Lightning Protection of Aircraft, Power Systems and Houses Containing IT Network Electronics

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***Abstract*—Over the past decade, there has been an increasing interest in lightning and lightning protection for several reasons, including the proliferation of microelectronic equipment and IT systems in mission-critical systems as well as in everyday use in banks to homes. Lightning strikes to power lines produce large fast transient voltage and current surges which trickle down to IT systems, military command and control systems as well as to several other microelectronic equipment and control systems. Moreover, aircraft are struck by lightning when it is parked on ground, landing and taking off or in military operations where the aircraft has to keep close to the ground even when the atmosphere is electrified by thunderclouds. In this paper, we explore the protection of electronic equipment, structures and in-house systems from lightning. The paper will also explore lightning related Electrostatic Discharge (ESD) threat to aerospace vehicles and microelectronic systems. This is especially so with the increased use of non-metallic, composite material for the aircraft body. Moreover, the paper will report on the important lightning techniques used in the protection of electric power systems and houses.**

***Index Terms*—Airborne Lightning Protection; Building and Systems Protection; Lightning Protection; Power Network Protection**

I. INTRODUCTION

There are significant changes observed on earth in lightning activity intensity and damage or deaths caused possibly related to climate change. Unusual phenomena have been recently observed which includes a lightning flash in the USA which stretched to over 350 km (say from Kuching to Bintulu), and in 2016 about 300 reindeer in Norway were killed by a single lightning strike to ground. Severe thunderstorms may soon become more common if the temperature signature of the earth surface with climate change continuous as at present. Whereas a single lightning phenomena was expected to last only for one second, it has been recently observed that a single lightning event may last as long as seven seconds, packing in immense amount of energy and repeated strikes at one location or to one object. The energy and intensity of lightning may continue to increase causing damage and electronic rust, as well as increasing threat to human life. Figure 1 shows a lightning strike to a commercial aircraft taking off from the Tokyo airport. One part of the lightning channel is seen to originate from the radome of the aircraft and move up towards the thundercloud. With the branches of the lightning segment pointing upward, the indication is that the aircraft imitated the origin of the lightning flash due to large accumulation of electric charges at the radome resulting in an electric field greater than the breakdown electric field for air. Moreover, the second portion of the lightning channel from the fin of the aircraft down towards the ground has branches pointing down\wards. This indicates that the second part of the lightning flash also originated from the aircraft, specifically the aircraft tail, and moved towards the ground. When connections with the thundercloud above the aircraft and the ground below the aircraft are made, then the high current (e.g. 200000 Amperes [1], with rise times of the order of one to 5 microsecond [2]) return stroke that emanates intense light, is initiated. The aircraft structure, as well as the internal power, electronic, control, navigation and information technology systems and equipment need to be well protected from adverse effects of aircraft-lightning electrodynamics. Figure 2 shows a lightning strike to an overhead power line. The multiple lightning channels from the point at which the strike is made indicates that there is not only one flash, but following that are subsequent strokes to the same point on the power line, imitating multiple number of destructive high voltage transient pulses that will travel along the line in both directions, that is, towards the power generating station and towards the power substation at which the transmission voltage is stepped down to lower voltages for power distribution.

In Figure 3 is shown lightning flashes, probably from the same thundercloud, to three tall buildings; lightning protection of the buildings, its surrounding environment as well as the electrical and information technology (IT) equipment inside the buildings need to be protected from the lightning currents and voltage impulses and radiated electromagnetic pulses produced by the lightning flash. In Figure 4 is shown an unusually long lightning flash stretching across the Oklahoma terrain to a distance of 350 km. It is probably a lightning flash between two large thunderclouds. It is expected that unusually intense lightning flashes, as well as long flashes that may last for several seconds (instead of the conventional one-second flash) will increase with climate change, especially the warming up of the earth’s surface. Much research and lightning strike parameter prediction for severe lightning flashes are urgent needs for the protection and preservation of electrical, power, telecommunication and emergency electronic systems (e.g. medical surgery and intense care unit electronic/computer systems) of the future.

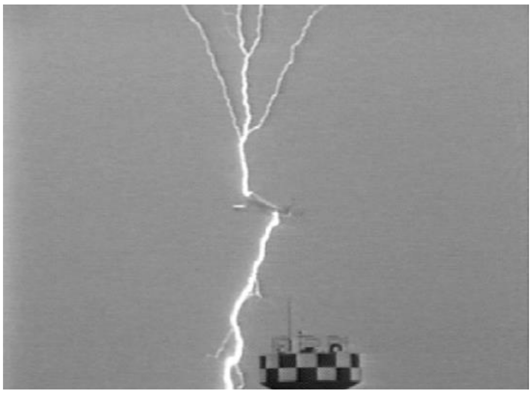


Figure 1: Lightning strike to a commercial aircraft taking off at the Tokyo airport [1]

Figure 2: Lightning flash to an overhead power line of a high voltage power transmission grid [3]

Figure 3: Simultaneous lightning strikes to three tall buildings in Chicago [4]

Figure 4: The longest lightning flash observed to date: 350 km long cloud to cloud flash [5]

The microphysical and thermodynamics nonlinear processes of the atmospheric disturbances and anthropogenic enhancements of heat emission play a crucial role in the cloud to ground electrification [6]-[14]. As articulated in the IEC 62305-1 article on International Standard on Protection Against Lightning [15], there are no devices or methods capable of modifying the natural weather phenomena to the extent that they can prevent lightning discharges. Lightning flashes are hazardous to people, to the structures (buildings, towers, aircrafts, etc.) and their contents and installations [15]. This is the overarching reason why protection measures in aircraft, structures and systems become vital against both direct and indirect effects of lightning. The need for protection, the economic benefits of installing protection measures, and the selection of adequate protection measures should be determined in terms of risk management [15].

Lightning interaction with structures is considered as direct effects and indirect effects. The direct effects of lightning stroke comprise high return currents. The current peak magnitudes are of the orders of several tens of kiloamperes. A value of 200kA [16] and up to 500 kA have been reported [2]. The four specific effects of lightning current due to direct effects considered to be of high severity in producing damages are [17], [18]: (1) the peak current which is the high current pulse flowing through a conducting surface is responsible of voltage induced on the surface of magnitude ($v = iR$), where i is the current pulse, and R is the resistance of the surface, (2) the maximum rate of change of current. This referred to the current steepness which gives rise to an electromagnetically induced voltage ($v = M\frac{di}{dt}$), where M is the mutual inductance of the loop of conductors, (3) the integral of the current over time ($Q = \int idt$ which is the electric charge transferred) that is responsible for the mechanical force and the heating effects, and (4) the integral of the current squared over time ($\frac{W}{R} = \int i^2 dt$), where W is the energy dissipated into a 1 Ω resistor (R) which is referred to as the specific energy or the action integral. R is temperature-dependent D.C resistance of the conductor and R/W is the specific energy which is responsible for the melting effects.

The indirect effects of lightning threats are due to the radio frequency interferences and lightning electromagnetic pulses (LEMPs). The LEMPs can induced disruptive voltages ($v = Ldi/dt$) and currents ($i = Cdv/dt$) that can impinge on an electrical and electronics systems through resistive and or electromagnetic couplings [18]. The advent of digital electronic technology in electrical/electronic systems and evolution of Internet of Things (IoT) through radio frequency identification devices, barcodes, smartphones, and the convergence of smart technologies in smart homes, smart industries, smart cities, smart environment and smart ecosystem in smart people with microchips implanted forming the smart planet by integrating modern communication and information technologies will heighten the requirements for a professional approach to lightning protection. LEMPs threats can have serious damaging effects as highlighted in [17]. The electrical and electronics systems are susceptible to LEMPs at frequencies between 1 and 500 MHz and produce internal field strengths of 5 to 200 V/m or greater [19]. Internal field strengths greater than 200 V/m of pulse widths less than 10 µs can result in lightning-induced voltages and currents ranging from several tens to thousands of voltages say from 50 V and 20 A to over 3000 V and 5000 A [19]. Electrical/electronic system susceptibility to LEMPs has been suspect as the cause of "nuisance disconnects," "hardovers," and "upsets" [20] in electronic systems. Generally, such malfunctions in digital electronics systems occur at lower levels of EM field strength than that which could cause component failures if no proper shielding or protection system is utilized. The discussion in the next sections will look at lightning effects on aircraft, electric power systems, and infrastructures and electronics systems.

II. EFFECTS OF LIGHTNING ON AIRCRAFT

Both commercial and military aircraft in flight are subject to many atmospheric disturbances for which lightning is no exception. As commercial aircraft are scheduled to fly fixed routes, it is often difficult to avoid thunderstorm formation along their paths. It is statistically reported in [21], [22] that on average, a commercial aircraft is struck by lightning once every year. The flight path is an influential factor that increases the probability of lightning strike rate on an aircraft. That is, a lightning strike to an aircraft is a function of both the aircraft flight path and altitude, and the thunderstorm altitudes [23]. Aircraft at a low altitude either in ascending or descending phases have an increased probability of being struck by lightning [23].

As the aerospace industry expands into both manned and unmanned commercial and military vehicles, preventing electric field enhanced aircraft initiated lightning strikes and protections against serious damage and accidents become a major concern to the aerospace industry [24]-[28].For an aircraft to be airworthy, the aircraft manufacturers need to provide the overall assurance of adequate lightning protections [24]-[29]. This process requires certification plans for tests done on components or systems of components such as the airframes, power and electrical wirings and components, fuel systems and components, avionics and communication and navigation systems such as the radar, and other control and automation components. The protection of aircraft against lightning strike can be summarized in the following steps as highlighted in [27] (i) determine lightning attachment zone; (ii) determine systems and components which are likely to be damaged by lightning; (iii) set lightning protection standards for systems and components; and (iv) confirm the rationality of the protection design by the use of test.

Using the new diploe charge simulator reported in [32], in the electric charges and electric fields may be calculated when the aircraft at a given point in space close to (within 50 km) the thundercloud. With a negatively charged cloud center, the electric charges obtained for the dipole charge on the top of the aircraft is positive and that on the underbelly of the aircraft is negative [29], [32]. For the A380 aircraft, for instance, at an altitude of 800 m and 200 m below the thundercloud charge center, the following parts of the aircraft experience electric fields that have potential to cause electrostatic discharge or electronic circuit flashovers: the radome, the wing tip, the wing surface and the stabilizer tip.

Figure 5 shows future aircraft body materials, where metal body surfaces are more and more replaced by composite materials, and fiberglass. Determining the lightning strike effects zones using prestrike electric field stress, become more critical to these non-electric shield materials. First return stroke current attachment zones are usually the extremities of the aircraft which are the radome, the wing tips, and the stabilizer tips. These are the areas of the aircraft surfaces where a first return stroke is likely during lightning channel attachment with a low expectation of flash hang on. Current at this zone of attachments may exceed 200 kA, [24], [32]. In Zone 2 is the aircraft surface where subsequent return stroke is likely to be swept with a low expectation of flash hang on. The current in Zone 2 can exceed 100 kA [24]. Zone 3 is made up of those surfaces not in Zones 1 and 2, where any attachment of the lightning channel is unlikely, and those portions of the aircraft that lie beneath or between the other zones and/or conduct a substantial amount of electrical current between direct or swept stroke attachment points [24]. In Figure 5 is shown materials used in modern aircraft with metal used along the extremities to dissipate the high return stroke currents induced on the surface into the atmosphere.

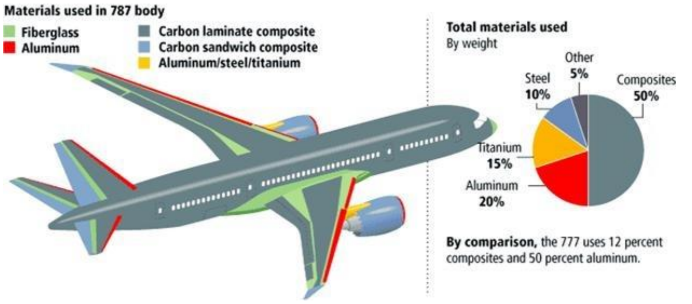
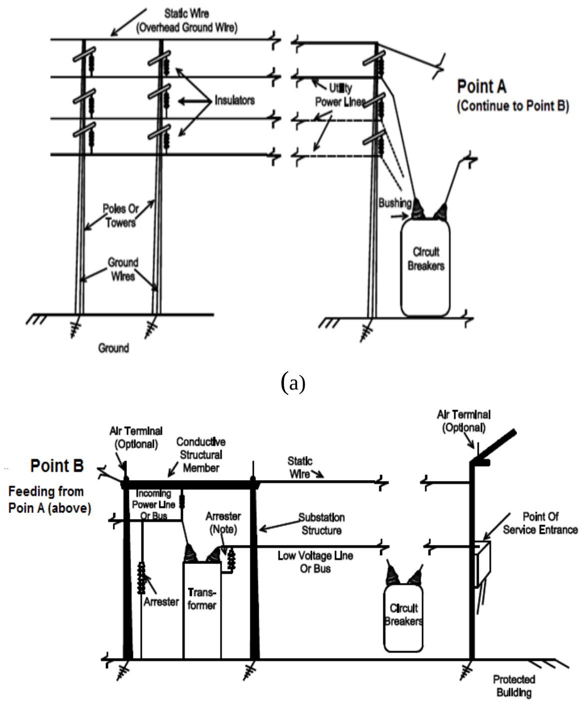


Figure 5: Future aircraft materials [33]

III. LIGHTNING EFFECTS ON ELECTRIC POWER SYSTEMS NETWORK

Electric power transmission and distribution grids are routed for miles in open fields. Thus they are prone to lightning strike. A lightning strike on structures such as high voltage overhead transmission line can induce voltage and current surges whose amplitudes far exceed the peak values of the nominal operating levels. The amplitudes are in the order of 1000 kV and 100 kA or more into the transmission line [28]. The values of the peak rate of rise can reach measured and simulation values of 100 kA/μs [2], [35], [36]. An overhead earth wire provides protection against direct lightning strikes in diverting the current and or voltage pulses to ground through the tower footings resistance. The tower footing resistance as defined by equations in [37] and [38] should be as low as 10 Ω or less so that negative reflection from the tower base. However, in the event of shielding failures, due to back flashover, or due to the induced voltage on a transmission line when lightning strikes a nearby object, high current and voltage pulses will reach the terminal equipment such as a transformer at substations. In such cases, surge protection devices (SPD) are required to divert the major part of the energy of the surge to ground via surge diverters, or by modifying the waveform to make it less severe via surge modifiers.

Surge diverters (or lightning arrestors) generally consist of one or more spark gaps in series, together with one or more non-linear resistors in series. Silicon Carbide (SiC) was the material most often used in these nonlinear resistor surge diverters. However, Zinc Oxide (ZnO) is being used in most modern day surge diverters on account of its superior voltampere characteristic [34]. An ideal lightning arrester should: (i) conduct electric current at a certain voltage above the rated voltage; (ii) hold the voltage with little voltage change for the duration of overvoltage; and (iii) substantially cease conduction at very nearly the same voltage at which conduction started. Figure 6 gives an illustration of lightning protection system with placements of shield wire, SPDs, circuit breakers, grounding systems, and the air terminals.



(a)

(b)

Figure 6: Illustrations of power network protection (a) Transmission line and (b) substation protection systems [39]

A. Substation Protection Systems

While we discuss here the conventional substation, it should be remembered that in the future the Digital Substation will replace the conventional substation, making lightning protection more critical and expensive with the presence of a large number of intelligent electronic devices (IEDs) and electronic potential and current transformers (ECT and EPT). Substations accommodate some of the most expensive equipment such as the power transformers, current transformers, voltage transformer and relays. Switchgear. Protection systems using arresters and breakers only protect the equipment from traveling waves induced by lightning. Protection against direct lightning strike requires masts, grounding and shielding wires. A lightning protection of a substation utilizes three methods: using masts, using shielding or static wires, and or using both masts and shielding wires. However, breakage of shielding wires (due to lightning current or poor maintenance) can cause catastrophic faults in substations when it snaps off [34]. Further, another disadvantage of using shielding wires is a high cost in comparison with the using of masts [34]. Moreover, a mast attracts lightning flashes more easily than the shielding wire when the tip is made small. Thus, application of mast in substations is preferred to shielding wires for lightning protection for substations [34].The requirements for the two different lightning protection mechanism are discussed below [40] (i) Shield wire lightning protection system will be generally used in smaller substations of lower voltage class, where number of bays are less, area of the substation is small and the height of the main structures are of normal height. The major disadvantage of shield wire type lightning protection is, that it causes a short circuit in the substation or may even damage the costly equipment in case of its failure (snapping off). (ii) Lightning mast - This type of protection is generally used in large, extra high voltage substations where number of bays are more. It has the following advantages, (i) It reduces the height of main structures, as peaks for shield wire is not required, and (ii) It removes the possibility of any back flashover to a nearby equipment or structure during discharge of lightning strokes.

Further, electrical substations require earth mat for good grounding. The earthing system provides a low resistance return path for earth faults within the plant, which protects both personnel and equipment. The earthing system provides a reference potential for electronic circuits and helps reduce electrical noise for electronic, instrumentation and communication systems [41]. It is required that substation earthing must allow for equipotential bonding which helps prevent electrostatic build up and discharge, which can cause sparks with enough energy to ignite flammable atmospheres. IEEE provides guidelines for AC substation grounding; IEEE Std 80 (2000), "Guide for safety in AC substation grounding." [41].

B. Rolling Sphere Method Applied in Substation Protections

The application of the rolling sphere method involves rolling an imaginary sphere of radius *S* over the surface of a substation [42].The sphere rolls up and over (and is supported by) lightning masts, shield wires, substation fences, and other grounded metallic objects that can provide lightning shielding. A piece of equipment is said to be protected from a direct stroke if it remains below the curved surface of the sphere by virtue of the sphere being elevated by shield wires or other devices [42]. An equipment that touches the sphere or penetrates its surface is not protected. The basic concept is illustrated in Figure 7 based on IEEE Standard 998-2012, "IEEE Guide for Direct Lightning Stroke Shielding of Substations" [43].

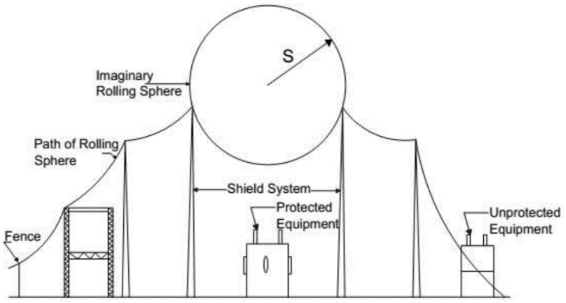


Figure 7: Illustration of rolling sphere protection method [43]

The calculation for the rolling sphere method is based on the Electro-geometrical model. It is summarized in the following equations for a 69 kV substation. The striking distance, *S* with respect to lightning strike peak current, I_s is calculated by using Equation (1) [43].

$$S = 10 \cdot I_S^{0.65} \tag{1}$$

I_S is a function of the surge impedance (Z_s) and the basic impulse level (BIL), for a 69 kV system an assumed $Z_s = 300\ \Omega$ and BIL = 350 kV then:

$$I_S = 2.2 \cdot \frac{BIL}{Z_S} \qquad (2)$$

Equation (2) yields a value of I_S of 2.567 kA.

Using the calculated current stroke value, the radius of the sphere can be computed using Eq. (1) which is 18.45 m. This is the length of the last leader as it strikes the mast. It is also the length of the upward leader from the mast tip as it meets the downward leader (from the cloud) at the stroke point.

For a four-mast protection method as highlighted in Figure 8, the following geometrical distances in Table 1 were computed using equations defined in [43] for a 69 kV substation mast protection. Similarly, the rolling sphere method using shield wire protection may be set up.

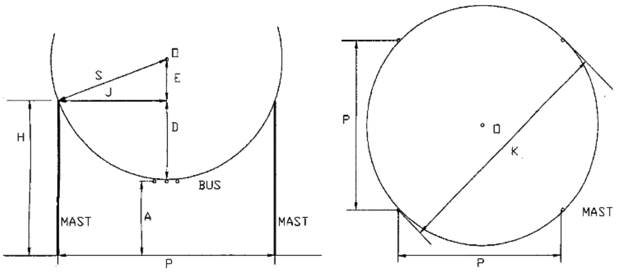


Figure 8: Geometrical dimensions for mast protection of 69 kV substation [43]

Table 1
Geometrical distance for 69 kV substation using four masts at a strike peak current of 2.567 kA

Parameter	Description	Calculated value (m)
S	Strike distance	17.72
H	Mast height (assumed height)	18.3
J	Horizontal distance between origin of sphere (OOS) and mast	16.9
E	Elevation difference between mast and origin of sphere (OOS)	5.22
D	Elevation difference between mast and bus	12.5
A	Bus height	5.8
P	Distances between mast when four masts support the sphere	23.944

A similar method of rolling sphere is applied for shield wire protection of substation. Lightning protection standards for electrical and electronics systems within building/structures are defined in IEC 62305-4 (EN 62305-4) on “Electrical and Electronics Systems with Structures” [44]. The protection system is categorized into three categories as illustrated in Figure 10. It covers (i) protection for buildings and installations against direct strike by lightning, (ii) protection system against overvoltage on incoming conductors and conductor systems, and (iii) protection system against the electromagnetic pulse induced by lightning striking a nearby object as an indirect effect [45].

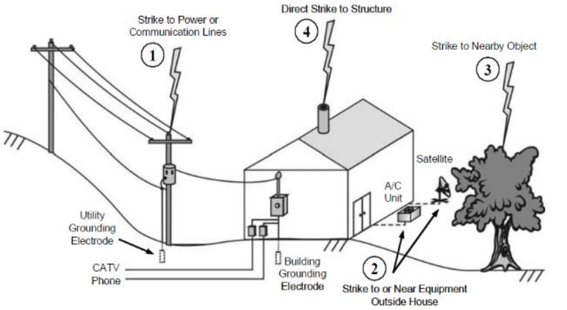


Figure 10: Illustration of a lightning strike through the direct hit, through an incoming conductor, and induced through objects nearby [45]

The protection against direct lightning strike requires air termination rods with good bonding to ground through down conductors via metallic structures on the external building structures as specified by grounding standards. Figure 11 gives an illustration of the rolling sphere requirements for buildings with areas indicated in red/dark line shows the need for air terminals to shield the building from the direct lightning strike. Further, a good bonding to the ground is necessary to provide an equipotential ground plane for all components within the building as specified by BS EN/IEC 62305. It contains recommendations for single integrated earth termination systems for structures, combining lightning protection, power and telecommunication systems [45]. Figure 12 gives an illustration of the equipotential bonding of an installation and the application of SPD in the protection of building components.

Figure 13 shows the complete protection system zones within a building. The protection systems cover both external protection devices using air terminals and down conductors to ground. This protects the building from both direct and also from induced voltages and currents from lightning striking nearby objects. The interior protection requires the necessary grounding of the building circuits and utility piping. The SPD devices are also used indoor for protection of lightning-induced LEMPs on appliances.

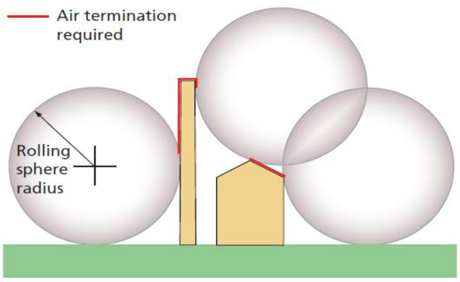


Figure 11: The rolling sphere method in building protection [44]

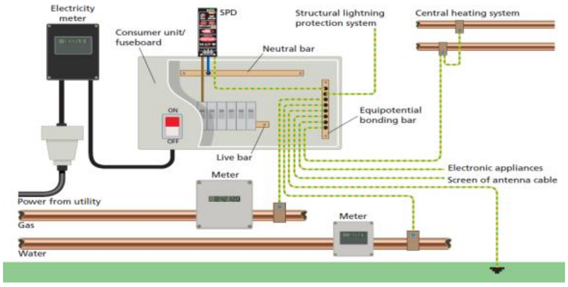


Figure 12: Equipotential bonding of building components [44]

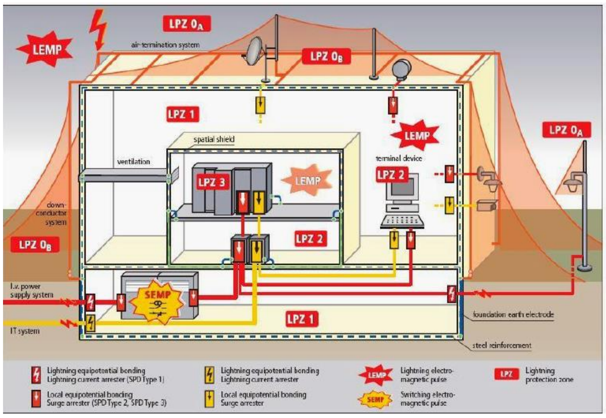


Figure 13: A building structure with lightning protection mechanisms. (IEC 62305-4/62305-4) [46]

IV. CONCLUSION

A description of the need to harden aircraft, power systems, structures, electronics, computers, electronic devices and other information communication systems against severe electric storm has been outlined in this paper. Electric storms remain a complex phenomenon that cannot be controlled or be prevented. Undoubtedly, it remains a serious threat to aircraft, power system, electronics, and communications systems. These threats are heightened further with aircraft industries continuously modifying and or adopting new designs into the aircraft such as the CFC in airframe design and the latest in the state of the art digital control, command, and communication systems. As digital microelectronic circuits are miniaturized they are very vulnerable to small transient surges that trickle down to electronic devices and systems, or those induced by LEMP. Similarly, lightning direct and indirect effects on power systems network, and building and system structures have become a serious threat. The threats can be contained through proper protection measures such as the SPDs, and proper shielding and grounding practices as defined in various standards on lightning protections highlighted. New measures in protection and standards will have to drive protection to a higher level for mitigation of lightning threats.

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