Chapter 4

Practice of Lightning Protection: *Risk Assessment, External Protection, Internal Protection, Surge Protection, Air Termination, Down Conductor, Earthing, and Shielding*

Abstract In this chapter, we review the risk analysis that needs to be performed to determine the probability of lightning strike to any structure that is to be protected from lightning damage. Moreover, presented herein is how different aspects of the structure will change the lightning damage risk. Details of protection of electrical and electronic installations inside a structure are presented, including the choice and placement of surge protection devices to prevent lightning damage to internal electronic and electrical equipment and installations. The practice of zoning for the design of lightning protection is described. The chapter also reviews external protection, including an air-termination system, bonding, and down conductor to a suitable earthing termination system and the earthing system. The chapter closes with a discussion of shielding from lightning electromagnetic pulse (LEMP) radiation.

4.1 Introduction

The components of a lightning protection system (LPS) are the air-termination system, the down-conductor system, earth-termination system, separation distances between conductors and lightning equipotential bonding, and, lastly, the surge protection devices and systems for electrical and electronic installations and devices. The external LPS should intercept a direct lightning strike to the structure, line, or people through air terminations. The down conductor must safely conduct the lightning currents to the ground through good grounding arrangements. The lightning current dissipated into the ground must be safely distributed without causing any underground coupling to other electrical systems or spark overs. The internal LPS must prevent dangerous sparking inside the structure and damage to electrical and electronic equipment and systems. Good electrical bonding is essential, as well as maintaining safe distance of separation between the LPS and internal wiring and devices.

A lightning current often peaks at 20 kA or more. Suppose an external lightning protection system installed with the building structures, which may take 99.9% of the current and dissipate it in the ground. Then the electrical wiring of the building

P. Hoole and S. Hoole, *Lightning Engineering: Physics, Computer-based Test-bed, Protection of Ground and Airborne Systems*,
https://doi.org/10.1007/978-3-030-94728-6_4

Fig. 4.1 The Four parts contained in Lightning Protection Standards

(household) takes the remaining 0.1% of 100 kA of lightning current which is 100 A. A 100 A surge can burn the whole electrical wiring system. Hence, the need for having a proper lightning protection system.

A lightning protection guide and the associated design standards are government approved for each country. These usually comprise four parts, as shown in Fig. 4.1. Pt 1 describes the general principles, Pt 2 describes the risk management, and Pt 3 describes the physical damage to structure and life hazards and the final part deals with protection from damage to electrical and electronic systems within a structure. The IEC standards are listed in the reference at the end of this chapter.

General Principles contain information on how to design a Lightning Protection System (LPS) in accordance with the approved standards. Risk Management concentrates more on risk of loss of human life, loss of service to the public, loss of cultural heritage, and economic loss. Protection of structure describes four classes or protection levels of LPS and protection methods used in designing an LPS. The Electronics Systems Protection covers the protection of electrical and electronic systems within the structure. It introduces Lightning Protection Zones (LPZs) for the design and installation of Surge Protection Methods (SPM).

4.2 General Principles of Lightning Protection

The general principles identify lightning damage and loss from the following four main sources: flashes to the structure, flashes near the structure, flashes to the lines connected to the structure, and flashes near the lines connected to the structures. Each of these flashes may result in injury to living beings through an electric shock, physical damage due to lightning current, or damage due to an electromagnetic impulse LEMP. These can result in losses including loss of human life, service to the public, structure with an economic value, or a cultural heritage. In Fig. 4.2, the zoning of lightning protection systems and the use of surge arresters to protect internal electrical and electronic equipment from lightning surges due to the direct and indirect effects of lightning are shown. There are direct lightning strikes to the house structure, traveling voltage surges from exposed power, and telecommunication lines, LEMP radiated from nearby lightning flash and ground potential gradients producing circulating

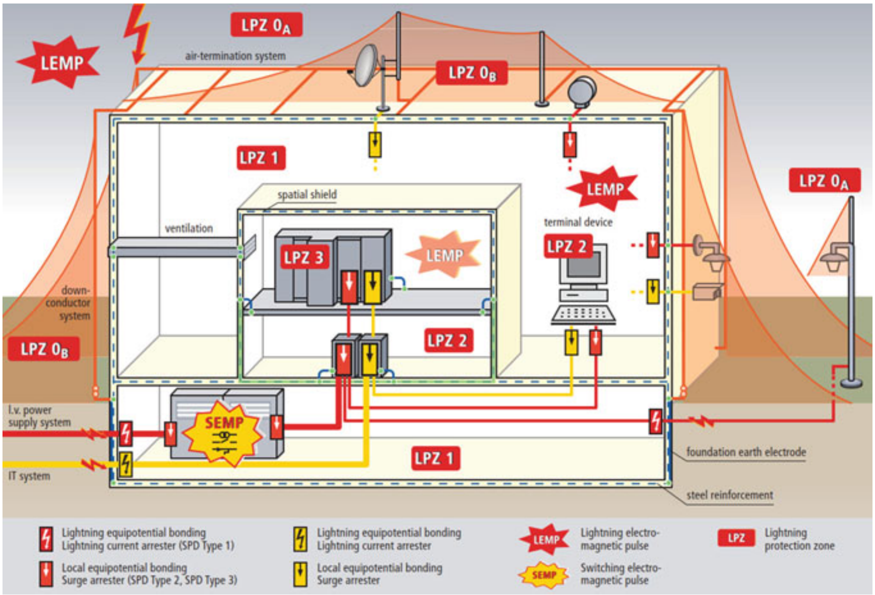

Fig. 4.2 Lighting protection zones (LPZ) and the placement of lightning surge arresters Credit: DEHN, with permission)

currents from the point at which the lightning struck and at which point the potential is temporarily raised to millions of volts.

The ideal protection scheme of any protection system would be to enclose the structure within an earthed and perfectly conducting metal shield box, known as a Faraday cage. Even though this will prevent any penetration of the lightning current and induced electromagnetic fields, it is neither practical nor cost-effective Hence under general principles, standards are set out to define a set of lightning current parameters and how they fall within limits defined as Lightning Protection Levels (LPL).

Four LPLs have been identified based on the maximum and minimum current parameters, as shown in Table 4.1.

The maximum values are used in the design of products such as lightning protection components and surge protection devices. The minimum current value has been used to derive the rolling sphere radius for each level. Depending on these LPLs the corresponding Lightning Protection System (LPS) is classed separately, as described in Table 4.2.

Table 4.1 Lightning current for each LPL based on a 10/350 μs waveform

LPL	I	II	III	IV
Maximum current (kA)	200	150	100	100
Minimum current (kA)	3	5	10	16

Table 4.2 Relationship between lightning protection level and class of LPS

LPL	LPS
I	I
II	II
III	III
IV	IV

4.3 Risk Management

4.3.1 Introduction

A risk assessment is performed to decide on the level of the Lightning Protection System (LPS) needed. As the first stage in risk assessment it is important to identify which of the four losses the structure and its contents can face. The four types of risks are as follows:

- R1—Risk of loss of human life.
- R2—Risk of loss of service to public.
- R3—Risk of loss of cultural heritage.
- R4—Risk of loss of an entity of economic value.

Each primary risk (RN) should be calculated according to data gathered about climate, population, etc. For each of the first three primary risks, a tolerable risk level (RT) can be set. If the actual risk (RN) is smaller or equal to tolerable risk (RT) then protection measures are not needed. If the actual risk is larger than the tolerable risk, then protection measures are needed and deployed.

This process is repeated using new values of the chosen protection measure until the actual risk is less than the tolerable risk. This process decides the choice of Lightning Protection Level (LPL) of a Lightning Protection System (LPS) and the Surge Protective Measures (SPMs) to be used to counter lightning surges and Lightning Electromagnetic Impulse (LEMP). Risk Management software is used to calculate risk of loss due to lightning strikes and transient overvoltages caused by lightning strikes. This software analyzes risks in a few minutes. If done manually it will take days to calculate risks.

4.3.2 Risk Assessment: Basics

Risk assessment is used by the owner of a building, a design engineer, the architect, and safety engineer to determine the risk of damage or injury due to a building being struck by lightning. The key concerns include issues such as continuity of electrical services, safety of a large crowd gathering, height of isolated buildings, density of lightning flash, and buildings with rare cultural heritage, and presence of inflammable and explosive materials. The factors taken into consideration are the type of construction, the environment in which the building stands, human occupancy, contents of the building, and consequences of the building being struck by lightning. The annual threat occurrence N_T is defined by the equation.

$$N_T = N_Y \times A_C \times C_L \times 10^{-6} \text{ events per year,} \tag{4.1}$$

where

N_Y = the yearly number of flashes per km^2.
A_C = the lightning collection area around the building.
C_L = the relative location factor.

If there are, for instance, 25 thunderstorms each year in the area where the building is located, then we have $N_Y = 4$ lightning flashes per km^2 each year. The value of N_Y ranges from 0.25 to 15. For a rectangular building structure, let the rectangular structure have the dimensions L (length) × W (width) and height H. For that rectangular building, the lightning collection area

$$A_C = LW + 6H(L + W) + 9\pi H^2. \tag{4.2}$$

The value of the location factor C_L varies. It is 0.25 when the structure is surrounded by tall structures or trees within a distance 3H, 0.5 for when the structure is surrounded by equal or lesser structures or trees within a distance of 3H from the building, 1 when the structure is isolated up to a distance of 3H, and 2 when the structure stands completely isolated or on top of a hill.

In order to determine the lightning risk to a structure, we compare the lightning frequency N_T to the risk of damage to a structure N_D. We determine the risk of damage to a structure N_D from

$$N_D = 0.0015/S \text{ events per year,} \tag{4.3}$$

where the structural coefficient

$$S = S_1 \times S_2 \times S_3 \times S_4. \tag{4.4}$$

The value of S_1 depends on the type of roof of the structure. S_1 is 0.5 to 2 for a metallic roof, 0.5 for metallic structure, 2 for a combustible structure, 1 to 2.5 when it is a nonmetallic roof, and 2 to 3 for a combustible roof. The value of S_3 depends on the contents inside the structure. The value of S_2 is 0.5 for low value, noncombustible material inside, 1 for standard value, noncombustible contents, 2 for high value, moderately combustible contents, 3 for exceptional value, flammable liquids, digital electronic equipment, and 4 for exceptional and irreplaceable contents such as cultural heritage artifacts. The value of S_3 is occupancy related. It is 0.5 for an unoccupied structure, 1 for normally occupied structure, and 3 for structure where it is difficult to evacuate the people inside. The value of S_4 depends on the requirement or not whether the continuous use of the building is required and whether or not there is any adverse impact on the environment. The value of S_4 is 1 if the continuity of the use of the facility is not required, 5 if the continuity of the use of the structure is required but environmental impact is negligible, 10 if there are serious consequences to the environment, as, for instance, a tree or a substation transformer struck by lightning and catching fire to set fire to other surrounding trees.

Once the measure of risk of damage N_D is determined, it needs to be compared with the lightning frequency N_T. If N_T is less than or equal to N_D then installing lightning protection is optional. However, if N_T is greater than N_D, then the design and installation of lightning protection is recommended.

Lightning flash counters are used to measure lightning flash densities. The CIGRE lightning flash counter is a standardized device, which, by registering the number of lightning flashes within a specified area, enables the density of lightning flashes to ground, per unit area, and per unit time, to be estimated. Long-term average values for the number of lightning flashes per year were obtained for a Pacific Island from a lightning flash counter network. These records are used with local storm observations to obtain the ground flash density N_Y. The average number of thunder days (T) and lightning days (L) are estimated. The values are compared with data from the literature of other regions used in transmission system design. Average values as high as about 20 lightning faults per 100 km per year were measured in the Pacific Region. It is apparent that designs from temperate countries would require adaptation for the higher incidence of lightning in this country, although the lower values of N_Y will compensate to some extent for the higher values of number of lightning flashes.

4.3.3 Advanced Risk Assessment

Let us define some variables

S_1 = Coefficient for direct lightning strike.
S_2 = Coefficient for lightning strike near structure.
S_3 = Coefficient for direct lightning strike to an incoming line.
S_4 = Coefficient for lightning strike near an incoming line.
L_1 = Coefficient for loss of human life.
L_2 = Coefficient for loss of service to public.
L_3 = Coefficient for loss of cultural heritage.
L_4 = Coefficient for loss of economic value.

The risk component

$$R_x = N_x . P_x . L_x, \tag{4.5}$$

where

N_x = Number of dangerous events.

P_x = Probability of damage.

L_x = Loss factor, quantitative evaluation of damage.

The risk component R_x should be less than R_t, the tolerable event.

Collection area of line, $A_L = 40\ L_l$, where L_l is about 1000.

The ground flash density is the lightning strikes per km^2 per year.

$N_G = 0.1\ T_D$, where T_D is thunder days per year.

Direct strikes $N_D = N_G.\ A_D.\ C_B.\ 10^{-6}$, where C_D = The location factor, including surrounding

$$A_D = LW + 2(3H).\ (L + W) + \pi(3H)^2. \tag{4.6}$$

For nearby lightning

$$N_M = N_G.A_M.10^{-6}, \tag{4.7}$$

with A_M (drawing line) at 500 m.

Lightning strikes lines at an annual rate of

$$N_L = N_G.A_l.\ C_I.C_E.C_T.10^{-6}, \tag{4.8}$$

where N_L is the annual number of surges in line section with maximum 1 kV surges. C_I = insulation factor, C_T = line type factor (building density). A_L= 40 L_L, with L_L= 1000.

$$N_I = N_G.A_I.C_I.C_E.C_T.10^{-6} \tag{4.9}$$

$$A_I = 4000\ L_L. \tag{4.10}$$

Let us work out the probabilities of damage. For direct lightning strikes, let P_A = The probability of physical damage (for example, from fire, explosion, mechanical, chemical reactions). Let P_C= the probability of failure of electric or electronic systems due to a direct lightning strike to a building or structure. If lightning strikes the ground near the structure, let P_M= the probability of failure of electrical/electronic systems. In the case of a direct strike to an incoming line (bringing electric power into a building), let P_U = the probability of injury, P_r = the probability of physical damage, and P_W = the probability of failure of electrical/electronic systems.

The probability of damage in case of a direct lightning strike is given by

$$P_A = P_{TA}.\ P_B. \tag{4.11}$$

$P_{TA,}$ the probability that the lightning strike will cause shock, is 1 for no protection, 10^{-1} for warning notice, 10^{-2} electric insulation with 3 mm XLPE (cross-linked polyethylene) down conductors, 10^{-2} effective potential control in the ground, and 0 for physical instructions or building framework as down conductor. P_B, the probability of damage to a physical structure that is hit is 1 for no coordinated SPD, with air termination it is 0.05, with lightning protection system it is 0.1 for class III to IV systems, 0.1 for class II, 0,02 for class I system with continuous metal down conductor it is 0.01. In the case where coordinated SPDs (surge protective devices) are installed, the probability of damage caused by direct lightning is

$$P_C = P_{SPD}.C_{LD}, \tag{4.12}$$

which is the probability that lightning strike will cause damage to the electrical or electronic systems.

Let LPL be the Lightning Protection Level, and then the probability of damage P_{SPD}, with coordination with lightning protection level (LPL) is 1 with no coordinated SPD, 0,05 (with class III to IV LPS), 0.02 (with class II LPS), and 0.01 with class I LPS. C_{LD} is either 1 or 0. For instance, it is 1 for shielded buried cable as the external line and 0 when there is no external line. C_{LI} is 1 for an unshielded external line, 0.2 for a power line for multi-grounded shield line (a shield line grounded at multiple points), and 0 for a multi-grounded shielded underground cable as the external line.

Probabilities of damage in case of nearby lightning strike is

$$P_M = P_{SPD}.\, P_{MS}, \tag{4.13}$$

where

$$P_{MS} = (K_{s1}.K_{s2}.K_{s3}.K_{S4})^2 \tag{4.14}$$

and K_{s1} is the shielding effectiveness of structure, K_{S2} is the shielding effectiveness of internal shields of structure at boundaries, K_{S3} is the shield effectiveness for shields of internal cables, and K_{S4} is the rated impulse voltage withstand voltage of protected system.

The probability of damage due to direct lightning strike to a power line is given by

$$P_U = P_{TU}.\, P_{EB}.\, P_{LD}, P_{LD}, \tag{4.15}$$

where P_{TU} is the probability of touch voltage protection warning notice (1 or 0.1, with physical restrictions from touching, 0), P_{EB} is the lightning equipotential bonding induced protection (1 with no SPD, 0.05 for LPS II, IV; 0.02 for LPS II; 0.01 with LPS 0.01; with surge protection devices it is 0.005 to 0.001). P_{LD} is the probability that the internal system will fail, and coefficient C_{LD} is considering earthing, shielding and insulation conditions of the line. We have for the probability of physical damage

$$P_V = P_{EB} . P_{LD} . C_{LD} . \tag{4.16}$$

The probability of internal system failure is

$$P_W = P_{SPD} . P_{LD} . C_{LD} . \tag{4.17}$$

And the probability of damage in case of indirect lightning strikes to line is

$$P_Z = P_{SPD} . P_{LI} . C_{LI} . \tag{4.18}$$

P_{LD} is 1 for impulse withstand voltages of 1 kV, 5 kV, or 6 kV with shielded overhead line without bonding of shield to the same equipment bonding bar; it is 0.6 (for 1 kV withstand voltage), 0.2 (for 5 kV withstand voltage), or 0.02 (for 6 kV withstand voltage) for a shielded overhead line or buried bonded cable bonded to the same equipotential bonding bar as equipment with shield resistance less than 1 Ω/km. It is closer to 1 if the shield resistance is in the range of 5 to 20 Ω/km. The values of P_{LI} are 1 for 1 kV withstand voltage, 0.3 for 2 kV withstand voltage, or 0.1 for 6 kV withstand voltage for power lines. It is much lower, that is, 0, 2 (2.5 kV) and 0.04 (6 kV) for telecommunication lines. The coefficient C_{LI}, depending on the type of external line, takes values of 1, 0.2, or 0. The risk factor varies according to whether it is agricultural land (10^{-2}), marble or ceramic (10^{-2}), gravel (10^{-4}) or asphalt or wood (10^{-5}).

The tolerable risk P_T/year is dependent on what is being considered, whether loss of human life or injury (tolerable value is 10^{-5}), service to public (10^{-3}), cultural heritage (10^{-4}), or economic values (10^{-3}).

4.4 Inspection of Lightning Protection System

The Lightning Protection System (LPS) should be regularly inspected over the entire phase of its design, installation, acceptance, and maintenance stages. Both measurements and visual inspection need to be made. The LPS used in critical systems and situations should be completely inspected annually. Class I and Class II LPSs should be annually inspected and a complete inspection made every 2 years. Class II and IV LPSs should be visually inspected once a year and a complete inspection performed every 4 years. Reports should be prepared giving information on structures, the LPS, fundamental inspection activities, the results of inspection, and the inspector. Maintenance should be carried out to prevent loss of LPS quality and the effects of direct lightning strikes and any damage to the LPS. Inspection of all conductors and components of the LPS system should be performed. Continuity of installation should be tested. The earth resistance at earth terminations should be measured. The

SPDs should be visually inspected. Fixings of conductors and components should be tested. It should be ensured that the effectiveness of the LPS remains unchanged.

4.5 Internal Lightning Protection

4.5.1 Surge Protection Measures

By careful design of the LPS, earth bonding of metallic services such as water and gas and cabling routes, structures, and screened rooms, the internal electrical and electronic systems can be protected from lightning surges. Proper installation of surge protective devices will ensure the proper operation of equipment and will protect them from damage. These are known as surge protection measures. Initially, according to the standards used, it needs to be determined whether structural and/or LEMP protection is required. Once the need is decided upon, the proper selection and location of Surge Protection Devices (SPDs) need to be done.

- Coordinated SPDs
  Coordinated SPDs have to work together to protect equipment. The lightning current SPD at the entrance of the service should handle most of the surge energy, sufficiently relieving the downstream overvoltage SPDs to control the overvoltage. The overvoltage SPDs as well as equipment to be protected can be damaged due to poor coordination.
- Enhanced SPDs
  Standard SPDs may only protect against common mode surges (between live conductors and earth), providing effective protection against outright damage but not against downtime due to system disruption. Enhanced SPDs provide lower let through voltage protection against surges in both common mode and differential mode (between live conductors). They also provide additional protection over bonding and shielding measures.

The Surge Protection Device is connected in parallel on the power supply circuit of the loads that it is to protect, as shown in Fig. 4.3.

According to the characteristics of the current wave or voltage wave, SPDs can be divided into three types, namely, Type1 SPD, Type 2 SPD, and Type 3 SPD.

- Type 1 SPD
  The Type 1 SPD is characterized by a 10/350 μs current wave. This type is recommended for the specific case of service sector and industrial buildings to be protected by a lightning protection system. It protects electrical installations against direct lightning strokes. It can discharge the back current from lightning spreading from the earth conductor to the network conductors.

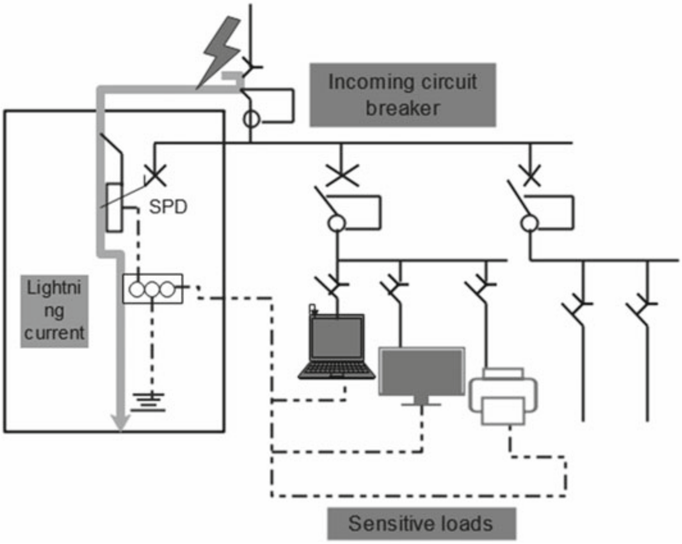

Fig. 4.3 SPD used in protection system. Adapted from DEHN

- The Type 2 SPD
  The Type 2 SPD is characterized by a 8/20 μs current wave. It is the main protection system for all low-voltage electrical installations. They are installed in each electrical switch board; it prevents spread of overvoltages in the electrical installations and protects the loads.
- The Type 3 SPD
  The Type 3 SPD is characterized by a combination of voltage waves (1.2/50 μs) and current waves (8/20 μs). These SPDs have low discharge capacity. They are installed as support to the Type 2 SPD and in the vicinity of sensitive loads.

Summary

1. A lightning protection system consists of an external and an internal lightning protection system. According to the International Electrotechnical Commission (IEC), the components that make up the lightning protection system are an air-termination system, a down-conductor system, separation distances, and lightning equipotential bonding. The separation distance between an external lightning protection system and metal structures is important to minimizing the probability of partial lightning current from entering the internal structures. The main purpose of a lightning protection system is to protect buildings from fire and persons from injury or death in the event of overcurrent due to lightning. The function of an external lightning protection system is to intercept lightning strikes via an air-termination system, to safely conduct lightning current to ground via a down-conductor system and distribute lightning current in the ground via an earth-termination system. On the other hand, the main function

of internal lightning protection system is to prevent dangerous sparking inside buildings by using equipotential bonding or maintaining a certain separation distance between components of the lightning protection system and conductive elements inside the structure. Lightning equipotential bonding reduces potential differences, between internal devices and between conducting parts, by connecting all conductive parts directly by conductors or through surge protective devices.

2. The selection for the appropriate design of the protection system and measures to be taken are calculated during risk assessment where the source and type of damage are evaluated to predict the severity and type of damage due to lightning. Four major sources of damage are flashes to the structure (S1), flashes near the structure (S2), flashes to a service line (S3), and flashes near a service line (S4). The types of damage that may be inflicted are injury due to step and touch voltages (D1), physical damage such as fire and explosion, mechanical damage or chemical release due to lightning current effects including sparking (D2), and failure of internal systems due to Lighting Electromagnetic Impulse (LEMP) (D3). Lightning Protection Standards define a set of parameters where protection measures should be taken to reduce damage due to a lightning strike. There are four classes of lightning protection levels (LPL) which are labeled as I, II, III, and IV. Each of these is determined using a set of construction rules. The LPLs are directly proportional to the class of Lightning Protection System (LPS). The higher the LPL, the higher the class of LPS required. LPL I has a maximum current of 200 kA and minimum current of 3 kA; LPL II has maximum current of 150 kA and minimum current of 5 kA; LPL III has maximum current of 100 kA and minimum current of 10 kA; LPL IV has a maximum current of 100 kA and minimum current of 16 kA. The above parameters are based on a 10/350 μs waveform. Other than lightning protection levels, lightning protection zones (LPZ) were introduced to determine protection measures to prevent LEMP in a building. LPZs are divided into external and internal zones. External zones LPZ 0_A are zones with risk of a direct lightning strike and LPZ 0_B are zones with risk of partial lightning current. LPZ 1, LPZ 2, and LPZ 3 are internal zones where the higher the number of the zone, the lower is the risk of electromagnetic effects.

4.5.2 Lightning Protection Zones

4.5.2.1 General

Electrical and electronic systems can be damaged if overvoltages occur near the sensitive parts of the components. Usually, overvoltage happens in areas of residential and functional buildings due to lightning discharge. Hence, protection is essential to prevent the owner wasting lots of money by repairing or replacing the damaged

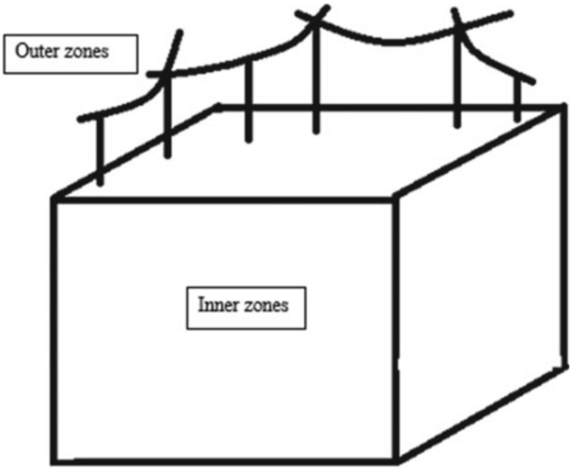

Fig. 4.4 Lightning protection zones. Adapted from DEHN

components. Nowadays, the operator also sets very high demands regarding the availability and reliability of these systems. In lightning protection zone (LPZ) principles, the inner zones and outer zones are identified as shown in Fig. 4.4.

Before designing the protection systems, information on the computer system in use, the electrical installation, and the earth-termination system must be collected and collectively evaluated for a comprehensive overall protection system. Protection of electrical and electronic devices can be classified into several parts because of the threat of direct lightning strikes and lightning electromagnetic field. The principle of lightning protection zones (LPZ) is implemented to get rid of incoming surges resulting from lightning electromagnetic pulses (LEMP). According to the LPZ principle, the building structure that needs to be protected must be divided into outer zones and inner zones based on the risk level. By using this flexible concept, the protection of the structure is maximized and the minimum damage and loss of service costs can be achieved. Regarding the inner zones and outer zones, these are classified as follows.

4.5.2.2 Outer Zones

LPZ0—This refers to zones where the threat results from un-attenuated lightning electromagnetic field and where the internal systems may be subjected to the full or partial lightning current. LPZ 0 is subdivided into $\mathrm{LPZ0_A}$ and $\mathrm{LPZ0_B}$.

LPZ0A—This is a zone where the threat is due to direct lightning strikes and the full lightning electromagnetic field. The internal systems may be subjected to the full lightning current.

LPZ0B—This is the zone that is protected from direct lightning strikes, but the threat is due to the full lightning electromagnetic field. The internal systems may be subjected to partial lightning currents.

4.5.2.3 Inner Zones

LPZ1—This is a zone where the impulse currents are limited by current distribution and isolating interfaces or by Surge Protection Devices (SPDs) at the zone boundaries. Spatial shielding may attenuate the lightning electromagnetic field.

LPZ2—This zone is where the impulse currents are limited by current distribution and isolating interfaces or by additional Surge Protection Devices (SPDs) at the zone boundaries. Additional spatial shielding may be used to further attenuate the lightning electromagnetic field.

The dielectric strength of the electrical and electronic systems to be protected plays an important role in determining the requirements for the inner zones. Equipotential bonding needs to be established at the boundary of each inner zone for all incoming metal parts and supply lines either directly or by means of suitable SPDs. These zone boundaries are formed according to the shielding measures used. Before commencing on the design of the protection systems, information such as the computer system, the electrical installation, and the earth-termination system must be collected and centrally evaluated for a comprehensive overall protection system.

4.5.3 SPM Management

The owner and operator usually emphasize optimum protection of the electronic systems with a minimum of expenses. However, this can be only achieved if the electronic devices and systems are designed together with the building and before its construction undergoes changes. The costs of the LEMP protection measures freshly installed for an existing, old structure are higher than for new structures. By choosing the LPZs appropriately when existing installations are used or upgraded, much cost can be reduced.

- The SPM should be planned by a lightning protection specialist having sound knowledge of Electromagnetic Compatibility (EMC).
- There ought to be close coordination between building and LEMP experts (e.g. civil and electrical engineers).

The SPM management plan is shown in Table 4.3.

- The final risk must be assessed and it must be proven that the residual risk is less than the tolerable risk.

The interconnection of all metal components by equipotential bonding inside the structure forms a low-inductance equipotential bonding network which is a three-dimensional meshed network. An ideal equipotential network is around 5 m × 5 m in size as it is able to reduce the electromagnetic field in an LPZ by a factor of 2 or by 6 dB. Electronic devices and systems are integrated in the equipotential bonding network by short connections. Hence, a sufficient number of equipotential bonding bars must be allocated in the structure as all the bars must be connected to the

Table 4.3 SPM management plan for new buildings and for comprehensive changes to the construction or use of buildings according to IEC 62305-4 (EN62305-4)

Step	Aim	Action to be taken by (if relevant)
Initial risk analysis	Assess the necessity for LEMP protection measures. If necessary, an appropriate LEMP Protection Measures System (LMPS) must be chosen based on a risk assessment	• Lightning protection specialist • Owner
Final risk analysis	The cost-benefit ratio of the protection measures chosen should be optimized again by a risk assessment. The following must be determined: • Lightning protection level (LPL) and lightning parameters • LPZs and their boundaries	• Lightning protection specialist • Owner
Design of the LEMP Protection Measures System (LPMS)	Definition of the LMPS: • Spatial shielding measures • Equipotential bonding networks • Earth-termination systems • Conductor routing and shielding • Shielding of incoming supply lines • SPD system	• Lightning protection specialist • Owner • Architect • Designer of internal systems • Designer of relevant installations
Design of the LPMS	• General drawings and descriptions • Preparation of tender lists • Detailed drawings and schedules for installation	• Engineering office or equivalent
Installation and inspection of the LMPS	• Quality of the installation • Documentation • Possible revision of the detailed drawings	• Lightning protection specialist • Installer of the LMPS • Engineering office • Supervisor
Acceptance of the LMPS	• Inspection and documentation of the system	• Independent lightning protection expert • Supervisor
Periodic inspections	• Ensuring an appropriate LMPS	• Lightning protection specialist • Supervisor

equipotential bonding network. Protective conductors and cable shields of data lines are integrated in the equipotential bonding according to specifications of the manufacturer, in a meshed or star configuration. It is important that all metal components of the electronic system must be sufficiently insulated against the equipotential bonding network when using a star configuration. Due to this matter, star configurations are typically limited to small applications or locally confined systems. The star configuration is connected to the equipotential bonding network at a single earthing reference point (ERP) and all lines must enter the structure at a single point. On the other hand, metal components of electronic systems do not need to be insulated against the equipotential network when using the meshed configuration. The difference between star and mesh configurations is that all components in the mesh configuration are integrated in the equipotential bonding network at as many equipotential bonding points as possible. As a result of that, the meshed configuration is extensive and is an open system with many lines between individual devices. An added advantage of the meshed configuration is that the system can enter the structure at different points unlike the star configuration where the system is only allowed to enter at a single point. For more complex systems, the star and meshed configurations are combined to benefit from the advantages of both systems.

4.6 Equipotential Bonding for Metal Installations

4.6.1 Prologue

Equipotential bonding provides protection by eliminating the potential difference between different devices or systems and thus prevents circulating lightning currents. There are two types of equipotential bonding, which are protective equipotential bonding and supplementary protective equipotential bonding. All buildings must be equipped with a protective equipotential bonding system as specified by the standards. Supplementary protective equipotential bonding is used when the conditions for disconnecting the supply cannot be met or for special installations or locations.

4.6.2 Equipotential Bonding for Metal Installations at the Boundary of LPZ0$_A$ and LPZ1

All metallic electrical lines or systems passing through the boundary between the electromagnetic compatibility (EMC) lightning protection zones must be integrated in the equipotential system. Measures must be taken to reduce the radiated electromagnetic field at this boundary. Lightning equipotential bonding must be implemented along with protective equipotential bonding for electrical and electronic lines at this boundary. A good practice is to implement the equipotential bonding as close as possible to the points where lines and metal installations enter the building and the lines should be as short as possible to lower line impedance.

4.6.3 Equipotential Bonding for Metal Installations at Boundary of LPZ 1 and LPZ 2

This is similar to the equipotential bonding at boundary of $LPZ0_A$ and LPZ1, where the equipotential bonding system must be installed as near as possible to where the lines and metal installations enter the zone of transition between LPZ1 and LPZ2. Applying ring equipotential bonding allows low-impedance connection of the system in this zone.

4.6.4 Protective Equipotential Bonding

There are a few individual conductive parts that must be directly connected in the protective equipotential bonding system such as the protective bonding conductor, metal foundation or lightning protection earth electrode, central heating system, metal water supply pipe, any conductive parts of a building structure such as lift rails, steel frame, ventilation or air conditioning ducts, metal drain pipe, internal gas pipe, earthing conductor for antennas and telecommunication systems, protective conductor of electrical installations, metal shields of electrical and electronic conductors, metal sheaths of power cables up to 1000 V, and earth-termination systems of power installations exceeding 1 kV.

Extraneous conductive parts are conductive parts that do not form part of an electrical installation, but are capable of introducing a potential called the earth potential. Conductive floors and walls are also classified as extraneous conductive parts as long as they are capable of introducing an electric potential. There are parts that must be connected indirectly via isolating spark gaps to the protective equipotential bonding system such as installations with cathodic corrosion protection and stray current protection measures, earth-termination systems of power installations exceeding 1 kV, traction system earth in case of AC or DC railways, and signal earth for laboratories if it is separated from the protective conductors.

Lightning equipotential bonding is an extension of protective equipotential bonding. Both equipotential bonding systems have to be connected with the main earthing busbar of the earth-termination system, as shown in Fig. 4.5. Lightning equipotential bonding provides safe integration of conductors entering the equipotential bonding system in the event of lightning strikes at the protection system or the entering conductors. Figure 4.5 illustrates a basic diagram of lightning equipotential bonding.

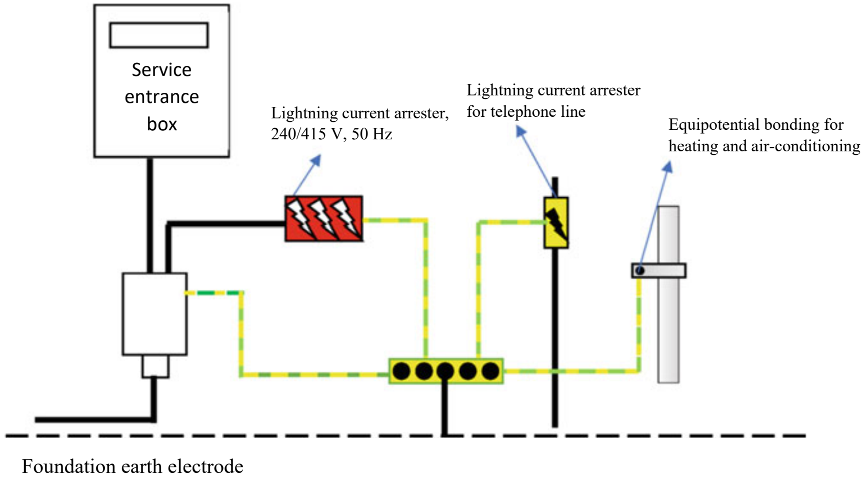

Fig. 4.5 Lightning equipotential bonding (Credit: DEHN. With permission)

4.6.5 Earth-Termination System for Equipotential Bonding

Low-voltage electrical installations require certain low earth resistances. The foundation earth electrode is capable of providing good earth resistances if installed effectively and it is a complement of the equipotential bonding system by improving earthing effectiveness.

4.6.6 Protective Bonding Conductors

Equipotential bonding conductors are labeled as protective conductors which are green or yellow as long as they are for protective purposes. Equipotential bonding conductors do not carry operating currents from the main supply and can either be bare or insulated. The minimum cross section of protective bonding conductors which are to be connected to the main earthing busbar is 6 mm^2 for copper, 16 mm^2 for aluminum, and 50 mm^2 for steel. The minimum cross section for earthing conductors of antennas is 16 mm^2 for copper, 25 mm^2 for aluminum, and 50 mm^2 for steel. The larger cross-sectional area required is due to higher frequency antenna currents needing a larger surface to flow in order to reduce the conductor resistance.

4.6.7 Equipotential Bonding Bars

Equipotential bonding bars must be able to clamp all connecting cables and cross sections so that they will have high contact stability and must be able to safely carry currents in addition to be sufficiently corrosion resistance. In order to get high contact stability, the equipotential bonding connections must be able to provide good and permanent contact.

4.6.8 Integrating Pipes in Equipotential Bonding System

Earthing pipe clams corresponding to the diameters of the pipes are used to integrate pipes in the equipotential bonding system. Typically, stainless steel earthing pipe clamps with tensioning straps are used because it offers greater flexibility to clamp pipes of different materials and also allows through-wiring.

4.6.9 Testing and Monitoring Equipotential Bonding System

A resistance value of less than 1 Ω is sufficient for equipotential bonding connections. The test equipment with 200 mA test current must be used in a continuity test.

4.6.10 Supplementary Protective Equipotential Bonding

If conditions for disconnection cannot be met, supplementary protective equipotential bonding is required to interconnect all accessible parts including stationary equipment and to connect all individual conductive parts to keep touch voltage to its minimum. For installations of Information Technology (IT) systems with insulation monitoring, supplementary protective equipotential bonding must be used. This type of bonding is also used if environmental conditions in special installations present a risk. These include areas containing bath or shower; basins of swimming pools; and other water basins, agriculture, and horticulture premises. The minimum cross sections required for supplementary protective bonding copper conductor are 2.5 mm^2 for protected installations and 4 mm^2 for unprotected installations. As compared to protective equipotential bonding, the cross section of conductors in supplementary protective equipotential bonding is smaller as it can be limited to a particular area.

4.6.11 Minimum Cross Section for Equipotential Bonding Conductors

Cross sections of conductors for lightning protection must be designed so that it is capable of handling high stress since it is carrying lightning currents. Hence, it must have larger cross sections. All classes of Lightning Protection System (LPS) have the following minimum cross sections depending on type of material: 16 mm^2 for copper, 25 mm^2 for aluminum, and 50 mm^2 for steel. The minimum cross sections for conductors that connect internal metal installations to the equipotential bonding bar can be smaller since only partial lightning currents of reduced amplitudes flow through these conductors. The cross section for copper is 6 mm^2, aluminum is 10 mm^2, and steel is 16 mm^2.

4.6.12 Equipotential Bonding for Power Supply Systems

Feeder cables of low-voltage installations need to be integrated in the equipotential bonding system. A unique feature of this system is that connections to the equipotential system is only possible via sufficient Surge Protection Devices (SPDs). As done for equipotential bonding for other metal installations, the bonding for feeder cables of low-voltage installations should be fixed directly at the entry point.

4.6.13 Equipotential Bonding for Power Supply Systems at the Boundary of LPZ0$_A$ and LPZ1

All electrical power and data lines entering the building transitions from LPZ0$_A$ to LPZ1 must be included in the equipotential bonding system. The boundary of LPZ0$_A$/LPZ1 as shown in Fig. 4.6 is assumed to be the boundary of the building if the installations are supplied by low-voltage systems.

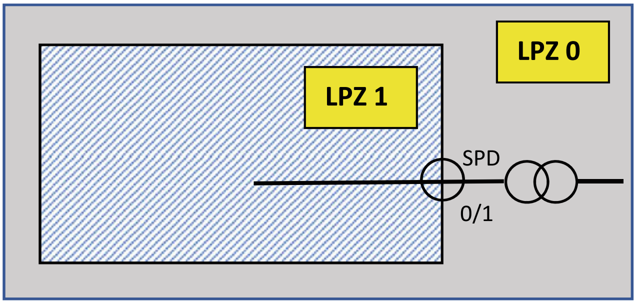

Fig. 4.6 Boundary of LPZ 0$_A$/LPZ 1 with transformer outside the structure. Adapted from DEHN

However, LPZ0_A is extended up to the secondary side of the transformer for installations which are directly supplied by the medium-voltage system as shown in Fig. 4.7. The lightning equipotential bonding is installed at the 240/415 V side of the transformer. It is advisable to install surge protective devices on the high-voltage side of the transformer to prevent damages. In addition, it is recommended that additional shielding measures at the incoming medium-voltage line be used to prevent lightning currents in LPZ0 from flowing into the system in LPZ1. Implementation of lightning equipotential bonding for all incoming metal, electrical power, and data lines at a central point prevents equalizing currents between various equipotential bonding points. Low-frequency equalizing currents are dangerous because they can be superimposed on power frequency current flow. This may cause cable fires in extreme cases. If such an arrangement is not possible, a ring equipotential bonding bar should be used instead. The discharge capacity of the lightning current arrester used in this zone is classified as a Type 1 surge protective device and must be capable of handling the stress from the lightning current. The level of lightning protection chosen is based on risk assessment. If risk assessment or information on lightning current distribution at the transition from LPZ 0_A to LPZ 1 is unavailable, the class of lightning protection system with the highest requirements is used (Level 1). The minimum lightning-carrying capacity of Type 1 surge protective device is 75 kA/m.

The lightning current distribution varies depending on the installation conditions. If there are several parallel load systems, the stress on the building which is hit by lightning will increase. The resulting earth resistance of a low-voltage system consisting of several connected buildings and a transformer is lower compared to the single earth resistance of a single building hit by lightning. Other than that, the current will not be evenly distributed between the low-voltage installation and the earth-termination system. Hence, the Type 1 surge protective devices in the low-voltage system discharge a significantly larger amount of current compared to the earth-termination system.

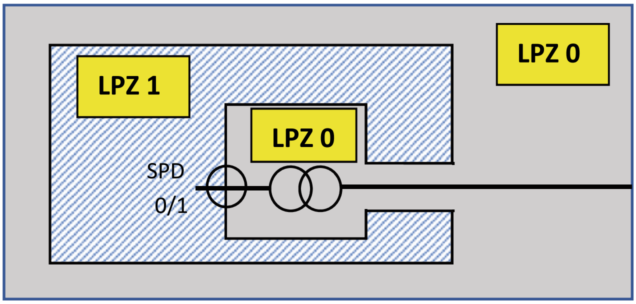

Fig. 4.7 LPZ 0 integrated in LPZ 1 with transformer inside the structure. Adapted from DEHN

4.6.14 Equipotential Bonding for Power Supply Systems at the Boundary of LPZ0$_A$ and LPZ2

Transition from LPZ0$_A$ to LPZ2 is usually found in compact installations. The layout of such transition is shown in Fig. 4.8. This type of transition places a high surge voltage stress on surge protective devices. Low voltage protection level and high limitation of the interference energy conducted by the arrester are the foundations for safe energy handling demands on surge protective devices in LPZ2 or with surge-limiting protective components of input circuits in equipment. Spark-gap-based combined arresters with voltage protection level less than 1.5 kV provide optimum protection of terminal devices and are suitable even for sensitive equipment with rated impulse withstand voltage of 1.5 kV. It also ensures safe operation of equipment and systems in LPZ2. Thus, it offers the advantage of combined lightning equipotential bonding and coordinated protection of terminal devices of a Type 1, Type 2, and Type 3 arresters in just a single device.

Both lightning protection zones are adjacent to each other for transitions from LPZ0 to LPZ2. Hence, it is very important and necessary to provide for a high degree of shielding at the zone boundaries. It is best to maintain the area of adjoining lightning protection zones LPZ0 and LPZ2 as small as possible. Optimally, LPZ2 should be enhanced with an extra zone shield which is installed individually away from the lightning current-carrying zone shield at the zone boundary of LPZ0, if the structure allows it. This is so that LPZ1 covers a majority of the installation as shown in Fig. 4.8. The implementation of this method not only decreases the magnitude of electromagnetic field in LPZ2 but also eliminates the need for constant shielding of all lines and systems found in LPZ2.

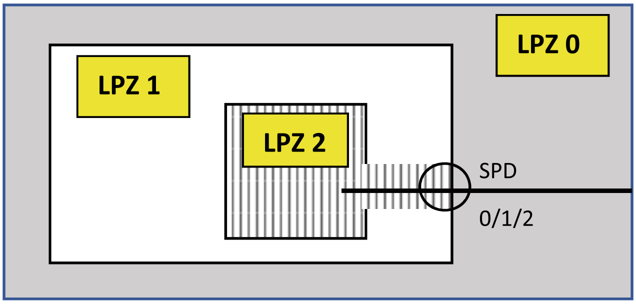

Fig. 4.8 Transition from LPZ 0A to LPZ 2 which is integrated in LPZ 1. Adapted from DEHN

4.6.15 Equipotential Bonding for Power Supply Systems at the Boundary of LPZ1–LPZ2

To limit surge voltage and decrease magnitude of electric field for transitions from LPZ1 to LPZ2 and higher transitions, the electrical power supply and data lines integrated in the equipotential bonding system at each LPZ transition have to be parallel to all metal systems. Shielding the rooms and devices, such as hospital operating rooms and monitoring devices, will further attenuate the electromagnetic effect. The main function of placing surge protective devices at the transitions from LPZ1 to LPZ2 is to further decrease the residual current from surge protective devices in the external zones. It must be capable of reducing induced surges affecting the lines and also surges generated within the LPZ. The discharge capacity of the SPDs used in this situation is Type 2 and it should be able to discharge at least 5 kA (8/20 μs) per phase without any damage. The 8/20 μs wave characterizes current waves from an indirect lightning strike. The surge protective devices can either be assigned to a device for device protection or to form infrastructural basis of a building for proper operation of a device or system depending on the location and type of protective measures taken. Hence, for LPZ transitions from LPZ 1 to LPZ 2 and higher transitions, different types of surge protective devices can be used.

4.7 Equipotential Bonding for Information Technology (IT) Systems

4.7.1 Introduction

It is required in lightning equipotential bonding that all metal conductive parts at the entrance point into the building to be integrated in the equipotential bonding system. This is to reduce the impedance to its minimum. Examples of parts in Information Technology (IT) systems are antenna lines, telecommunication lines with metal conductors, and optical fiber installations containing metal elements. The arresters and shield terminals must be chosen according to the expected lightning current parameters. The following additional steps are recommended to minimize induction loops within buildings: cables and metal pipes should enter the building at the same location, power and data lines should be laid spatially close but shielded. Lastly, unnecessarily long cables should be avoided by laying lines directly.

4.7.2 Equipotential Bonding for IT Systems at the Boundary of $LPZ0_A$ and LPZ1

Lightning current arresters with adequate discharge capacity must be placed as close as possible to entry points into the building to protect information technology lines. Typically, transition from $LPZ0_A$ to LPZ1 requires a discharge capacity up to 2.5 kA (10/350 μs) per core of information technology lines. However, this method is not used to rate discharge capacity for installations containing multiple information technology lines. The partial lightning current to be expected for the information technology cable is calculated. This is followed by determining the impulse current per core by dividing the expected lightning current with the number of single cores in the cable. Therefore, partial lightning current stress per core is lower in multi-core cables compared to cables with only single cores. In this situation, surge protective devices specified with discharge current of 10/350 μs are used. Other than that, surge protective devices with impulse current discharge capacity of up to 20 kA (8/20 μs) are compatible if equipotential bonding is set up for lines at the transition from $LPZ0_B$ to LPZ1. This is because there would be no galvanically coupled partial lightning currents flowing through.

4.7.3 Equipotential Bonding for IT Systems at the Boundary of $LPZ0_A$ and LPZ2

A majority of interference energy from lightning current is discharged by the lightning current arrester from LPZ0 to LPZ1 to protect systems and devices in the building. However, it is also a common occurrence that the level of residual interference from the lightning current arrester is still too high for the terminal devices. To remedy this problem, additional surge protective devices are installed at the transition from LPZ1 to LPZ2 to restrict interference so that residual voltage level is adjusted to dielectric strength of the terminal device. This is so that the electric field will not exceed the level in which the devices are designed to handle and to ensure that the devices are not damaged.

If equipotential bonding is implemented from LPZ0 to LPZ2, partial lightning current of single cores and shields must be determined using the method similar in boundary of $LPZ0_A$ to LPZ1 and the place of installation is chosen after calculating risks and taking into account the layout of the structure. The requirements of the surge protection device to be installed at this point of transition and the requirements on the wiring cause this transition change to be in the latter part of the system. A combined arrester coordinated with the terminal device must be used because such arresters have exceptionally high discharge capacity and low residual interference level and is particularly suited to protect the terminal device. In addition to that, the outgoing line from the protective device to the terminal device is shielded and both ends of the cable shield are included in the equipotential bonding system to prevent inflow of interference.

The installation of combined arresters is recommended in the following situations: the terminal devices are close to the entry point of cables into the building, low-impedance equipotential bonding between protective device and terminal device, line from protective device to terminal device is always shielded and earthed at both ends, and if cost-effective solution is needed. The use of lightning current arresters and surge arresters is recommended if cable distances between the protective device and the terminal device are long, inflow of interference is to be expected, the surge protective devices used for power supply and information technology systems are earthed via different equipotential bonding bars, use of unshielded lines, and existence of high interference in LPZ1.

4.7.4 Equipotential Bonding for IT Systems at the Boundary of LPZ 1 and LPZ 2 and Higher

Additional protective measures are taken at LPZ transitions in buildings to reduce interference level in IT systems. Most terminal devices are installed in LPZ2. Therefore, the protection measures at this zone must ensure that any residual interference is below the nominal value which the terminal device is able to cope with. This can be achieved by installing surge protective devices in areas near the terminal devices, integrating cable shields in the equipotential bonding system, connecting low-impedance equipotential bonding system of the surge protective device for information technology systems with the terminal device, surge protective device for power supply systems, coordinating energy flow of upstream surge protective device with the terminal device, maintaining a distance of at least 130 mm between telecommunication lines and gas discharge lamps, placing distribution board and data distributor in different cabinets, making sure that low-voltage and telecommunication lines cross at 90°, and crossing the cable along the shortest possible route.

4.8 Protection of Antenna Systems

Antenna systems are typically mounted in exposed locations for convenience of radio communication. Hence, it is more likely to be affected by lightning currents and surges if there is a direct lightning strike. Parts of antenna that are connected to an antenna feeder, but cannot be directly connected to the equipotential bonding system, should be protected by lightning current-carrying arresters. It can be assumed that 50% of the direct lightning current flows away via the shields of all antenna lines. If an antenna system is dimensioned for lightning currents up to 100 kA (lightning protection level LPL III), the lightning current splits so that 50 kA flows through the earthing conductor and 50 kA flows through the shields of all antenna cables.

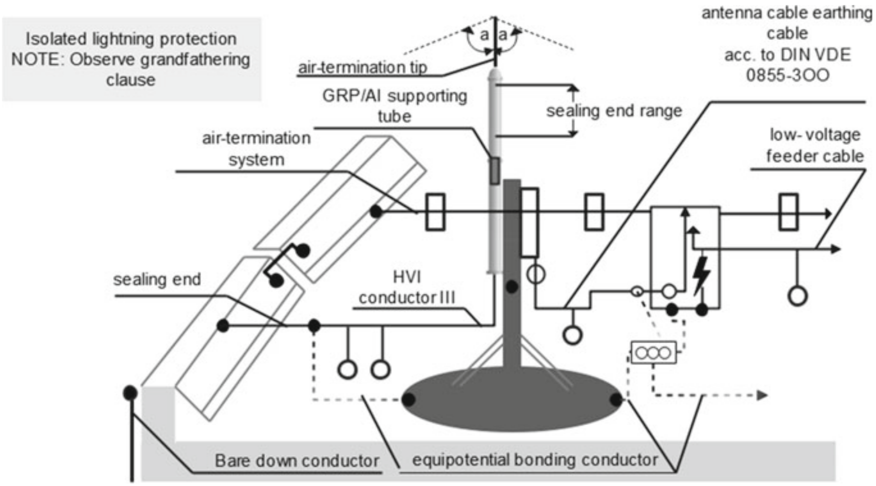

Fig. 4.9 Protection of roof top communication antenna (Credit: DEHN)

Antenna systems which cannot carry lightning currents must be equipped with air-termination systems. The factors that must be taken into account when choosing a suitable cable is the lightning current shared by the antenna line with the down conductor. The required dielectric strength of the cable is determined from the transfer impedance, length of antenna line, and the amplitude of lightning current. Antenna systems on buildings can be protected by air-termination rods, elevated wires, or spanned cables as stated in the lightning protection standard where a certain separation distance must be maintained for each of the methods above, as shown in Fig. 4.9. The main function of electrical isolation of lightning protection system from conductive parts of buildings and isolation of lightning protection system from electrical lines in buildings is to prevent partial lightning currents from entering the control and power supply. Therefore, such isolation is able to prevent electrical and electronic devices from being affected or destroyed by lightning currents.

4.9 Protection of Optical Fiber Installations

Optical fiber installations with metal elements are typically divided into the following categories, namely, cables with metal core but with metal sheath or metal supporting elements, cables with metal elements in the core and with metal sheath and lastly, and cables with metal elements in the core but without metal sheath. The minimum peak value of lightning current must be determined for all types of cables since it has adverse effects on the transmission of optical fiber cables. For such situations, cables capable of carrying lightning currents must be chosen and the metal parts must be connected to equipotential bonding directly or through a surge protection device.

The metal sheath is connected by shield terminals at the entrance point into the building while the metal core is connected by earthing clamp, for example, installing a protective conductor terminal near the splice box. An indirect connection is required via a spark gap to prevent equalizing currents.

4.10 Telecommunication Lines

Telecommunication lines with metal conductors usually consist of cables with balanced or coaxial stranding elements and can be divided into various types. The types are cables without additional metal elements, cables with metal sheath and metal supporting elements, and cables with metal sheath and additional lightning protection reinforcement. The individual cables must be integrated in the equipotential bonding system according to the following methods:

(i) Unshielded cables are connected by surge protective devices which are able to carry partial lightning currents. Partial lightning current per core is obtained by dividing the partial lightning current of the cable by the number of single cores.

(ii) If the cable is shielded and the shield is capable of carrying lightning currents, the lightning current flows through the shield. However, capacitive or inductive interferences can reach the cores and hence it is necessary to use surge arresters. The requirements for this type of cables are that the shield at both cable ends must be connected to the main equipotential bonding system such that it can carry lightning currents. The lightning protection zone concept must be used in the building where the cable ends. The active cores must be connected in the same lightning protection zone, typically LPZ1. LPZ1 is an inner zone protected against direct lightning strikes and is defined as a zone where impulse currents are limited by current distribution and isolating surfaces or by surge protective devices. Spatial shielding may be used to decrease the intensity of lightning electromagnetic field. Unshielded cables in a metal pipe are treated as a cable with a lightning carrying cable shield.

(iii) If the cable shield does not carry lightning currents then the procedure of integration into the equipotential bonding system is similar to a signal core in an unshielded cable if the shield is connected at both ends. The partial lightning current per core is calculated by the partial lightning current of the cable divided by the number of single cores added with a shield. However, if the shield is not connected at both ends, it is treated as if it were not there and the partial lightning current per core is obtained by dividing the partial lightning current of the cable with the number of single cores.

Figure 4.10 shows typical lightning and surge protection for a telecommunication system.

If the exact core load cannot be determined, the appropriate threat parameters given in protection standards must be used. For telecommunications lines, the maximum

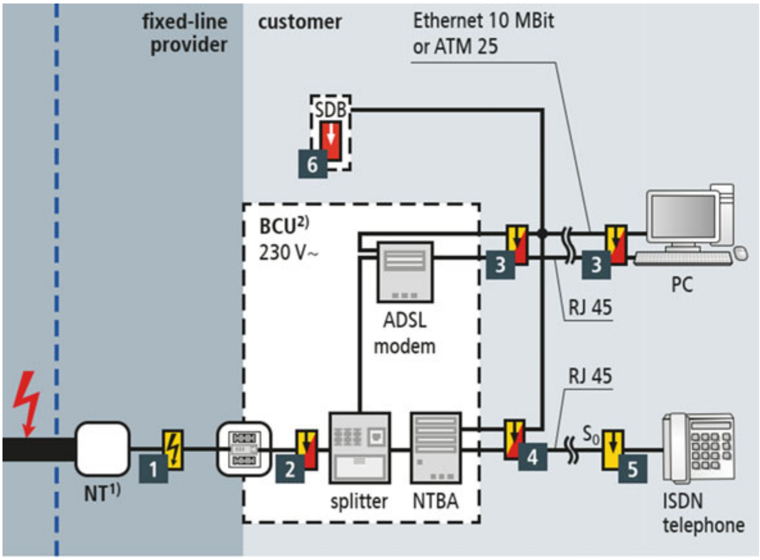

Fig. 4.10 Lightning and surge protection of telecommunications system: ISDN connection with ADSL. Credit: DEHN, with permission

lightning current load per cable core is an impulse of 2.5 kA (10/350 μs). A 10/350 μs current wave indicates a direct lightning stroke with a 10 μs rise time in which the magnitude of current reaches its peak within 10 μs and the impulse has a 350 μs voltage surge duration. The surge protective devices must be able to withstand the lightning current and have a discharge path to the equipotential bonding system.

The advantages of having lightning protection zones are minimal coupling of surge voltages into other cable systems because dangerous lightning currents are directly attenuated at the entry point of the building and at the transition points between zones. It also reduces equipment malfunction due to magnetic field.

4.11 Choosing Internal Lightning Protection System: Type of Surge Protection Devices (SPDs)

Surge protection devices are essential in the protection system. There are three classes of surge protection devices. It is important to choose the appropriate surge arrester because each type is designed for different situations. The Type 1 lightning current arrester is capable of discharging powerful lightning currents and is installed in the main switchboard or at the entry to the building and should be incorporated in lightning protection system, for example, when lightning rods or meshed cages are installed. Type 2 surge arresters are used in main and sub-distributors. It discharges currents from indirect lightning strikes, protects from inductive and conductive overvoltages, and also switching transients. The Type 3 surge arrester has very low discharge capacity. Surge voltages typically occur between the phase to neutral cable. The Type 3 surge arrester is used to protect against inductive coupling and switching surges in device power circuits. It is a supplementary surge protective device used in surge arrester Types 1+2+3 combinations where there is a lightning protection system or in Types 2+3 combination when there is no lightning protection system. Choosing a suitable lightning protection system involves risk assessment to determine which areas are at the most risk or at least risk. A rule of thumb is to always install a Type 2 surge arrestor and if the distance between the surge arrestor and the equipment to be protected is greater than 10 m, a Type 2 or Type 3 arrestor is added because wave reflection starts increasing from 10 m. Surge wave reflections can double the voltage at 30 m. Therefore, it is necessary to install a surge protection device if the distance to the equipment exceeds 10 m. Although surge arrestors do not trip, it is important to protect them to work optimally and prolong its lifespan. There are a few situations that damage the surge protection device. One such situation is thermal runaway which is caused by constant excessive current which does not exceed the device specification, but it eventually leads to slow destruction of internal components. This is sometimes called electronic rust. In this situation, a thermal fuse in the surge protection device disconnects it. Next, short circuit occurs because of a fault at power frequency system at 50 Hz electrical distribution network or due to the current exceeding the maximum current flow capacity. To protect the surge protection device, an external or integrated short circuit protection device such as a fuse or circuit breakers is installed to disconnect the surge protection device.

When designing the protection system for a building, it is important to determine the quantity and type of surge protection device, maximum discharge current, and short circuit current at the point of installation. Table 4.4 summarizes the location and type of surge protection device to be installed.

Table 4.4 Summary of type of SPD to be used

Distance between sensitive equipment from lightning protection system in main switchboard	Lightning rod on the building or within 50 m of the building	
	No	Yes
D < 30 m	One Type 2 SPD in main switchboard	One Type 1+2 SPD in main switchboard
D > 30 m	One Type 2 SPD in main switchboard, one Type 2 or Type 3 SPD in enclosure near to sensitive equipment	One Type 1+2 SPD in main switchboard, one Type 2 or Type 3 SPD in enclosure near to sensitive equipment

4.12 External Lightning Protection

A lightning protection system is a system that protects buildings from direct lightning strikes, injected lightning current as well as from potential fire. The function of external lightning protection system is to prevent direct lightning strikes to buildings via an air-termination system. Moreover, the external protection systems conduct the lightning current to the ground safely via a down-conductor system and distributes it in the ground via an earth-termination system.

When there is a lightning strike there is a possibility of an explosion at a structure under construction. Hence, it is essential to design either an isolated or non-isolated protection system depending on the material with which the structure is constructed. If the structure is built with a combustible material, there is a high chance of explosion due to a lightning strike and this requires the design and installation of an isolated lightning protection system.

An external LPS consists of

- An air-termination system.
- Down-conductor system.
- Earth-termination system..

Air rods may be used for air termination. These are small, vertical protrusions designed to act as the "terminal" for a lightning discharge. Most are topped with a tall, pointed needle or a smooth, polished sphere. Alternatively, they may be in the form of catenary (suspended conductors) or meshed conductor network. These should be installed at corner, exposed points, and edges of the structure. The places where these air-termination systems should be positioned are determined by one of the following methods.

i. **The Rolling Sphere Method (RSM)**

This is a method which identifies the areas of the structure that need protection, taking into account the possibility of side strikes to the structure. This method uses rolling spheres to identify the areas that are vulnerable and that require air termination. This is illustrated in Fig. 4.11.

Rolling sphere method is based on an electro-geometric model. For a cloud-to-ground lightning, a downward leader grows from cloud towards the earth. As the downward leader gets close to the earth, when it is at about ten to hundreds of meters from the earthed structure, upward leaders start to grow towards the head of downward leader. The intersecting point at which the downward leader and the upward leader meet is the point of lightning strike. The closest distance between starting point of the upward leader and the head of downward leader is known as the final striking distance, which corresponds to the radius of the rolling sphere. The proportionality between final striking distance (radius of the rolling sphere) and peak value of lightning current I is given by

$$r = 10 \cdot I^{0.65} \tag{4.19}$$

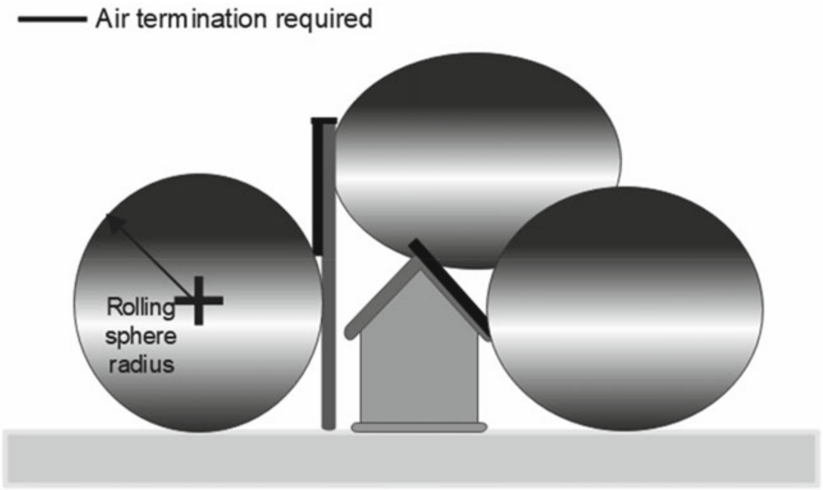

Fig. 4.11 Application of the rolling sphere method

where

r is the radius of the rolling sphere in m and I is the peak value of the lightning current in kA.

In order to use the rolling sphere method, a scale model of the structure to be protected is required. The rolling sphere is rolled around the scale model, and the points where the circumference of the sphere touches the model may be vulnerable to lightning strikes. The relation between the lightning protection level (LPL) and the radius of the rolling sphere is shown in Table 4.5. The area where the sphere does not touch is less vulnerable to lightning strikes, as shown in Fig. 4.11.

ii. The Protective Angle Method (PAM)

Table 4.5 Relationship between lightning protection level, interception probability, final striking distance, and minimum peak value of lightning current

Lightning protection level (LPL)	Probabilities for the limits of the lightning current parameters		Radius of the rolling sphere (final striking distance), r in m	Minimum peak value of lightning current, I in kA
	Minimum value	Maximum value		
I (maximum risk)	0.99	0.99	20	3
II	0.97	0.98	30	5
III	0.91	0.95	45	10
IV (minimum risk)	0.84	0.95	60	16

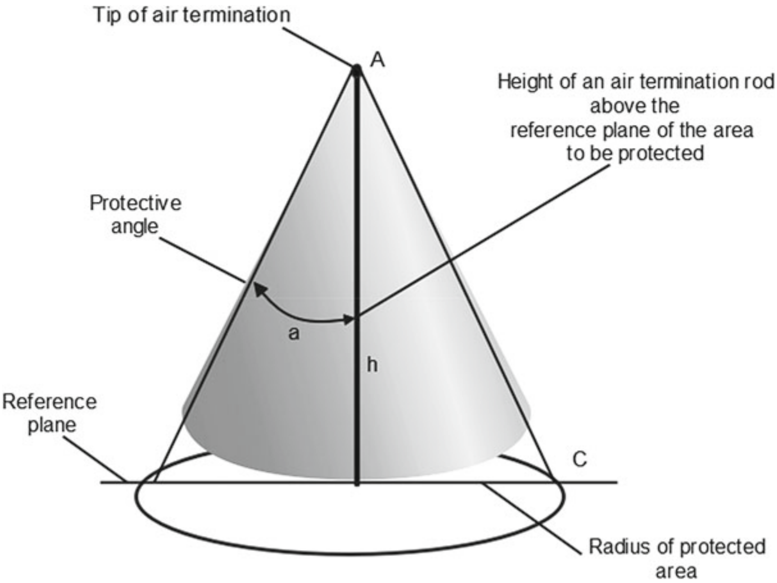

Fig. 4.12 The protective angle method for a single air rod. Adapted from DEHN

The protective angle is defined by the angle created between the tip of the vertical rod used for air termination and the line projected down to the surface on which the rod sits. The cone from the rod is called a cone of protection. The protective angle differs depending on the class of LPS. But in most cases it is 45°.This method is best suited with simple shaped buildings and is valid only up to a height equal to the rolling sphere radius for the corresponding LPL. The PAM is shown in Figure 4.12.

iii. The Mesh Method (MM)

Meshed air-termination system can be used regardless of the height of structures and shape of the roof. By using the outer edges and ridge of the structure serving as an air-termination system, the individual meshes can be placed at any desired points. The air-termination conductor on the outer edges of the building must be placed as close as possible to the edges. Using the rolling sphere method on meshed conductor network, the mesh must be mounted at certain distance above the roof plane, to make sure that the rolling sphere does not touch the roof plane, as shown in Fig. 4.13. Table 4.6 shows the typical mesh sizes.

- Down conductors:

Down conductor is the direct route from the air-termination system to the earth-termination system. The earth-termination system can be ground rods which are long, thick, and heavy buried deep into the earth around a protected structure. The down-conductor cables (which carry lightning currents from the air-termination rods to the ground) are run along the top and around the edges of roofs, then down one

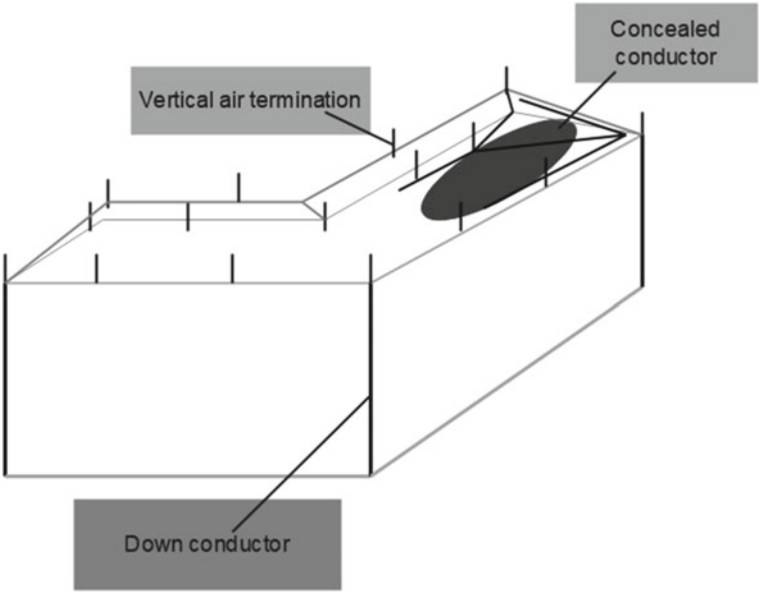

Fig. 4.13 Concealed air-termination network. Adapted from DEHN

Table 4.6 Mesh size based on lightning protection level

Lightning Protection Level (LPL)	Mesh size
I	5 × 5 m
II	10 × 10 m
III	15 × 15 m
IV	20 × 20 m

or more corners of a building to the ground rod. They are connected to these rods to complete a safe path for a lightning discharge around a structure.

It is advisable to use metal parts on or within the structure to be incorporated into the Lightning Protection System (LPS). Examples of these are when the internal reinforcing bars are connected to external down conductors through clamps or using the reinforcing bars as down conductors. But when doing so the continuity from the air termination must be tested.

- Earth-termination system:

The earth-termination system is vital for the dispersion of lightning current safely and effectively to the ground. A good earthing connection should possess the following characteristics:

1. Low electrical resistance between the electrode and the earth.
2. Good corrosion resistance.

The standards state that the earthing resistance should be 10 Ω or less for a good and efficient lightning protection.

There are three types of basic earth electrode arrangements which are given below:

- Arrangement A: Horizontal or vertical electrodes connected to each down conductor fixed on the outside of the structure.
- Arrangement B: This is a fully connected ring earth electrode that is suited around the periphery of the structure and is in contact with the surrounding soil.
- Foundation earth electrode: These are the conductors that are installed in the concrete foundation of the structure as described above.

Adding a protection system doesn't prevent a strike, but gives it a better, safer path to ground. The air terminals, cables, and ground rods work together to carry the large lightning currents away from the structure, preventing fire and most appliance damage:

4.13 Air-Termination Systems

4.13.1 Isolated and Non-isolated Air-Termination Systems

Isolated air-termination system protects the buildings from a direct lightning strike by using air-termination rods and mast with cables spanned over it. During the installation of air-termination systems, the separation distance between air-termination system and the buildings must be fixed. Isolated air-termination system is usually installed for structures with roof that are covered with flammable materials and structures located in hazardous area. Glass Reinforced Plastic (GRP) air-termination system is frequently used for buildings with roof-mounted system, such as heat exchanger and ventilation system. An isolated air-termination system consists of air-termination rods and air-termination conductors. A single air-termination rod is able to protect a small roof-mounted structure, such as a small roof-top fan. Self-supporting air-termination rods up to the height of 14 m are installed by using tripod stand that is fixed on a concrete base. Additional supports are required for higher air-termination rods so that they can withstand the wind load. Usually, they are widely used for lightning protection of Photovoltaic (PV) solar systems and antennas. Air-termination conductors are usually installed above the structure that need to be protected. These conductors create a tent-shaped protected region at the side and a cone-shaped protected region at the ends. The protective angle varies according to the class of LPL and the height of the air-termination system above the structure that needs to be protected. The dimensions of the air-termination conductors are determined by using the rolling sphere method (RSM).

Non-isolated air-termination system can be installed in two ways, depending on the type of the roof material. If the roof is made of non-flammable material, the conductors of air-termination system are installed directly on the surface of the buildings. However, if the roof is made of highly flammable materials, the flammable parts of the roof must be kept at a certain distance from the conductors of the air-termination system to ensure there is no direct contact between the flammable parts of the roof and air-termination system.

4.13.2 Air-Termination System for Buildings with Different Types of Roof

Every type of roof must install its unique, suitable design of air termination in order to maximize the efficiency of the external lightning protection system. There are eight different types of buildings that have their own specific designation:

1. Gable roofs.
2. Flat roofs.
3. Metal roofs.
4. Thatched roofs.
5. Accessible roofs.
6. Green roofs.
7. Steeples and churches.
8. Wind turbines.

4.13.3 Air-Termination System for Building with Gable Roofs

Buildings with gable roof are usually installed with meshed network of air-termination system. The individual meshes are placed by using ridge, outer edges and other metal parts as a part of the air-termination system. Normally, a metal gutter is used for closing the meshed network of air-termination system on the surface of the roof. If the gutter is connected in an electrically conductive way, a gutter clamp is mounted at the cross point between the gutter and air-termination system.

Non-conductive roof-mounted structures are sufficient to protect the roof against lightning strikes provided they do not exceed the final striking distance of 0.5 m from the plane of the meshed network air-termination system. If exceeded, it is required that these structures are connected to the nearest air-termination conductor and equipped with air-termination system. On the other hand, metal roof-mounted structures with non-conductive connections do not need to be equipped with air-termination system as long as the roof-mounted structures are less than 0.3 m from roof level, have a maximum enclosed area of 1m^2, and with a length of less than 2 m.

Air-termination rod must be installed for a chimney so that the whole chimney is under the lightning strikes protection region. The dimension of the air-termination rod is determined by using the Protective Angle Method (PAM). If the chimney is made of bricks, the air-termination rod can be mounted directly on the chimney. However, if there is metal pipe within the chimney, the chimney must be equipped with isolated air-termination system and installed with air-termination rods using spacers. The metal pipe is then connected to the equipotential bonding system.

A similar method is used to protect parabolic antennas. If there is a direct lightning strike to the antenna, the lightning current will enter the building through coaxial cable, causing damages and interference. This can be avoided by equipping the antenna with isolated air-termination system.

4.13.4 Air-Termination System for Buildings with Flat Roofs

The meshed network of air-termination system is installed for buildings with flat roofs according to the mesh size and LPL as shown in Table 4.5. The roof parapet which acts as the natural component of the air-termination system is connected with air-termination conductors. The length of materials of the roof parapet changes according to the changes in temperature. Therefore, the individual segments are connected by using bridging braids, brackets, or cables to ensure that they are always interconnected and electrically conductive when they are changing length due to changes in temperature. Unfortunately, the material used can be melted when struck by lightning. Thus, an air-termination tip is installed using the rolling sphere method. Roof sheeting will move across the roof surface during windy condition if they are not fixed properly on the roof surface. A common way of fixing the air-termination conductor safely is by using the roof conductor holder with strips. The roof conductor and strips have to be placed next to a roof sheeting joint at a distance of around 1 m. If the slope of the roof is less than 5°, every second roof conductor holder is fixed, while if the slope of the roof is more than 5°, every roof conductor holder must be fixed. However, some roof conductor holder is not suitable for use if the angle of the roof slope is more than 10°.

4.13.5 Air-Termination System for Buildings with Metal Roofs

When lightning strikes a metal roof without any protection system, it will leave a hole and damage the metal roof. Therefore, an external lightning protection system with lightning current-carrying wire and clamps are installed on the metal roof to avoid this kind of damages. A separate air-termination system with many air-termination tips is installed on the metal roof to ensure the rolling sphere does not touch the metal roof. The recommended height of air-termination tip is shown in Table 4.7.

There are numerous types of air-termination conductor holders available for metal roof, such as round standing seam, standing seam, and trapezoidal. The conductor in the air-termination conductor holder located at the highest point of the metal roof must be fixed, while the conductors in other air-termination conductor holders are routed loosely because of the changes in length with changes in temperature.

Table 4.7 Lightning protection for metal roofs

Distance of the horizontal conductors, in m	Height of the air-termination tip, in m
3	0.15
4	0.25
5	0.35
6	0.45

4.13.6 Air-Termination System for Buildings with Thatched Roofs

Buildings with thatched roofs are usually installed with external lightning protection systems of Lightning Protection Level (LPL) Class III. Air-termination conductors on buildings with thatched roof have to be fastened with insulating material in order to allow them to move freely. Note that some distance should be maintained around the eaves. The exact distance between each down conductor can be calculated according to the separation distance specified in the lightning protection standard. Generally, ridge conductors must have span with 15 m width and 10 m length of down conductors without any other supports. Anchor bolts and washers are used to connect span stakes to the roof structure. The metal parts around the roof surface such as antennas, metal sheet, and wind vanes have to be protected by isolated air-termination system. Air-termination rods and air-termination conductors must be installed on the building in order to increase the efficiency of lightning protection system. If the thatched roof is located near to a metal roofing material, non-electrically conductive roofing material is inserted between the metal roofing material and thatched roof.

A new possibility to install an isolated lightning protection system is by the use of insulated down conductors. This type of lightning protection system is widely installed in historical farmhouses. The rolling sphere method is used when designing the air-termination system to determine the protected region from lightning strikes. A GRP supporting tube is used to elevate the air-termination system and support the insulated down conductors.

4.13.7 Air-Termination System for Buildings with Inaccessible Roofs

It is impossible to mount air-termination conductors on inaccessible roof. However, the air-termination conductors can be installed in the joints between the decks. The air-termination studs are then fixed at the intersections of the meshed network of air-termination system as the point of lightning strike. The rolling sphere and protective angle methods are used to determine the dimension of the air-termination system when designing an external lightning protection system. These air-termination systems consist of air-termination rods and these rods are fixed to the parapet.

4.13.8 Air-Termination System for Buildings with Green Roofs

Meshed air-termination system is installed for buildings with green roofs. A meshed air-termination system is usually installed on the surface of the green roof for easier inspection. The common wire material used for air-termination system of green roof is stainless steel.

4.13.9 Air-Termination System for Steeples and Churches

A lightning protection system of class III LPL is required for steeples and churches. Steeples with the height of less than 20 m must be equipped with a down conductor. This down conductor has to be connected to an external lightning protection system of the nave if the steeple is joined together with the nave. Steeples with the height that is higher than 20 m must be equipped with two or more down conductors and one of the down conductors must be connected to the external lightning protection of the nave. The down conductors of the steeples have to be routed along the outer surface of the steeple to the ground because the installation inside the steeple is not allowed.

Some of the modern churches are made of reinforced concrete. The reinforced steel can be used as a natural component of down conductors provided that it has permanent, electrically conductive connection. Lightning equipotential bonding or surge protection of the electrical equipment, for instance, power installation, telephone, and loudspeaker system, is installed at the entrance of the building, while for the bell controller in the steeple, surge protection is installed at the control system.

4.13.10 Air-Termination Rods Subjected to Wind Loads

Self-supporting air-termination rods are installed on the roof of the building. They experience mechanical stress due to wind speeds. Therefore, isolated air-termination rods must meet the requirement regarding their mechanical stability. The local wind conditions and the height of the buildings have to be taken into account when calculating the wind load stress.

In order to design self-supporting air-termination rods which are able to withstand required wind load stress, the tilt resistance, bending resistance of the air-termination rods, and the fixed separation distance between the protected structures must be determined. The stability of the air-termination rods is calculated by considering the following: the area of the air-termination rods exposed to wind, the area of the braces exposed to wind, the weight of the air-termination rods and braces, the weight of the post, and tilt lever of the post. Since the wind load stress will exert bending stress on the air-termination rod, the break resistance of the air-termination rod has to be determined. The calculation to determine bending stress of the air-termination rod must include the following information: Finite Element Method (FEM) calculation model, characteristics of the material used (density, elasticity, cross-sectional value), and wind loads.

4.13.11 Safety System and Lightning Protection

Industrial buildings with flat roofs are commonly installed with safety rope system. The advantage of using safety rope system is that the operators can walk along the rope by hooking the rope slide or rope guide within the safety rope system. Lightning protection system and rope safety system are two different systems that are installed on the roof of the building. Each of them works independently and therefore they must be installed with their own experts. The rope safety system should be installed within the protected region of the air-termination system to prevent it getting damaged from lightning strikes.

4.14 Down Conductors

4.14.1 Determination of the Number of Down Conductors

A down conductor is an electrically conductive connection between earth-termination system and air-termination system. The function of the down conductor is to conduct the lightning current straight to the earth without causing any damage to the building. There are some factors that need to be paid attention to when mounting the down conductor to minimize or avoid the damage caused by the lightning current when discharging to the earth-termination system:

- The length over which the current flows should be kept as short as possible, preferably vertical and straight without looping.
- Several parallel current paths may exist.

The number of the down conductors required is determined using the perimeter of the projection from the external edges of the roof to the ground surface. The distance between each consecutive down conductors is categorized depending on the class of LPL as shown in Table 4.8. The exact number of down conductors required can only be obtained through calculation of the separation distance. The separation distance can be reduced through balancing the distribution of the lightning current by interconnecting down conductors at the ground level.

Table 4.8 Distance between down conductors based on class of LPL

Class of LPL	Typical distance in m
I	10 m
II	10 m
III	15 m
IV	20 m

4.14.2 Down Conductors for a Non-isolated Lightning Protection System

Down conductors for a non-isolated lightning protection system are usually direct mounted onto the building without separation distance. This is due to the rise of temperature when lightning strikes the external lightning protection system. Another reason why down conductors are mounted directly on the building is because of the non-flammable material used for the wall. If the wall is made of flammable material it must be ensured that the rise of temperature due to lightning current flows is not dangerous.

4.14.2.1 The Installation of Down Conductor

Down conductor is installed with direct continuation from air-termination system and shortest possible vertical straight line connection to the ground directly. Down conductors cannot be installed in the downpipe or gutter because the moisture of the gutter and downpipe will corrode the down conductor. The down conductors are recommended to have a fixed separation distance from windows and doors.

4.14.2.2 Natural Components of Down Conductor

Some of the parts of the structure that may be used as natural components of down conductor are stated as follows:

i. Metal installations.
ii. Metal framework of structure.
iii. Interconnected reinforcement of the structure.
iv. Precast parts.
v. Facade elements, ISO (International Standards Organization) standard rails, and metal sub-structures of facade.

4.14.2.3 Internal Down Conductors

Internal down conductors are installed if the edges of the structures are four times greater than the distance of down conductors, depending on the class of LPL. Some of the lightning current may flow through the internal down conductors within the building, which needs to be constrained.

4.15 Earth-Termination System

Earth-termination system is an external lightning protection system that allows energy from lightning strikes to be dissipated quickly into the earth with the usage of earth electrodes. The overall resistance for the whole earth-termination system should be less than 10 Ω. The earth electrodes are categorized according to their installation location.

1. Surface earth electrodes consist of the following:
   Earth electrodes are installed into the ground up to 1m depth.
   Round materials or flat strips are used.
   Common designs are radial, ring, or meshed earth electrodes.
2. Earth rods are earth electrodes that are driven vertically into the deep ground.
3. Foundation earth electrodes: one or more conductors that are combined together and connected to the earth in a large area.
4. Control earth electrode: arrangement and the shape of earth electrodes which serve to control the ground potential.
5. Ring earth electrodes: earth electrodes that are formed in a closed ring.
6. Natural earth electrode: metal parts that are in contact with water or with earth.

The earth electrode consists of three types of resistance-related parameters which are the earth resistivity, ρ_E; the earth resistance, $\mathrm{R_A}$; and conventional earth impedance, $\mathrm{R_{st.}}$ The earth resistance $\mathrm{R_A}$ can be explained with the aid of a metal sphere that is buried into the ground. The earth resistance $\mathrm{R_A}$ includes some of the resistances of the single sphere layer. The resistance of the sphere layer is calculated by using following formula:

$$R = \rho_E \cdot \frac{l}{A}, \tag{4.20}$$

where

ρ_E is the earth resistivity of the ground,
l is the assumption of the thickness of the sphere layer, and
A is the center surface of the sphere layer.

The earth resistance $\mathrm{R_A}$ is then calculated by using the following formula:

$$R_A = \frac{\rho_E \cdot 100}{2\pi \cdot r_k} \cdot \frac{1 + \frac{r_k}{2d}}{2} \tag{4.21}$$

where
ρ_E is the earth resistivity of the ground in Ωm,
d is the burial depth in cm, and
r_k is the radius of the metal sphere.

The earth resistivity ρ_E can be calculated from the measured resistance R by using the following formula:

$$\rho_E = 2 \cdot \pi \cdot d \cdot R, \tag{4.22}$$

where
d is the probe spacing in m,
R is the measured resistance in Ω, and
ρ_E is the earth resistivity of the ground.

If there are a few earth rods that are installed near to each other in an area, Table 4.9 can be used to calculate the earth resistance from the distance between the electrodes. As shown in Fig. 4.14, the earth resistance of the earth electrodes is frequency dependent.

We may classify two types of earth electrode arrangement for earth-termination system. These are the Type A and Type B arrangements. The arrangement of Type A earth electrodes is the placement of earth rods (vertical earth electrodes) or surface earth electrodes (horizontal radial earth electrode) that are connected to the down conductor. This type of arrangement needs two or more earth electrodes. If different types of earth electrodes (horizontal and vertical electrodes) are used together, the

Table 4.9 Calculating earth resistance

Earth electrode	Approximate formula	Auxiliary
Surface earth electrode (radial earth electrode)	$R_A = \frac{2 \cdot \rho_E}{l}$	–
Earth rod	$R_A = \frac{\rho_E}{l}$	–
Ring earth electrode	$R_A = \frac{2 \cdot \rho_E}{3 \cdot d}$	$d = 1.13 \sqrt[2]{A}$
Meshed earth electrode	$R_A = \frac{\rho_E}{2 \cdot d}$	$d = 1.13 \sqrt[2]{A}$
Earth plate	$R_A = \frac{\rho_E}{4.5 \cdot a}$	–
Hemispherical or foundation earth electrode	$R_A = \frac{\rho_E}{\pi \cdot d}$	$d = 1.57 \sqrt[3]{V}$

R_A is Earth resistance (Ω),
ρ_E is Earth resistivity (Ωm),
l is length of the earth electrode (m),
d is diameter of a ring earth electrode, the area of the equivalent circuit or a hemispherical earth electrode,
A is area (m^2) of the enclosed area of a ring or meshed earth electrode,
a is edge length (m) of a square earth plate
(in case of rectangular plates: a is substituted with $\sqrt[2]{b \cdot c}$, where b and c are the two sides of the rectangle), and
V is volume of a single foundation earth electrode

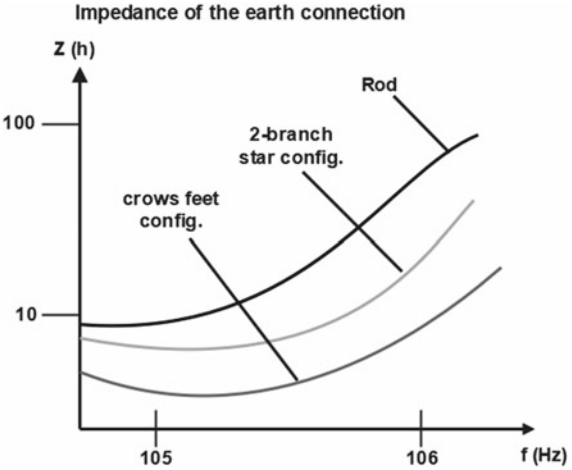

Fig. 4.14 Frequency-dependent earth impedance of different earthing systems. Adapted from: DEHN

equivalent total length of horizontal and vertical earth electrodes has to be determined. Generally, earth rods are installed vertically deep into natural soil because the deeper the soil layers they are installed into, the lower the earth resistivity, as compared to the areas that are close to the earth surface. The earth electrodes should be placed at least 500 mm below the ground surface. The electrodes must be distributed as evenly around the building as possible to prevent electrical coupling. Earth rods which are made of high-alloy stainless steel are used widely due to its large range of benefits.

Type B earth electrode arrangement is the arrangement with earth electrodes encircling the structures or buildings that need to be protected from lightning strikes. The arrangement is also known as foundation earth electrodes. If the building cannot be encircled in a closed ring arrangement, the ring must be completed by using the conductors inside the building, such as pipework or other electrically conductive metal components. About 80% length of the earth electrodes is driven into the soil so that it can be used as a base to determine the separation distance. The earth electrodes should be driven at least 500 mm below the surface of the ground. The ring earth electrode is recommended in natural soil to ensure that the earth resistance is not affected. The earth electrode chosen should resist corrosion, preferably made of stainless steel. Type B earth electrode arrangement is suitable for installing on rocky ground because it is often the only way to install earth-termination system on a rocky ground with a resulting low resistance. Ideally, Type B earth electrode is always used for: (i) dissipating lightning current from down conductors to the ground, (ii) connecting equipotential bonding of down conductors at the ground, (iii) manipulating the potential in the vicinity of electrically conductive wall of a building, and (iv) buildings with high fire risk or with many electronic equipment.

Some of the systems that need special requirements when installing earth-termination system are: (i) electrical systems with the disconnection requirements of the relevant system configuration, (ii) equipotential bonding, (iii) electronic systems such as data information systems, (iv) antenna earthing, (v) electromagnetic compatibility (EMC) earthing, and (vi) transformer power substation.

4.16 Manufacturer's Test of Lightning Protection Components

Lightning protection components that are made of metal material such as air-termination conductors, air-termination rods, earth electrodes, or clamps, which are exposed to seasonal changes or different weather conditions must undergo artificial conditioning or aging which are tested to ensure their suitability for real-time application. The testing of metal lightning protection components with artificial conditioning or aging can be done in two steps.

1. Salt mist treatment:

   This test forms an artificial saline condition to test the metal lightning protection components to determine whether they can withstand it for a long period of time. The test chamber consists of a salt mist chamber, where the metal components are sprayed with sodium chloride (NaCl) solution three times with 2-hour period at a temperature between 15 and 35 °C and relative humidity of 93% for 20 to 22 h, to ensure their sustainability.

2. Humid sulphurous atmosphere treatment:

   This test forms a condensed humidity condition that is filled with sulphur dioxide. The metal lightning protection components are accessed in seven test cycles. Each cycle has an 8-h heating process at a temperature around 40 °C followed by a 16-h duration of saturated humidity condition, with a total duration of 24 h.

Another test that needs to be done is the testing of connecting components such as clamps, which are used to connect air-termination conductors, down conductors, and earth entries with one another during the installation of external lightning protection system. These clamps must be able to withstand the thermal and electrodynamic forces that are produced by lightning current flow. Table 4.10 shows that the permissible material combinations of air-termination system and down conductors with one another or with other structural parts.

Table 4.10 The possible material combination of air-termination system and down conductors with one another or with other structural parts

	Steel	Aluminum	Copper	StSt (V4A)	Titanium	Tin
Steel (StZn)	Yes	Yes	No	Yes	Yes	Yes
Aluminum	Yes	Yes	No	Yes	Yes	Yes
Copper	No	No	Yes	Yes	No	Yes
StSt (V4A)	Yes	Yes	Yes	Yes	Yes	Yes
Titanium	Yes	Yes	no	Yes	Yes	Yes
Tin	Yes	Yes	yes	Yes	Yes	Yes

4.17 Shielding of electrical and electronic systems against LEMP

4.17.1 Magnetic Field Calculations for Shielding

The primary interference for devices and installations is from the lightning currents and the associated electromagnetic field LEMP. First approximation is used to determine the complex distribution of the magnetic field inside a grid-like shield. Magnetic field coupling of each rod in the grid-like shield (shown in Fig. 4.15) with all other rods including the simulated lightning channel is considered in performing the calculations. To determine either the electromagnetic field of the first return stroke or the subsequent return stroke, the magnetic fields produced by the following are considered:

- Maximum value of the current of the first positive return stroke ($i_{f/max}$).
- First negative return stroke current ($i_{fn/max}$).
- Maximum value of the current of the subsequent return strokes ($i_{s/max}$).

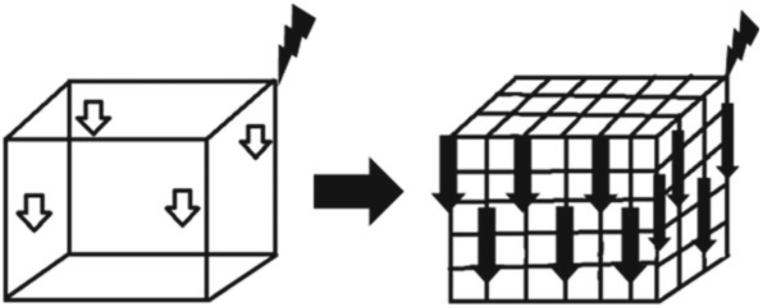

Fig. 4.15 Reduction of the magnetic field using grid-like shields (Adapted from DEHN)

Internal electronic systems may only be installed within a safety volume with a safety distance from the shield of the LPZ. To calculate the safety distances, the following must be considered:

$d_{s/1}$—Safety distance in case of a spatial shield of LPZ1 if lightning current flows into the spatial shield. (The spatial shield of LPZ1 produces a magnetic field due to the currents induced in it by the LEMP.)

$d_{s/2}$—Safety distance in case of spatial shield if no lightning current flows into these spatial shields.

4.17.2 Calculation of the Magnetic Field Strength in Case of A Direct Lightning Strike

In order to attenuate the amount of lightning LEMP radiated energy penetrating into sensitive electronic equipment, we need to form cage-like shields which would attenuate the energy that gets into the shielded area. It is important to ensure that the size of the grid mesh is less than the minimum wavelength of the electromagnetic field it needs to keep out. The main task is to determine the size of the mesh-like cage we need to construct to get a particular shielding factor to keep the equipment safe and stable. To calculate the magnetic field strength in case of a direct lightning strike, the following formula may be used:

$$H_1 = \frac{k_h.I_0.h_m}{d_w.\sqrt{d_r}} \text{in A/m}, \tag{4.23}$$

where

d_r is the shortest distance between the point considered and the roof of the shielded LPZ 1 in m;

d_w is the shortest distance between the point considered and the wall of the shielded LPZ 1 in m;

I_0 is the lightning current in LPZ 0A in A;

k_h is the configuration factor, typically kh = 0.01 in $1/\sqrt{m}$; and

h_m is the mesh size of the grid-like shield of LPZ 1 in m.

Depending on which lightning stroke is being considered, the current I_0 may be set as one of the following three currents:

$I_{f/max}$ is the maximum value of the first positive stroke current in accordance with the LPL in A;

$I_{fn/max}$ is the maximum value of the first negative stroke current in accordance with the LPL in A; and

$I_{s/max}$ is the maximum value of the subsequent stroke current in accordance with the LPL in A.

Depending on the shielding factor SF required, we have

$$d_{s/1} = \frac{h_m.SF}{10}\ for\ F \geq 10\ in\, m \tag{4.24}$$

$$d_{s/1} = h_m\ for\ SF \leq 10\ in\, m \tag{4.25}$$

where

SF is the shielding factor in dB and

h_m is the mesh size of the grid-like shield in m.

4.17.3 To Determine the Magnetic Field in Case of Nearby Lightning Strike

To calculated the magnetic field strength in case of a nearby lightning strike:

$$H_0 = \frac{I_0}{2.\pi.r} \text{in A/m}, \tag{4.26}$$

where

I_0 is the lightning return stroke current in LPA0A in Aand

r is the distance between the point of strike and the center of the shield volume in m.

From this follows, for the maximum value of the magnetic field in LPZ 0, the shielding factor SF is determined from Table 4.11.

h_m = mesh size [M] (hm ≤ 5m); rc = rod radius [m]; the permeability of the shield wires is μ and it approximates to 200.

In Table 4.12, the shielding factors for different materials used and the size of the shield mesh at two different frequencies of the LEMP frequency spectrum are shown. In Table 4.12, w_m is the width of the mesh and r is the distance of the lightning strike from the mesh. Note that where shielding from very high-frequency wireless communication system signals need to be constructed, with frequencies much higher (e.g. 2 GHz, or 2×10^9 Hz) compared to much lower frequencies for lightning (e.g. 5 to 100 MHz or 5×10^6 to 10^8 Hz), mesh sizes should be very much smaller. If the frequency of the signal is f, then the wavelength is $\lambda = c/f$, where c is the velocity of light, $c = 3 \times 10^8$ m/s.

Table 4.11 Determining the shielding factor SF

Material	Shielding factor SF (dB)	
	25kHz (first stroke)	1MHz (subsequent stroke)
Copper or aluminum	$20\log(8.5/h_m)$	$20\log(8.5/h_m)$
Steel	$20\log\frac{(8.5/h_m)}{\sqrt{1+(18\times10^{-6})/r_c^2}}$	$20\log(8.5/h_m)$

Table 4.12 Magnetic attenuation of grids in case of a nearby lightning strike

Example steel grid			
w_m (m)	r (m)	dB at 25 kHz	dB at 1 MHz
0.012	0.0010	44	57
0.100	0.0060	37	39
0.200	0.0090	32	33
0.400	0.0125	26	27

The reduction of the magnetic field intensity from H_0 to H_1 in the LPZ 1 depends on the SF and is given by

$$H_{1/max} = \frac{H_{0/max}}{10^{\wedge}(SF/20)} \text{ in A/M}, \tag{4.27}$$

where

SF is the shielding factor and

H_0 is the magnetic field in LPZ 0 in A/m.

4.17.4 Implementation of the Magnetic Shield Attenuation of Building/Room Shield

To implement the magnetic shield attenuation of the building/room shields, extended metal components are crucial when shielding against the magnetic fields. Generally, a meshed interconnection is used to create an effective electromagnetic shield. The distance between adjacent mesh wires should be less than the lowest wavelength of the incoming signal from which we want to shield the systems inside the shielded cage. The steel reinforcement, when used in building, can be designed into an electromagnetic cage (hole shield). In reality, it is not possible for us to weld or stick together every junction in very large structures. A system typically having a size around 5 m is usually used to install a meshed system of conductors into the reinforcement. This meshed network is connected in an electrically safe way at the cross points.

Reinforcement mats in concrete are suitable for shielding purposes and it is usually laid at a later date when upgrading the existing system. It requires reinforcement mats to be galvanized to protect them from corrosion. The magnetic field inside the structure can be reduced over a wide frequency range by means of reduction loops, which arise as a result of the meshed equipotential bonding network. Three-dimensional meshed equipotential bonding network is formed by the interconnection of all metal components both inside and on the structures. This equipotential bonding network when installed in the lightning-protection zones will reduce the magnetic field by a factor of 2.

4.17.5 Cable Shielding

Cables need to be shielded as well. By shielding the cable, we reduce the effect of interference on the active cores and the interference emitted from the active cores to neighboring systems.

4.17.5.1 *Double-Ended Shield Earthing*

For good conductivity, shielded cables must be continuously connected along its length and the shields must be earthed at least at both ends. This is because only a shield earthed at both ends is able to reduce inductive and capacitance coupling. Cross-sectional area of the cable shields entering a building needs to be considered as a certain minimum to avoid the risk of the dangerous sparking. Without doing this, the shields are hardly able to carry the lightning current.

Minimum cross section of a cable shield (S_{Cmin}):

$$A_{cmin} = \frac{I_f.\rho_c.L_c.10^6}{V_w}\left[\mathrm{mm}^2\right], \qquad (4.28)$$

where

ρ_c is shield resistivity;

I_f is lightning current flowing along the shield;

V_w is impulse with stand voltage of the system; and

L_c is cable length.

The shield connection system is typically tested with lightning current up to 10 kA (10/350 μs). For the first approximation, the lightning current of 10 kA can be used as the maximum value. Besides, V_w can be interpreted in different ways. The impulse withstand voltage strength of the cable is decisive.

4.17.5.2 *Indirect Single-Ended Shield Earthing*

For common operation, cable shields are sometimes earthed at only one end. This protection may only provide a certain attenuation from capacitive interference fields. However, it does not provide any protection against the electromagnetic induction arising from lightning strikes. The reason we sometimes use shields with single-ended earthing is to prevent the flow of low-frequency equalizing currents. In the extended installation like a bus cable, it can often stretch many hundreds of meters between buildings. For the older installations, one part of the earth-termination system may not operate normally if the meshed equipotential bonding network is absent. This will lead the interferences to occur as a result of multiple shield earthing. For a building, resulting potential differences of the different earth-termination system can allow low-frequency equalizing currents and the transients superimposed thereon, to flow.

At the same time, the current cable may burn if current is up to a few amperes. Furthermore, if signal frequency is in the similar frequency range to the interference signal, crosstalk can cause signal interference.

Implemented Electromagnetic Compatibility (EMC) requirements and preventing equalizing current can solve the signal interference by combining direct single-ended and indirect shield earthing. These shields are directly connected to the local equipotential bonding system at a central point such as the control room. The shields are indirectly connected to the earth potential via isolating spark gaps at the far ends of the cable. Basically, the resistance of the spark gap is around 10 GΩ, which means that during the surge-free operation, the current will be prevented from being equalized. If lightning strike occurs, the spark gap will need to ignite and discharges the interference pulse without destruction. This helps to reduce the residual impulse on the active cable cores and the terminal devices are subjected to become less stressed. Furthermore, a gas discharge tube is recommended at one side between the cable shield and the equipotential bonding system to eliminate the interference impulses.

4.17.5.3 *Low-Impedance Shielding Earthing*

A cable shield has to conduct impulse currents up to several kA. The impulse current will flow to the shield, then from the shield to the earth when it is discharging. At the same time, the potential differences between shield and the earth is created by the impedances of the cable shield and the shield terminal. This can be very dangerous since the potential differences formed are able to destroy the insulation of the conductors or connected device. Therefore, quality of the cable shield used needs to be considered and it will affect the number of shield earthings required. Suitably large-area contact terminals with the slipping spring elements are used for shield protection.

4.17.5.4 *Maximum Length of the Shielded Cables*

The interference impulse currents usually flows through the shield resistance, creating a voltage drop on the cable shield. Thus, the length of the cable needs to be controlled because it will determine the permissible transfer impedance for the cable shield. Voltage drop due to the length of the shield cannot be ignored in this case. This is because if the voltage drop becomes higher than the insulation strength of the system, a surge arrester needs to be present.

4.17.5.5 Extension of the LPZs with the Help of Shielded Cables

Surge protectors or arrestors are not needed if the shielded cable is used in between two identical LPZs. This is because the interferences from the surroundings of the shield cable and the meshed equipotential bonding will be suppressed by the shield.

However, this needs to be monitored because adverse situations may arise due to peculiar installation conditions. Potentially adverse situations may arise due to (i) the supply of the terminal devices at a different main low-voltage distribution boards, (ii) the TN-C systems, (iii) high transfer impedance of the cable shield, or (iv) insufficient earthing of the shield. Failure could lead to residual interferences with the signal transferred by the cable core. This type of interferences can be controlled by using a high-quality shielded cable or surge protection devices.

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