2 m. Taller lines require smaller shielding angles [13]. Figure 8 illustrates pole line shielding.

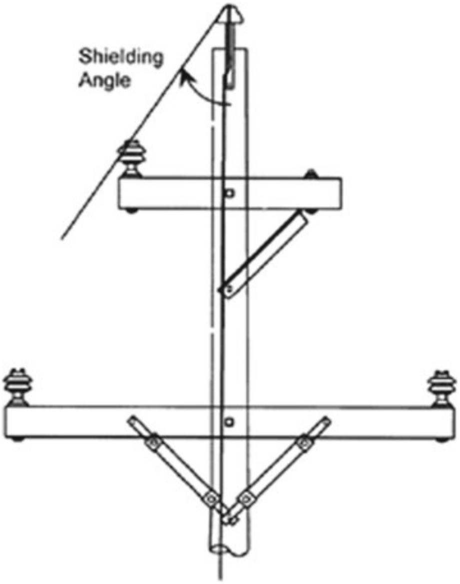


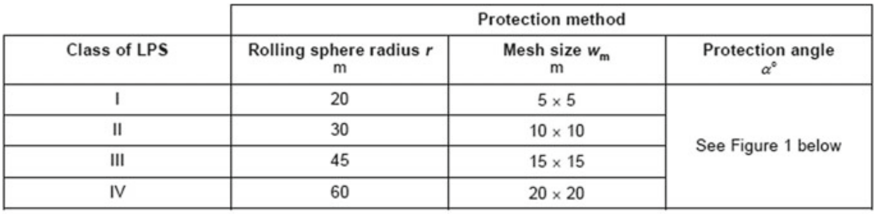
Fig. 8 Direct lightning protection of pole lines. Adpated from [13]

1.5 *Structures and Buildings*

IEC Standard [3] recommend the following protection levels (Fig. 9):

Following recommendations should be implemmented [3]:

1. Acceptable methods to be used in determining the position of the air-termination system include: (a) the protection angle method; (b) the rolling sphere method; (c) the mesh method. The rolling sphere method is suitable in all cases.
2. An isolated external LPS should be considered when the thermal and explosive effects at the point of strike, or on the conductors carrying the lightning current, may cause damage to the structure or to the contents. Typical examples include structures with combustible covering, structures with combustible walls and areas at risk of explosion and fire. An isolated external LPS may also be considered when the susceptibility of the contents warrants the reduction of the radiated electromagnetic field associated with the lightning current pulse in the down-conductor.
3. Natural components made of conductive materials, which will always remain in/on the structure and will not be modified (e.g. interconnected steel-reinforcement, metal framework of the structure, etc.) may be used as parts of an LPS.
4. Air-termination components installed on a structure shall be located at corners, exposed points and edges (especially on the upper level of any facades).
5. The type and location of an LPS should be carefully considered in the initial design of a new sructure, thereby enabling maximum advantage to be taken of the electrically conductive parts of the structure.



Class of LPS	Protection method		
	Rolling sphere radius *r* m	Mesh size w_m m	Protection angle $\alpha°$
I	20	5 × 5	See Figure 1 below
II	30	10 × 10	
III	45	15 × 15	
IV	60	20 × 20	

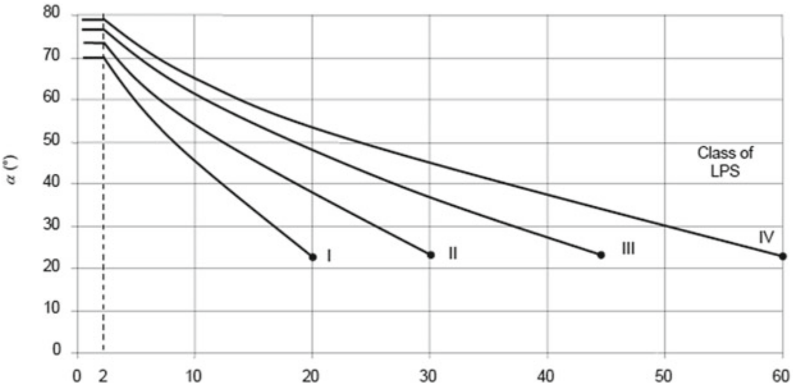


Fig. 9 Class of Lightning protection system according to IEC [3]

6. Regular consultation between LPS designers and installers, architects and builders is essential in order to achieve the best result at minimum cost.

2 Lightning Current to Ground

Generally speaking, metal building of petrochemical plants are inherently self-protected, Fig. 4 [6]. Normally, tall structures and smokestacks are protected with either self-protected scheme or with air terminals bonded to the structure metal (non-isolated protection) and very frequently bonded to down conductors with suitable transversal section according to IEC recommendation [3]. If the down conductor is conventional one (cylindrical stranded copper) the inductance is in the order of 1 µH/m. Figure 10 shows the potential rise of various one-meter long down conductors for a 10 kA 8/20 µs waveshape lightning current impulse. The voltage drop due to lightning current flowing in a conductor is [3, 4, 6]:

$$V = L \cdot \frac{di}{dt} \tag{1}$$

where L is the inductance [µH/m] of the down conductor and di/dt [kA/µs] the rate of rise of lightning current.

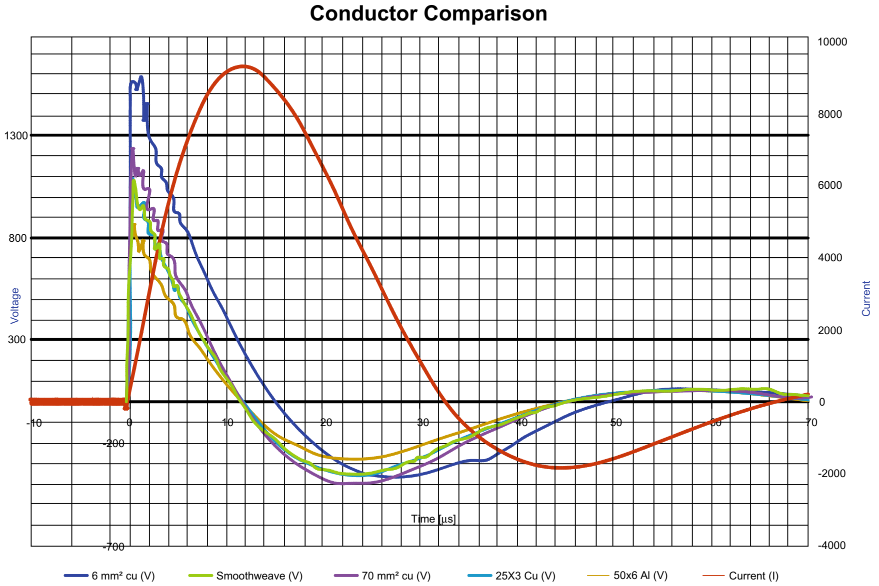


Fig. 10 A 10 kA 8/20 µs impulse applied to various conductors. Adapted from Tompson [6]

The maximum rate of rise is at the start, from zero, of the impulse and here the inductive voltage is the greatest. At the peak of the current curve, di/dt is zero and the voltage due to resistance of the cable is apparent (apart from the 6 mm^2 conductor, it is almost zero). Thus for typical types of downconductor about 1 kV/m/10 kA is expected. So for the plant as shown in Fig. 4, it can be concluded that, since it is all metal, it is self protecting and the best downconductors are the bodies of the tall structures, tanks and vessels themselves [6].

However there must be a voltage rise at the top of any structure that is struck by lightning and therefore any instruments mounted on that structure will rise in potential along with the structure. Unfortunately a potential difference will then exist between the instrument and the I/O of the SCADA or PLC equipment in the control room. Damage to both instrument and I/O is inevitable and no amount of structural lightning protection will solve this problema [6]. This will be discussed in the following Sections.

3 Equipotential Bonding Measures

Equipotential bonding is a very important measure in lightning protection. This measure allows a rapid flow of lightning current to ground and avoid dangerous potential differences over ground and upon the wiring electronic and electrical systems.

3.1 High Metallic Structures

Since most of the structures in refinery and chemical plant units are of steel, a high degree of protection is possible by the simple expedient of grounding the steel framework in several places.

3.2 Oil Storage Tanks or Vessels

IEC Standard [3] establishes that structures like tanks or vessels, should be equipotential bonded to ground once for 20 m diameter, or twice over 20 m. However, the author believes (and normally put in practice) that increasing the number of equipotential bonding to ground, the safety of the tank, vessel or structure is greatly increased. The higher the amount of equipotential bonding conductors to earth, the lesser the lightning current density in the bonding conductors and, consequently, the lesser the rise of potential. Figure 11 shows the concept of bonding to ground of tanks or vessels and Fig. 12 shows de concept of bonding to ground water pipes.

In the case of floating-roof tanks (FRT), the floating-roof shall be effectively bonded to the main tank shell. The design of the seals and shunts and their relative locations needs to be carefully considered so that the risk of any ignition of a possible explosive mixture by incendiary sparking is reduced to the lowest level practicable. On floating roof tanks, there are two natural points of contact between the floating roof and the tank shell, eventhough they do not guarantee a good and permanent contact. (a) when the floating roof reach the lowest level, resting on the base of the tank through the pontoons, see Fig. 3, (b) through the access metallic stairs from the top of the tank to the floating roof by the guide pole, see Fig. 13 [15].

Therefore, additional measures are required. (1) Multiple shunt connections shall be provided between the floating-roof and the tank shell at about 1.5–3.0 m intervals

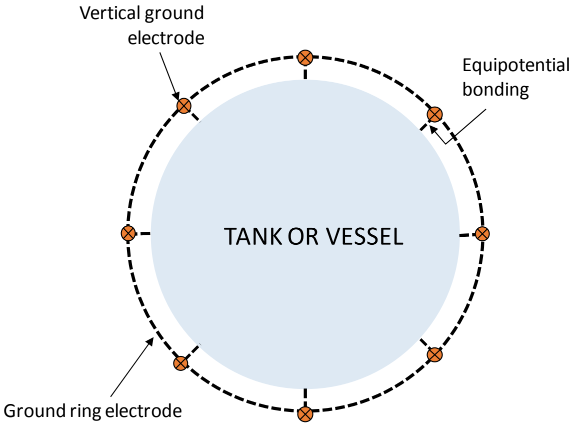


Fig. 11 Bonding to ground connections for tanks or vessels

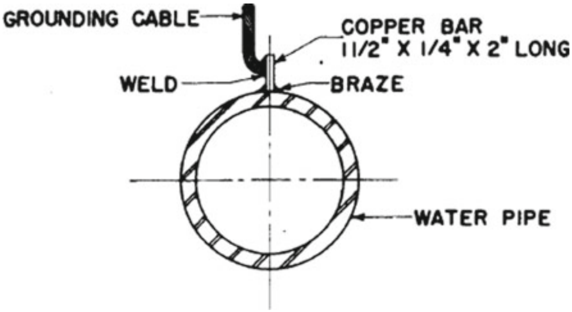


Fig. 12 Water pipe bonding to ground connection. Adpated form Benjamin and Cundelan [1]

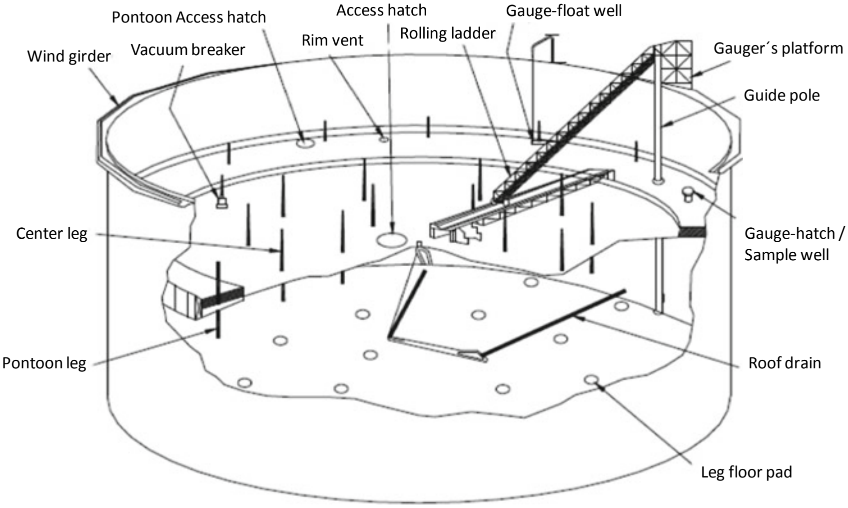


Fig. 13 Two natural points of contact between the floating roof and the tank shell (**a**) when the floating roof reach the lowest level, resting on the base of the tank through the pontoon legs, (**b**) through the access metallic stairs from the top of the tank to the floating roof by the guide pole. Adapted from API 2517 [16]

around the roof periphery. Material selection is decided by product and/or environmental requirements [1, 9], as shown in Fig. 14; (2) Alternative means of providing an adequate conductive connection between the floating roof and tank shell for impulse currents associated with lightning discharges are only allowed if proved by tests and if procedures are utilized to ensure the reliability of the connection [3]. For the last, retractil grounding conductors are able to be used in order to ensure the bonding connection between floating roof tank and the body of the tank [14], as shown in Fig. 15, where the aspect of conductor inductance should be taken into consideration.

Above-ground metal piping network inside a production facility but outside the process units should be bonded to ground every 30 m, or should be connected to

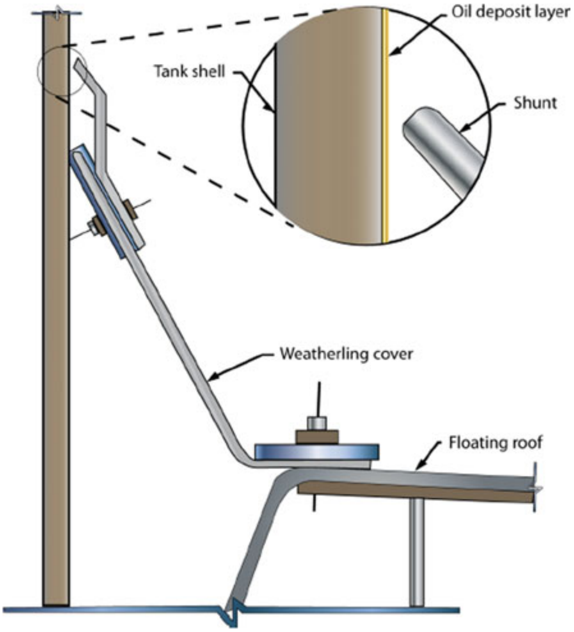


Fig. 14 Shunt connections between the floating-roof and the tank shell. Due to the loss of the tank circumference during the day (metal heating deformation), up to half of the shunt connections to the tank can be lost

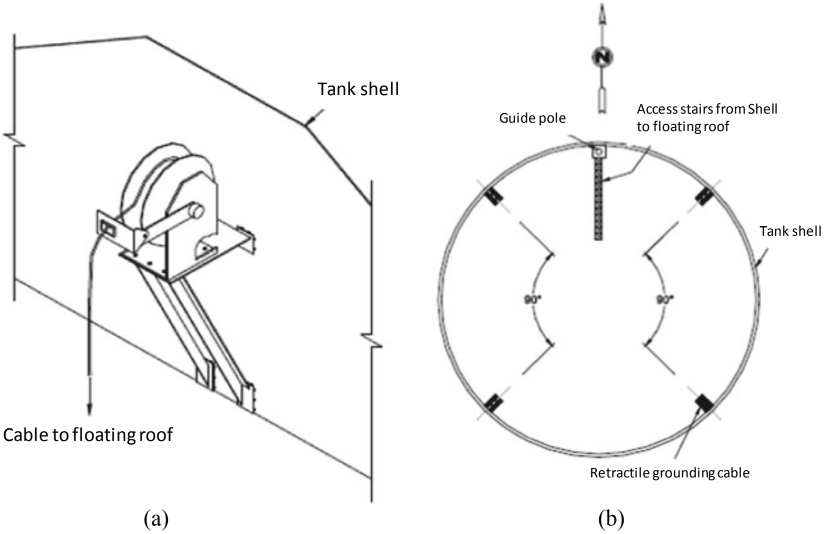


Fig. 15 **a** Retractile grounding cable device located at the top of the tank shell. One end is connected to the tank shell and the other one to the floating roof. **b** Recommended location of Retractile grounding cable devices along the perimeter of the FRT

ground by a surface earth electrode or an earth rod. Isolating supports of the piping should not be considered [3].

3.3 Protection Against Accumulation of Static Charges

Industrial plants such as refineries and chemical plants may have a potentially hazardous condition because of the accumulation of static charges due to a number of causes, among them, the movement of gases and liquids, the spraying of caustic solutions in tanks, acid bubbling, and even certain phases of the processes themselves. Liquids in a tank, if agitated, may accumulate static charges. It has been noted that liquids discharging from a pipe above the surface of the liquid in a storage tank will produce static charges in the liquid. Fortunately, most of the problems presented can now be dealt with. Static caused by the flow of gases or liquids in piping systems is probably carried off harmlessly by the piping itself. This is particularly true in refinery work because of the continuous electric path provided by present day pipe welding procedures. Potentials on piping may also be dissipated through pipe hangers and other supports electrically bonded to grounded structures. On occasion, however, it may be necessary to provide grounding for certain piping. This can usually be best determined after plant operation has begun. Each time that an oil tank is filled, a degree of turbulence exists which probably results in the formation of static charges in the oil and on its surface. Since petroleum is a dielectric, it has the capacity for holding electric charges. Grounding of the shell of the tank and of the piping attached thereto, while important, is not the entire solution since the electric charges are not readily given up by the petroleum product involved. When the potential gradient becomes steep enough an arc over long the surface of the oil to the tank shell may occur [1].

4 Equipment and Electrical System Bonding to Ground

Connections between fixed equipment to be grounded and the grounding system are usually made with stranded copper conductors. Sizes may vary as specified by the NEC [17], ranging from no. 8 to 3/0 American wire gauge depending upon the size of the service conductor. Exact grounding conductor size may also be determined by the maximum available fault current and the circuit protective device interrupting time. IEC Standard [18] recommends the cross-sectional area of protective bonding conductors for connection to the main earthing terminal need not exceed 25 mm^2 Cu or an equivalent cross-sectional area for other materials. The actual grounding connections between equipment and grounding electrode usually take the form of a loop to which the individual equipment may be joined by short cable connections. The loop is then connected at one or more points to grounding system. This main grounding loop or bus which will serve motors driving process equipment, lighting panels, motor control, and other electric equipment should be buried at least 18 inches below finished grade. All below grade connections to the ground bus should be made by copper brazing, fusion welding, or equivalent process capable of sustaining reasonable temperature. Bolted connections should be avoided because of the danger of high-resistance joints due to corrosión [1].

Connections to individual pieces of electric equipment take a variety of forms. Grounding of motors is best accomplished by drilling and tapping the motor frame after which the grounding conductor, equipped with a copper terminal, may be bolted directly to the frame. Satisfactory protection from physical damage may be afforded the grounding conductor, if a suitably formed length of 1/2-inch conduit has been cast in the pump foundation block. Figure 16 illustrates this clearly. Similar grounding connections should be provided at lighting panels, motor starters, switchboard frames, switchgear ground busses, steel instrument control boards, and all other metallic enclosures and supports of electric apparatus. Some equipment is supplied with grounding lugs by the manufacturer, others must be tapped—as are the motors—to receive a grounding connection. A point sometimes overlooked by the designer is the case of conduits terminating just above grade in motor control centers and cubicle-type switchgear. Since such conduits are not connected electrically to the equipment, they should be strapped to the enclosure or to the equipment ground bus if one has been provided. Grounding bushings are useful for this purpose [1].

Petrochemical plants are increasingly faced with the need to upgrade their control centers to support the installation of more advanced control systems and to better protect operations personnel in the event of catastrophe, in a hope of improving plant-wide communications, increasing operating efficiency, and reducing construction costs.

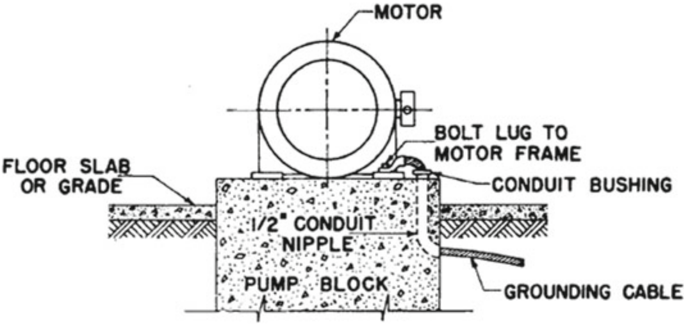


Fig. 16 Motor bonding to ground connection. Adapted form Benjamin and Cundelan [1]

5 Local and General Grounding Arrangements

5.1 *Local Ground of Tall Structures*

Since most of the structures in refinery and chemical plant units are of steel, a high degree of protection is possible by the simple expedient of grounding the steel framework in several places to the local grounding grid.

5.2 *Local Ground of Oil Storage Tanks*

Oil storage tanks and vessels should have a grounding electrode type B, according to IEC Standard [3], as shown in Fig. 17. Several aspects should be considered:

1. Keep the buried ground ring electrode electrically continuos for the entire path around the tank. Use welded connection to join final extremes of the ring.
2. Enhance the local ground ring electrode type B by three (at least 12 m long) buried cable as shown in Fig. 17 in order to reduce dramatically the lightning-generated rise of potential. The place of the installation should be at the points where the lightning masts are located or where the connection point to the ground ring from the tank is made.
3. Enhance the local ground ring electrode type B by vertical ground electrodes located every 6 m (or double the length of the vertical ground electrode). The

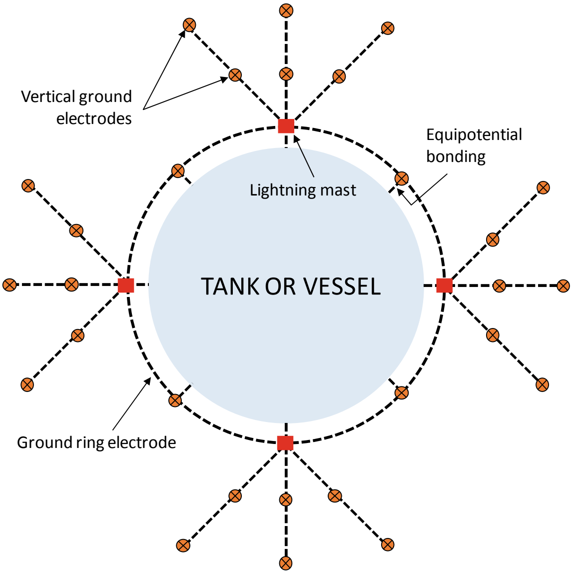


Fig. 17 Example of buried grounding ring type B for oil storage tanks, according to IEC standard [3] and additional protective arrangements. *Note* multi-path arrangements for the points where the lightning current flows to ground (lightning masts)

length of the ground vertical electrode will depend on the trend and value resistivity of the soil. Use welded connections to join the vertical electrods with the ground ring electrode.
4. It is strongly recommended to apply welded connections to the tank.

5.3 *Local Ground of Power Substations*

A satisfactory grounding system for substations may be achieved by installing a ground cable or ground bus underground, surrounding the substation area and connected at intervals to ground rods. A connection to metallic underground water piping is desirable. In larger substations, a grid may be formed by installing several underground cables across the substation area to connect opposite sides of the ground bus. All electric equipment installed in the substation should be connected to the ground bus. Substation fences should be similarly connected to the bus at frequent intervals and structural steel substation structures should also be grounded in at least two locations [1].

The objective of substation grounding as described above is to ensure that all parts of structures and equipment enclosures be at ground potential. In the event of a breakdown in insulation, flashover, or accidental contact with high voltage, the potential difference between the equipment and any point on the ground should not be great enough to constitute a hazard to personnel [1].

IEEE recommendation [19] may be used to design the grounding grid of the substation, considering the following aspects:

1. Design the grounding grid in such a way that the pieces of equipment and structures may connect to ground with suitable cables in a path as short as possible.
2. Calculate fault current for different levels of high voltages and identify the maximum fault current that will circulate in the grounding grid conductors in order to calculate the cross section of the buried conductor, taking into account the material of the conductor.
3. Calculate the ground resistance of the grounding grid by using soil resistivity data obtained by measurements (avoid using generic tables).
4. Calculate the rise of potential upon the soil considering the portion of the fault current that will circulate in the ground when the source that feed the fault is located at a remote place of the substation (take into account the current division from metallics return path).
5. Estimate the step and touch voltages according to the estimated allowable voltages, in order to guarantee the protection of personnel (staff).
6. In equipment of big size, it is strongly recommended to use more than one connection to ground, considering even to increase the cross section of the bonding cable to ground.
7. It is strongly recommended for each equipment to install vertical ground electrodes at the point of the bonding with the grounding grid, in order to guarantee

the connection to ground reach more stable moisture soil conditions. The length of the vertical ground electrodes will depend of the layers resistivity value of the soil.

8. Optimize the grounding grid by using suitable size of mesh and vertical ground electrodes upon the periphery of the grid.

5.4 Local Ground of Distribution Lines

The connection to ground of distribution lines obeys to the following two aspects:

1. Connect to ground the overhead grounding wire used to shield the line against direct ligthning stroke to live overhead conductors. Ii is recommended to ground the overhead grounding wire every pole of the line.
2. Connect to ground equipment and surge arrestes of equipment located in the line.

Both require low values of ground resistance, up to 25 Ω (when measured at low frequency). The arrangement of the grounding grid or electrode will depend of the soil resistivity.

5.5 Local Ground of Structures and Buildings

Eventough IEC recommendation [3] allows to use type A for grounding of structures and buildings, the author strongly recommend to apply arrangement type B (ground ring electrode), as shown in Fig. 18, for buildings and structures in petrochemical plants. Aspects mentioned in section 5.2 apply, with the additional considerations:

1. Ground resistance of the arrangement type B should be up to 10 Ω.
2. The ground ring electrode should preferably be buried at a depth of at least 0.5 m and at a distance of about 1 m away from the external walls, and be interconnected to concrete foundations of the building.
3. Ground electrodes shall be installed in such a way as to allow inspection during construction.
4. Interconnected reinforcing steel in concrete foundations, or other suitable underground metal structures, should preferably be used as a ground electrode (avoid using pre-stressed concrete). When the metallic reinforcement in concrete is used as a ground electrode, special care shall be exercised at the interconnections to prevent mechanical splitting of the concrete.

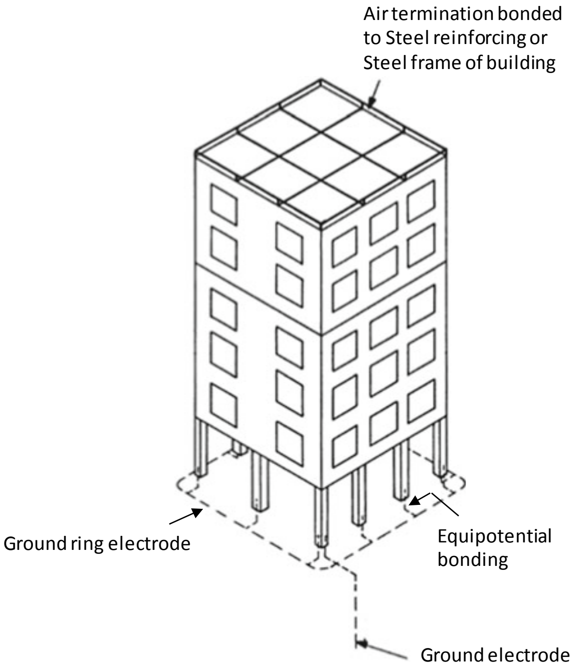


Fig. 18 Example of grounding arrangement type B for buildings, according to IEC recommendation [3]. Adapted from IEC 60364-5-54 [18]

5.6 *Local Ground of Information Technology Systems*

Electrical/electronic equipment damage from lightning may be placed into three major categories [20]:

1. Improper or insufficient grounding, which will result in the equipment being stressed and/or damaged (potential difference) from nearby equipment/objects.
2. Lack of protection from ground potential rise GPR, which will result in the equipment being stressed from its connection to remote earth at some distant location through communication wire-lines or power supply wiring and/or from intrabuilding GPR arising from the voltage drop between power and telecommunication ground references.
3. Lack of protection from lightning transients, namely surge protective devices SPDs. This will be discussed on next section.

Sites without telecommunication towers may experience Lightning Ground Potential Rise LGPR effects as much, if not more, than sites with towers as they are less likely to have extensive grounding infrastructure. Sites at most risk are areas with a higher occurrence of lightning and high soil resistivity.

IEEE recommendation [20] gives very useful measures to define the grounding arrangements. Following considerations should be taken into account [3, 20].

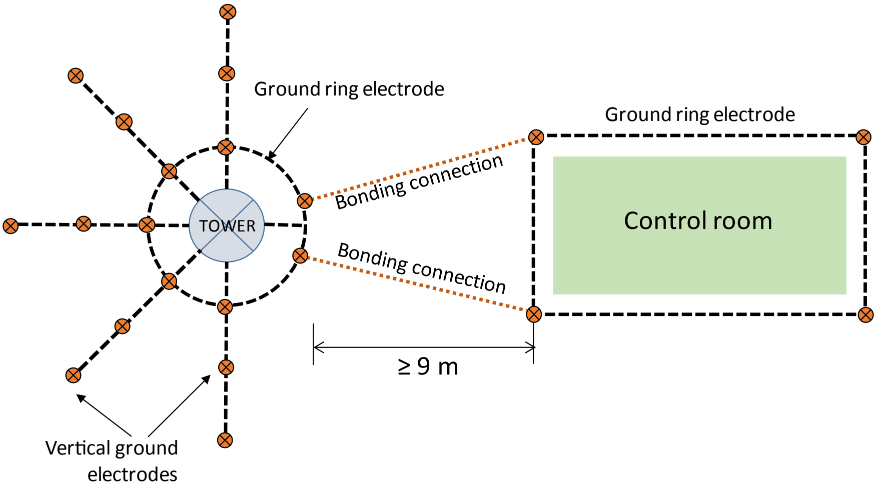


Fig. 19 Grounding arrangement recommended for telecommunication tower and control room

1. Both telecommunication tower and control room should have arrangement type B, according to IEC recommendation [3].
2. Enhance the local ground ring electrode type B by multi-path (at least 12 m long) buried cable in tower location as shown in Fig. 19 in order to reduce dramatically the lightning-generated rise of potential.
3. Enhance the local ground ring electrode type B by vertical ground electrodes located every 6 m (or double the length of the vertical ground electrode). The length of the ground vertical electrode will depend on the trend and value resistivity of the soil. Use welded connections to join the vertical electrods with the ground ring electrode.
4. Hardening against lightning ground potential rise (GPR) damage requires specially designed tower radial counterpoise grounding system with a grounding resistance not exceeding two (2) ohms. If the objective is not economically achievable, provide the lowest possible ground resistance value, using radial counterpoises, to minimize the grounding impedance (and thus GPR) as much as posible.
5. Hardening against lightning ground potential rise (GPR) damage requires an associated tower equipment building grounding system with a grounding resistance not exceeding two (2) ohms. If the objective is not economically achievable, provide the lowest possible ground resistance value, using radial counterpoises, to minimize the grounding impedance (and thus GPR) as much as possible
6. Both grounding arrangements should be joined together.
7. The total overall site ground resistance (tower and building) should not exceed one (1) ohm. This may require significant real estate space if the site soil resistivity is greater than 500 Ωm at the anticipated grounding electrode depth.

If the objective is not economically achievable, provide the lowest possible ground resistance value, using radial counterpoises, to minimize the grounding resistance (and thus GPR) as much as posible (see Fig. 19).

8. The recommended minimum distance between the equipment buildings associated with nearby antena towers is 9 m in order to minimize the effects of the electromagnetic field associated with lightning and to reduce the risk of damage to equipment circuits. In general, electromagnetic field strength drops off as the square of the distance. This is one of those rare exceptions in which a lengthy bond is an advantage in supporting a robust grounding system to lightning.

5.7 General Grounding Grid

General grounding grid aims to low grounding resistance, reduce hazard voltage differences and join local grounding systems (like lightning protection, fault current protection and signal reference subsystems to ground) [8]. There are two ways of implementing a general grounding grid: (a) Make a grounding grid meshed to interconnect local grounding grids or (b) Make a intermeshed local ground systems, as shown in Fig. 20.

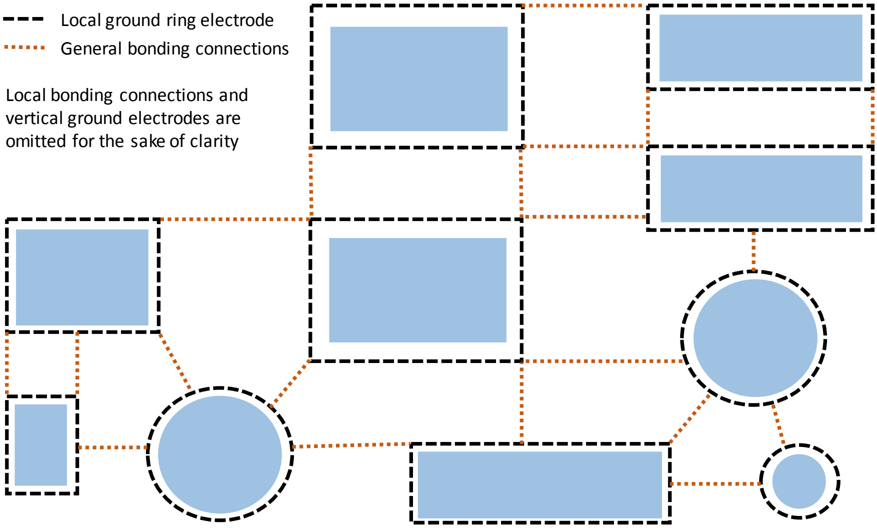


Fig. 20 Example on intermeshed local ground systems

6 Surge Protection Systems

6.1 Low Voltage Distribution System

The installation of a lightning and surge protection system for electrical installations represents the latest stage of the art and is an indispensable infrastructural condition for the trouble-free operation of complex electrical and electronic systems without consequential of damage [21]. The requirements on Surge Protective Device (SPD) are defined in IEC Standards as part of the lightning protection zone (LPZ) concept [22] and protection for power supply systems [23], as shown in Fig. 21.

According to IEC Standard [15], a low voltage distribution system in its entirety, from the power source to the las piece of equipment, is typically characterized by:

1. Earthing conditions of the power source (e.g. low voltage side of the distribution transformer) and,
2. Earthing conditions of the bodies of the equipment in the electrical consumer´s installation.

Due to the above earthing mentioned conditions (source-equipment), there are three basic types of distribution systems: **TN** (Terra-Neutral) system, **TT** (Terra-Terra) system and **IT** (Isolated-Terra) system. Depending on the type of the distribution system, the protective devices which can be installed in the various systems are:

TN system: (a) overcurrent protective device, (b) residual current protective device.

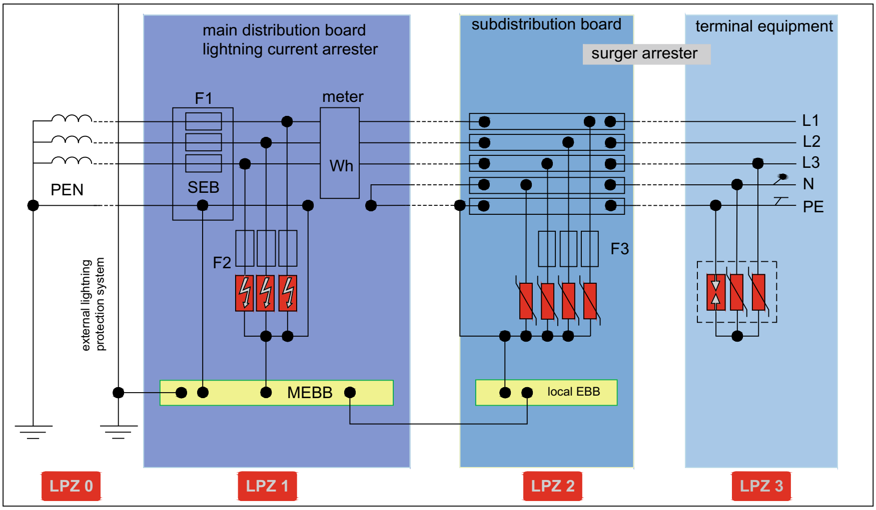


Fig. 21 Schematic diagram of use of arresters in power supply systems. Adapted from DEHN + SOHNE [21]

TT system: (a) overcurrent protective device, (b) residual current protective device, (c) fault-voltage-operated protective device (in special cases).

IT system: (a) overcurrent protective device, (b) residual current protective device, (c) insolation monitoring device.

According to IEC Standard [24], the designation class (types) of the SPD are:

Class (Type) 1. Lightning current arrester/combined arrester.

Class (Type) 2. Surge arrester for distribution boards, sub-distribution boards, fixed installations.

Class (Type) 3. Surge arrester for socket outlets/terminal devices.

The following considerations should be observed when using SPDs [21, 25]:

1. Ensure the energy coordination of the individual SPDs and make sure it takes into account all possible interferences such a switching overvoltages, partial lightning currents, etc.
2. SPD needs to withstand TOV (Temporary Overvoltage) related to power frequency surges.
3. For SPDs used in TN systems, both type 1 and 2 SPD should be used upstream of the residual current protective device in order to be effective for the protection against electric shock under fault conditions. Type 3 SPDs are installed downstream residual current protective device RCD.
4. For SPDs used in TT systems, both type 1 and 2 SPD must always be installed upstream of the RCD and must be arranged in such a way that the conditions for the use of overcurrent protective devices for the protection against electric shock under fault conditions are met. As in the case with TN system, type 3 SPDs are installed downstream residual current device RCD.
5. For SPDs used in IT systems, it is also advisable to install both type 1 and 2 SPD upstream of the RCD. Unlike TN and TT systems, the first fault in an IT system only creates an alarm. However, the voltage of the intact conductors to earth corresponds to the voltage between the phase conductors. Therefore, this stage must be taken into account when choosing the SPD with respect to their maximum continuous operating voltage.
6. Be aware that installation of SPDs in IT systems will depend on the condition of the incorporation or not of the neutral conductor in the distribution system.
7. Related to connecting cable lengths of SPDs, an optimum protective effect is achieved if the impulse voltage level at the installation to be protected is equal to the voltage protection level of the SPD. To accomplish this, the inductance of the connecting cable must keep as low as possible, and thus its length. IEC Standard [23] recommends that total cable length of SPD in cable branches should not exceed 0.5 m, and a maximum cable length of 1 m.

6.2 Information Technology Systems

Unlike power supply systems, the types of signals to be transmitted in automation and measuring and control systems have different parameter conditions, like [21]:

1. Voltage (e.g. 0–10 V).
2. Current (e.g. 0–20 mA, 4–20 mA).
3. Type of signal transmission (balanced, unbalanced).
4. Frequency (DC, LF, HF).
5. Type of signal (analog, digital).

The challenge in this case is to achieve that the useful signal must not be impermissibly influenced by lightning current and surge arresters in measuring and control systems. Therefore, the selection of arresters in order to protect downstream terminal devices (reducing also the risk of cable damage) depends, among other things, on the following criteria:

a. Lightning protection zones of the place of installation, if any.
b. Energies to be discharged.
c. Arrangement of the protective devices.
d. Immunity of the terminal device.
e. Differential mode and/or common mode protection.
f. System requirements, e.g. transmission parameters.
g. Compliance with product or application-specific standards, if required.
h. Adaptation of environmental/installation conditions.

The standard surge protective devices (SPD) in the telecommunications industry, for the termination of communication wire-line services is the gas discharge tube (GDT). GDTs are also called gas tubes. GDTs can be found on virtually every telephone pair terminated in homes, buildings, and similar locations. GDTs are designed to shunt most current to ground. If the magnitude shunted does not exceed a certain threshold the SPD will help protect equipment, and personnel, from harm [20].

Most shunting devices, however, do not fully protect network electronic equipment from a GPR or "outgoing current," whether induced from lightning or from a faulted power line. When shunting devices are connected to an elevated ground (outgoing current) during a GPR event, they merely offer an additional current path off the site to remote earth (the other end) [20].

When SPDs (GDTs, MOVs, ABDs, SCRs, SADs, SASs, etc.) are used as ground shunting devices, they will not protect equipment from GPR. These devices merely offer an additional path to remote earth through the communication pairs for any and all outgoing currents. When there is a GPR event the SPD provides a connection of the communication path in the reverse direction from which they were intended to operate and increases the possibility of equipment damage to telephone and power installations. The most susceptible locations are those where the equipment is located near, or under, towers and/or are located at a higher altitude than the surrounding área [20]. That's why the ground resistance should be kept as low as posible to protect electronic equipment from damage insulation.

Effective protection of sensitive equipment with SPD shunting devices is complex. A well-designed installation requires coordination of the protection for low-voltage power feeds (ac and dc) with the protection for telecommunications facilities in order to minimize the effect of intrabuilding GPR. The use of secondary SPD is recommended to supplement the primary SPD [26]. Surge resistibility and impedance of the terminal equipment must be compatible with the selected primary SPD. Even with a well-designed installation, part of the lightning current will reach the equipment and, in some cases, can affect service quality and/or cause equipment damage [20].

References

1. Benjamin EC, Cundelan JV (1955) Grounding, bonding, and lightning protection. Electr Eng 400–403
2. Galván DA, Gómez C (2013) Protection of oil storage tanks against direct lightning strikes: self protection scheme or standalone LPS? In: International symposium on lightning protection (XII SIPDA), Belo Horizonte, Brazil, 7–11 Oct 2013
3. IEC 62305-3 (2010) Protection against lightning—part 3: physical damage to structures and life hazards, 2010 edn
4. NMX-J-549-ANCE-2005 (2005) Protection against lightning—especification, materials and measuring systems. Mexican Standard (in Spanish)
5. Welker AJ (1998) Lightning—its effects and some simple safeguards in regards to oilfield operations. In: Proceeding of annual Southwestern petroleum short course, pp 329–346
6. Tompson P, Lightning protection of industrial plants, earthing, lightning & surge protection forum—IDC Technologies
7. NFPA 780 (2018) Standard for the installation of lightning protection systems, 2018 edn
8. MIL-HDBK 419A (1982) Grounding, bonding and shielding for electronic equipments and facilities
9. API Recommended Practice (2003) Protection against ignitions arising out of static, lightning and stray currents. American Petroleum Institute
10. API/EI Research Report (2009) Verification of lightning protection requirements for above ground hydrocarbon storage tanks, 1st edn. Energy Institute, London
11. Denov B, Zoro R (Nov 2017) Lightning protection system for oil and gas installation case on cilacap area at Central Java, Indonesia. In: Proceedings of the 2017 6th international conference on electrical engineering and informatics: sustainable society through digital innovation, ICEEI 2017, pp 1–7
12. IEEE STD 998-1996 (R2002) Guide for direct lightning stroke shielding of substations
13. IEEE STD 1410 (2010) Guide for improving lightning performance of electric power overhead distribution lines
14. Galván A (2006) Retractile grounding cable used for floating roof tanks: four-year experience. In: 28th international conference on lightning protection, Sep 2006, Kanazawa, Japan
15. IEC 60364-4-41 (2005) Low voltage power installations. Part 4-41: protection for safety. Protection against electric shock
16. API 2517 (1989) Evaporative loss from external floating roof tanks, 3rd edn
17. National Electrical Code NEC 2018
18. IEC 60364-5-54 (2011) Low voltage electrical installations. Part 5-54: selection and erection of electrical equipment. Arrangements and protective conductors
19. IEEE 80 (2000) Safety in AC substation grounding
20. IEEE 1692 (2011) IEEE guide for the protection of communication installations from lightning effects
21. DEHN + SOHNE (2014) Lightning protection guide, 3rd edn
22. IEC 62305-4 (2010) Protection against lightning. Part 4: electrical and electronic systems withing structures

23. IEC 60364-5-53 (2019) Low voltage electrical installations. Part 5-53. Selection and erection of electrical equipment. Devices for protection for safety, isolation, switching, control and monitoring
24. IEC 61643-11 (2011) Low voltage surge protective devices. Part 11: surge protective devices connected to low-voltage power systems. Requirements and test methods
25. Lightning protection book (2010) In: Cooray V (ed) Chap 17. The Institution of Engineering and Technology IET, ISBN 978-0-86341-744-3 (hardback)
26. ITU-T K.11. Protection against interference. Principles of protection against overvoltages and overcurrents