Protection of Selected Cases: PV Systems, Wind Turbines and Railway Systems

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Abstract The lightning protection and the surge protection of large ground-mounted photovoltaic power plants as well as of small roof-mounted photovoltaic systems is considered. Basics for external and internal lightning protection as well as special requirements, especially for surge protection, are presented. The measures result from experiences in the last years, are today recognized widely and are realized to a large extent. Lightning and surge protection of wind turbines has received increasing attention in recent decades due to considerable damage caused by direct lightning strikes. Today, onshore and offshore wind turbines are equipped with lightning protection systems according to the highest level of lightning protection and the declining damage shows the effectiveness of the measures. Special attention is paid to the protection of the rotor blades. But also surge protection for electrical energy and information technology systems including EMC measures is of great importance and is described. Many specialities have to be taken into account in the lightning and surge protection of wind turbines. For railway facilities and systems, national and international comprehensive concepts for lightning and surge protection have hardly been described. The considerations and measures presented here also do not claim to be complete, but are intended to address important aspects. These include above all measures for the protection of control and command technology systems as well as information on personal protection. In addition, lightning and surge protection of the power supply, measurement systems and EMC measures are addressed.

Keywords Photovoltaic · Solar power plant · Wind turbine · Rotor blade · Railway facilities and systems · Lightning and surge protection · Air termination system · Earthing system · Equipotential bonding · Surge protective device (SPD)

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a. **Protection of PV Systems**

1 Limitation of PV Systems to be Considered

In the following, large ground-mounted photovoltaic (PV) systems or solar power plants and roof-mounted photovoltaic systems or small PV systems will be considered [1].

The photovoltaic system includes not only the solar modules for the direct conversion of solar radiation into electrical power, but also other components such as the d.c. connecting cables between modules and inverter(s), usually fuses, earthing, lightning protection, disconnecting devices, meters and undervoltage or overvoltage monitoring relays. Some of these components are mandatory for legal reasons, while others, e.g. lightning protection, are often only recommended depending on the exposure of the system [1] (IEC 62093 2005).

Solar power generation are part of today's electrical engineering. Their professional design includes lightning and surge protection, which contributes to the longest possible trouble-free use of this regenerative electrical power source [2].

2 Lightning and Surge Protection for Ground-Mounted Photovoltaic Power Plants

i. Importance of lightning protection for solar power plants

Every year, photovoltaic ground-mounted power plants with an electrical output of several gigawatts are newly installed. Together with the high number of small rooftop photovoltaic systems, photovoltaics is developing into a relevant part of modern and, in particular, regenerative power supply in many countries [3].

Large power plants with 100 MW and more are now being built, which often feed directly into the medium or high-voltage level. Photovoltaics has thus become an integral part of the supply system and must therefore meet the requirements for stable grid operation. Consequently, supply interruptions and loss of yield must be avoided or minimized. Furthermore, the high investment volume and the required 20-year minimum service life make it necessary to assess the risk of damage from lightning strikes and to implement protective measures [2].

a. Lightning risk for solar power plants

Photovoltaic systems are exposed to lightning due to slightly elevated systems with a large area in the open field (lightning impact area roughly equal to the base area of the PV system, some ha to km^2) [4, 5].

There is a correlation between solar radiation, humidity and frequency of lightning strikes. Regions with high sun intensity and high humidity in which PV power plants are built are exposed to an immediately higher risk of lightning. The regional lightning frequency (ground strikes per square kilometer and year) and the location and size of the PV power plant are the basis for calculating the probability of lightning strikes into the system.

In general, PV power plants are exposed to the local weather influence of thunderstorms for decades.

Studies of 25 PV solar parks in Germany in the period from 2005 to 2015, i.e. with construction around the year 2010 and the consideration of localized ground flashes +/–5 years before and after construction have shown:

- negative flashes: significant shift towards larger amplitudes, increase in amplitudes and no change in numbers after construction of PV parks
- positive flashes: slight shift towards larger amplitudes, no change in amplitudes and no change in numbers after PV parks have been constructed
- exceeding probability distribution: displacement of the part with higher negative lightning current amplitudes in the direction of CIGRÉ characteristic of the negative first stroke and of the mean amplitude part in the direction of CIGRÉ negative subsequent stroke characteristic after construction of the PV parks.

The installation of a solar power plant results in an increased lightning risk to it.

b. Necessity of lightning and surge protection for solar power plants

Damage in PV systems is caused both by the destructive effect of direct lightning strikes and by inductive or capacitive coupled voltages from the electromagnetic lightning field. Voltage peaks from switching operations in the upstream a.c. or d.c. grid can also cause damage. Defects can occur in PV modules, inverters and their monitoring and communication systems. In addition to the replacement and repair costs, the economic damage is also reflected in the loss of yield and culminates in the costs for calling up reserve power plant capacity.

The aim is to protect both the operating building and the PV system from fire damage, i.e. direct lightning, and the electrical and electronic systems, such as inverters, generator main lines and remote diagnosis systems, from the effects of lightning electromagnetic pulses (LEMP).

Lightning pulse impacts also lead to premature aging of bypass diodes, power semiconductors and the input and output circuits of the data systems, which in turn means increased repair work for the subsequent period. In addition, grid operators make demands on the availability of the generated power, which are determined by grid codes. Increasingly, these points are also being considered by financing and insurance companies, and lightning protection measures are also used in the so-called Due Diligence examinations for financing purposes.

c. Measures to protect solar power plants against the effects of lightning

A lightning protection system (LPS), which is often designed for LPL III according to [6, 7], usually meets the requirements for PV power supply systems. The risk of damage due to lightning strikes must be determined on the basis of [8] and the results taken into account during planning.

Effective protection requires a LPS whose elements are coordinated with each other. Starting with the air termination system, earthing system, lightning equipotential bonding up to surge protective devices (SPD) for the power and data side.

Surge protective devices (SPD) can be used according to [6] or [7] In addition to the minimum discharge capacity of SPD, information is also given on the design of the earthing system for ground-mounted photovoltaic power plants.

ii. External lightning protection for solar power plants
a. Air termination system and down conductors

In order to protect against direct lightning strikes into the electrical systems of a PV power plant, it is necessary to arrange these in the protective area of air termination system. The number of air-termination rods can be determined using the rolling sphere method and, as a rule, protection class III (Fig. 1) [9]. They form a protected space across module tables, operating rooms and wiring. With regard to the inductive coupling of faults, it is recommended that generator junction boxes and decentralized inverters mounted on module tables are mounted as far away as possible from air termination devices. All down conductors must be connected to the terminal lugs of the earthing system. Due to the risk of corrosion at the outlet point of the terminal lugs from the ground or concrete, these must be corrosion-resistant (stainless steel or shrink tubing). For mechanical fastening, the air termination devices can often be connected to the module tables.

In addition to air-termination rods to protect the solar modules, small air termination tips at the highest points of modules (Fig. 2) with frames capable of carrying lightning currents can also be used. In general, it makes sense to mount the modules on earthed metal tables/frames.

b. Earthing system

The earthing system (Figs. 2 and 3) is the basis for the effective implementation of lightning and surge protection measures in PV power plants. An earthing resistance of less than 10 Ω is recommended for the earthing system [9]. With flat strip 30 mm ×

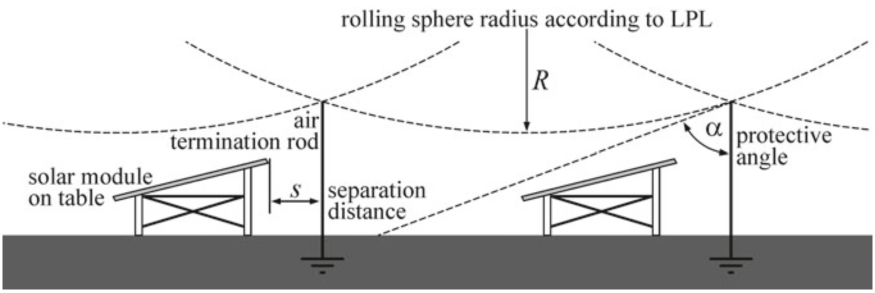


Fig. 1 Determination of the protective space by means of rolling sphere method or protective angle method [2]

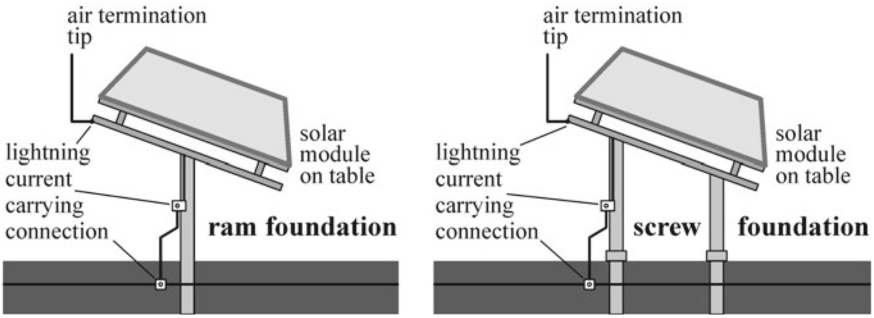


Fig. 2 Ram and screw foundation with lightning current carrying connection of air termination and earthing system [7]

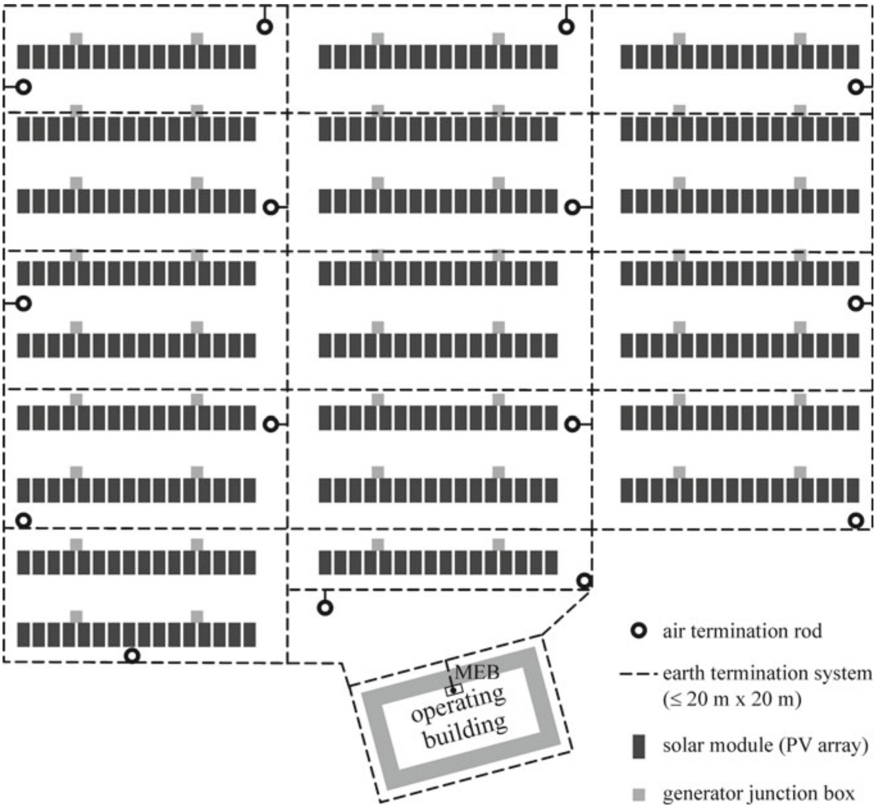


Fig. 3 Schematic of the earthing system of a large outdoor solar power plant (PV generator) including operating building [2, 7]

3.5 mm or 10 mm wire made of stainless steel or copper or galvanized steel in the form of closed meshes (meshed ring earth electrode), not larger than 20 m × 20 m, which are laid below freezing depth, there is a long-term resistant earthing system. The metal module tables can be used as part of the mesh if they meet the requirements for natural components according to [9] and are interconnected.

The individual earthing systems of the PV generator and the operating building must be connected, which reduces the overall earthing resistance. The intermeshing of the earthing systems creates an equipotential surface which significantly reduces the voltage stress on the electrical connecting cables when lightning strikes between the PV module field and the operating building. The meshes are to be connected with lightning current-tested connecting components. The metal support frames on which the PV modules are mounted must be connected to each other and to the earthing system. Frame constructions using pile driving or screw foundation technology can be used as earth electrodes (Fig. 3), if their material and wall thickness meet the requirements of [9].

iii. Internal lightning protection for solar power plants

a. Lightning equipotential bonding

Lightning equipotential bonding is the direct lightning current carrying connection of all metal systems. If the modules, the entire cabling and the operating building together with the weather station are within the protective space of the external lightning protection, no direct lightning currents are to be expected on the cables. If the mains connection to the distribution grid operator is made on the low-voltage level, SPD type 1 lightning current arresters must be used at this transition point and connected to the main earthing bar (MEB), as part of the lightning current flows here. The same applies to incoming telecommunication cables.

b. Cable routing within installations in solar power plants

When laying all cables, care must be taken to avoid the formation of conductor loops over large areas [1]. This applies within the single-pole serial connections of the d.c. circuits in one string, as well as to several strings among each other. It must also be avoided that data or sensor cables run across several strings and form large-area conductor loops together with the string cables. The power cables for d.c. and a.c., data and equipotential bonding should be routed together as far as possible.

c. Surge protection measures for solar power plants

Surge protective devices (SPD) (Fig. 4) must be used to protect the electrical systems within PV power plants [10]. When a strike occurs in the external lightning protection of an open field system, on the one hand high voltage pulses are coupled into all electrical conductors, on the other hand partial lightning currents occur within the open field wiring (d.c., a.c. and data cables), the peak value of which is influenced by the design of the earthing system, the specific earthing resistance on site and the design of the wiring.

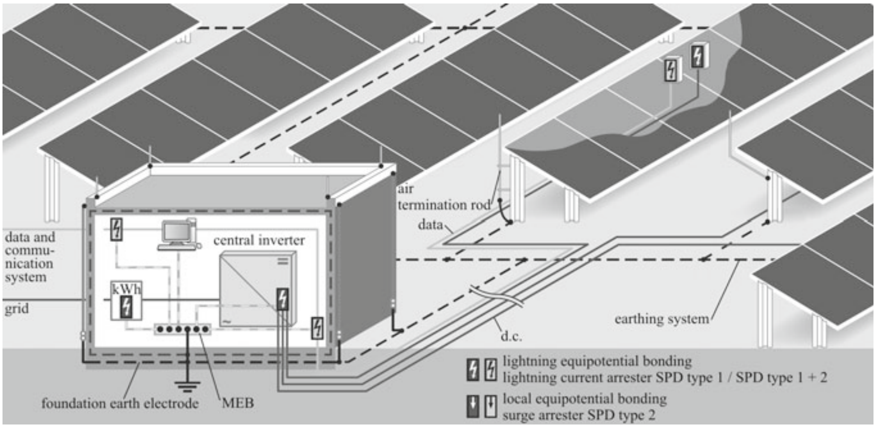


Fig. 4 Lightning protection concept for PV power plant with central inverter

Plant concepts with central inverter technology (Fig. 4) involve extensive d.c. cabling in the field.

Use voltage limiting type 1 d.c. SPD with a minimum discharge capacity of 10 kA (10/350 μs). SPD with high short-circuit strength must be used, also because of possible reverse currents.

DIN EN 62305-3, 5 [6] or IEC TR63227 [7] also contains an estimate of the lightning current distribution. To calculate the lightning current distribution, the down conductors of the lightning protection system, the possible earthing connections of the module array and the d.c. cables must be taken into account. The peak value of the partial lightning currents which are fed into the d.c. lines via the SPDs depends not only on the number of down conductors but also on the impedance of the SPD. This SPD impedance in turn depends on the rated voltage of the SPD, the SPD topology and the SPD type, voltage-switching (crowbar-type) or voltage-limiting (clamping-type). Characteristic for partial lightning currents through SPD on the d.c. side of the PV system is a shortening of the pulse shape. When selecting suitable SPD, both the maximum surge current and the pulse charge must be taken into account. In order to simplify the SPD selection for the user, the necessary lightning impulse current carrying capacity of type 1 SPD can be selected depending on the SPD type, voltage-limiting varistor arrester or voltage-switching spark gap arrester according to Table 1. The maximum occurring surge currents are considered as well as the partial lightning currents of the waveform 10/350 μs, so that the SPD can discharge the pulse charge of the lightning currents.

d. Solar power plants with decentralized string inverters

If PV power plants are designed with decentralized string inverters, a large proportion of the power cabling is shifted from the d.c. side to the a.c. side. The inverters are mounted in the field under the module tables of the respective solar generators. Due to its proximity to the modules, the inverter also performs typical functions of generator

Table 1 Minimum discharge capacity of voltage-limiting or combined SPD type 1 and voltage-switching SPD type 1 for a solar power plant at lightning protection level (LPL) III [6, 7]

Highest lightning current peak value I_{imp}	Clamping and combined (series connected) SPD Type 1				Crowbar and combined (parallel connected) SPD Type 1	
	$I_{10/350}$		$I_{8/20}$		$I_{10/350}$	
	Per protected path	I_{total}	Per protected path	I_{total}	Per protected path	I_{total}
100 kA	5 kA	10 kA	15 kA	30 kA	10 kA	20 kA

junction boxes. The lightning current distribution is influenced by the power wiring of string or central inverters. In string inverters, too, the power cabling acts as an equipotential bonding conductor between the local earth potential of the module field in which the lightning strikes and the remote potential of the mains transformer. The difference to the system with a central inverter is that in systems with string inverters, the partial lightning currents flow on the a.c. lines. Accordingly, type 1 SPD must be installed on the a.c. side of the string inverters and on the low-voltage side of the mains transformer.

The minimum discharge capacity of Type 1 SPD is listed in Table 1, depending on SPD technology. Type 2 SPD are sufficient on the d.c. side of the string inverters. The string inverters and the associated module field form a local equipotential surface when the earthing system is suitably designed, so that no lightning currents are to be expected in the d.c. wiring, but the surge protective devices essentially limit induced interference pulses and thus also protect the modules. Several a.c. outputs of outdoor inverters are combined and fused in so-called a.c. collective distributors. If type 1 SPD are used there, they protect all inverter outputs at a cable distance of up to 10 m. The additional a.c. field cabling is brought together in the operating building; SPD type 1 or combined SPD type 1 + type 2 must also be used at this grid transition point. Other operating equipment such as grid and system protection, alarm center or web server, which are less than 10 m cable length from this SPD, are also protected with regard to their network supply.

e. Surge protection measures for information systems

In operating buildings, the data information from the field is combined for remote maintenance by the plant operator and for power measurement and control by the grid operator. Reliable data transfer must be ensured at all times so that service personnel can determine the causes of faults by remote diagnosis and remedy them on site. String and inverter monitoring, weather data acquisition, theft protection and external communication are based on a wide variety of physical interfaces. The sensors, electrical interfaces and data lines must be protected with information technology surge protective devices.

Large-area induction loops are formed in the interaction of power cables, metal module table rows and data cables (Fig. 5). This is an ideal environment for transient surges due to lightning discharges that can be coupled into these lines. Such voltage

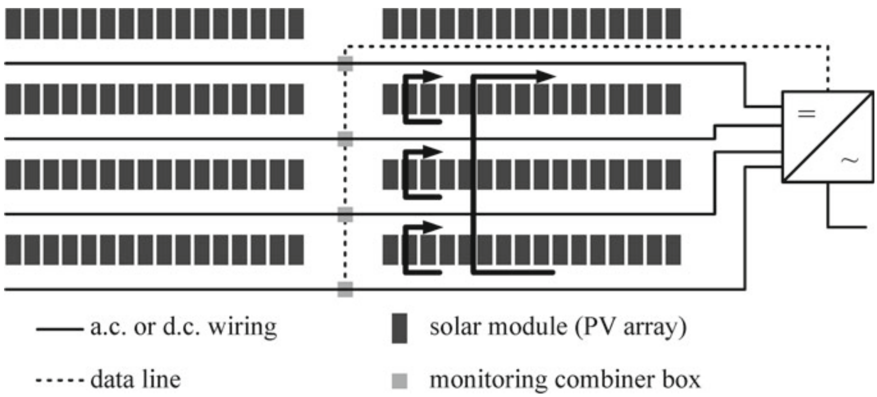


Fig. 5 Schematic diagram of induction loops in PV power plants

peaks are capable of exceeding the insulation/impulse strength of these systems. Overvoltage damage is the result. SPD must therefore also be used for data transmission in monitoring generator connection boxes or in decentralized string inverters. Cable shields must be properly connected at all connection points. In order to prevent malfunctions such as ripples and vagabonding currents, this can also be done with indirect shield earthing via arresters.

3 Lightning and Surge Protection for Roof-Mounted Photovoltaic Systems

i. Importance of lightning protection for roof-mounted PV systems

Roof-mounted photovoltaic systems are also exposed to lightning because they usually represent the highest installation on a building roof (lightning impact area equal to occupied roof area plus three times building height; area of the PV system several 10 m^2) [4, 5].

Many millions of small PV systems are currently installed worldwide. The worthwhile consumption of power and the pursuit of a degree of independence in power supply will make PV systems an integral part of electrical installations in the future. The PV systems are exposed to the effects of weather and must withstand these for decades. The high and rising number of small rooftop photovoltaic systems is also already contributing to renewable power supply in some countries. Small roof PV systems are connected at the low-voltage level. Usually, PV cabling is introduced into the building and there are often long cable runs to the grid connection point.

Lightning discharges cause field and conducted electrical interference. This effect increases with the length of the line or the size of the conductor loop. Damage caused by surges occurs not only on the connected PV modules, inverters and their monitoring electronics, but also on devices in other domestic installations. In commercial buildings, additional damage can be caused to production systems, resulting in production downtimes. If surges are coupled to grid-independent applications, so-called PV island systems, these can then cause a malfunction of the solar-powered systems, e.g. medical equipment, water supply.

Transient overvoltages from switching operations of the upstream a.c. or d.c. grid cause damage. Defects can occur in PV modules, inverters, charge controllers or d.c./d.c. converters.

a. Necessity of lightning protection system on buildings with roof PV systems

In the case of a direct lightning strike into a building, the protection of persons and fire is the first priority. The released energy of a lightning discharge is one of the most frequent causes of fire. With PV systems, a distinction must be made between installations on buildings with and without lightning protection. Even when planning a PV system, it is usually clear whether the building is already equipped with lightning protection. For public buildings (e.g. meeting places, schools and hospitals), for example, building codes require lightning protection systems. In the case of commercial or private buildings, the necessity of lightning protection is differentiated according to location, type of construction and use. It must be determined how easily a lightning strike can occur or whether a lightning strike can lead to severe consequences. Systems in need of protection must therefore be equipped with permanently effective lightning protection systems. In privately used buildings, lightning protection is often not installed. This is partly for financial reasons, but also due to lack of sensitivity to the subject.

According to the current state of the art, the installation of PV modules on buildings does not increase the risk of lightning strikes, so that the need for lightning protection cannot be directly deduced from the mere existence of a PV system. However, a lightning strike can increase the risk for the building's electrical systems. This is due to the fact that the cabling of the PV lines inside the building in existing risers and cable trays can cause strong conducted and radiated interference from lightning currents. The risk of damage from lightning strikes must therefore be determined in accordance with [8]. The results must be implemented during the construction of the roof PV system.

DIN EN 62305-3, 5 [6] and IEC TR63227 [7] describe that a LPS designed for lightning protection level III (LPL III) meets the normal requirements for PV systems (>10 kWpeak) on buildings. In principle, photovoltaic systems on buildings must not impair with existing lightning protection measures.

b. Necessity of surge protection within roof PV installations

In case of lightning discharges, surges are coupled into electrical conductors. Surge protective devices (SPD) have proven their worth in protecting electrical systems against these destructive voltage peaks. In many cases, this surge protection is already required in insurance conditions for photovoltaic systems. In particular, the inverter must be protected by SPD. In PV installations on the a.c. and d.c. side as well as in existing signal and communication circuits, surge protection measures must therefore be provided.

c. Cable routing in installations of roof-mounted PV systems

When laying the cables, make sure that no large conductor loops are formed [1]. This applies to the wiring of the d.c. circuits to the string and also to several strings among each other (Fig. 6). Furthermore, it must be avoided that data or sensor cables run across several strings and, in combination with the string cables, form large-area conductor loops. This must also be taken into account when connecting the inverter to the grid connection. It is important that the power lines (d.c. and a.c.) are laid together with the equipotential bonding throughout.

ii. External lightning protection for roof-mounted PV systems
a. Earthing of roof PV systems

PV modules are mainly mounted on metal mounting systems. The active d.c.-side PV components have double or reinforced insulation. The combination of a variety of technologies on the module side and on the inverter side, e.g. with or without galvanic isolation, results in different grounding requirements. Functional earthing of the metal substructure is carried out if the system is within the protective area of interception devices and the separation distance is maintained. A conductor cross-section of at least 6 mm^2 copper or equivalent is required for this functional earthing

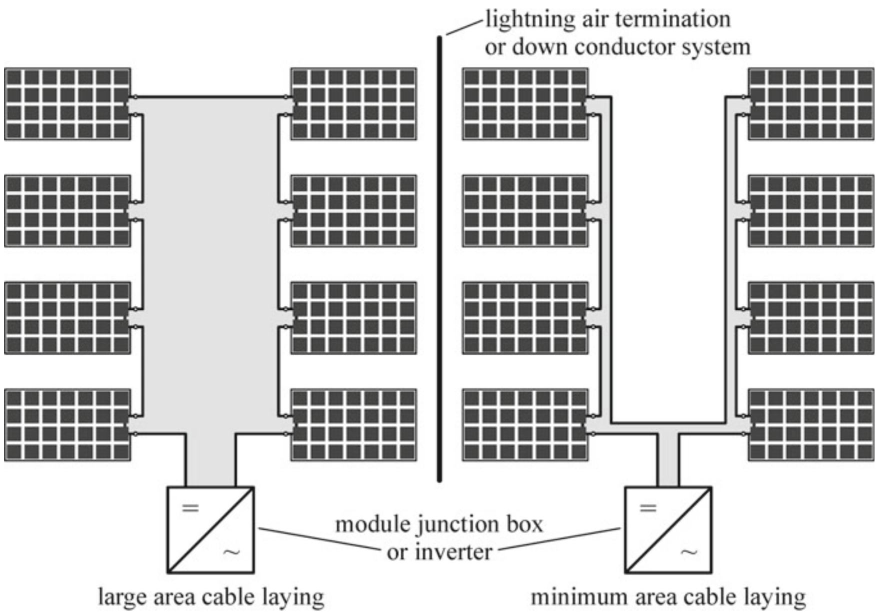


Fig. 6 Low-induction laying of d.c. cables. Avoid large conductor loops [6, 7]

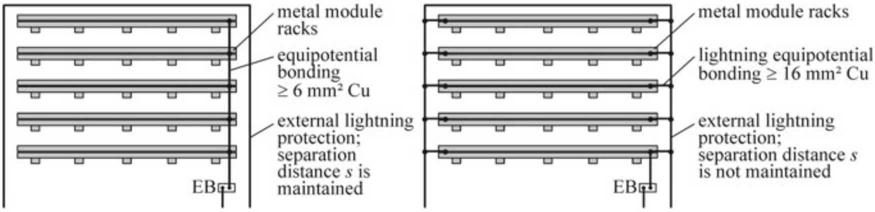


Fig. 7 Functional earthing of module racks without external lightning protection or if separation distance is maintained (left)—Lightning equipotential bonding on module racks if separation distance is not maintained (right) [7]

(Fig. 7). With conductors of this cross-section, the modular rack rails must also be permanently connected to each other. If the mounting system is directly connected to the external lightning protection because the separation distance cannot be maintained, these cables become part of the lightning equipotential bonding. A lightning current carrying capacity of these elements is therefore a basic requirement. The minimum requirement for a lightning protection system according to LPL III is 16 mm^2 copper or equivalent. Here, too, the modular rack rails must be permanently connected to each other. The requirements for natural components according to [9] (Fig. 7) apply.

b. Separation distance

The separation distance between the lightning protection system and the photovoltaic system must be taken into account. It describes the sufficient distance which prevents an uncontrolled flashover into adjacent conductive parts in the event of a lightning strike into the external lightning protection [9]. In the worst case, an uncontrolled flashover can trigger a building fire. But this also results in damage to the PV system.

A further technical possibility to realize the separation distance is the use of high-voltage-insulated down conductors. Insulated down conductors can come into contact with the PV system directly after the voltage-controlled termination range (sealing unit).

iii. Internal lightning protection for roof-mounted PV systems

In general, surge protection on the d.c. and a.c. sides of the inverter or inverters is necessary to protect against overvoltages from the PV system and the a.c. grid. The shielded routing of the d.c. cables from the module strings to the inverter is best suited as supporting protective measure or as compensating measures. The shielding may have to be capable of carrying lightning currents [11, 12].

In order to simplify the selection for type 1 SPD for the user, the required lightning surge current carrying capacity can be taken from Table 2 depending on the lightning protection level and the number of down conductors of the external LPS [2, 11].

If there is no lightning protection system or if the separation distance is maintained, equipotential bonding must be carried out with at least 6 mm^2 copper (Table 3). If the

Table 2 Selection of the minimum discharge capacity of voltage-limiting SPD type 1 (varistor) or combined SPD type 1 (series connection of varistor and spark gap); according to [7]

Lightning protection level LPL	Highest lightning current peak value I_{imp} (kA)	Number of down conductors of external lightning protection			
		<4		≥4	
		Clamping and combined (series connected) SPD type 1			
		Per path $I_{8/20}/I_{10/350}$ (kA)	I_{total} $I_{8/20}/I_{10/350}$ (kA)	Per path $I_{8/20}/I_{10/350}$ (kA)	I_{total} $I_{8/20}/I_{10/350}$ (kA)
I	200	17/10	34/20	10/5	20/10
II	150	12.5/7.5	25/15	7.5/3.75	15/7.5
III, IV	100	8.5/5	17/10	5/2.5	10/5

Table 3 Summary of separation distance, equipotential bonding and surge protection

Initial situation	Measure	Separation distance maintained	Equipotential bonding	Surge protection
External lightning protection	Adjust lightning protection system	Yes	At least 6 mm^2 copper	d.c.: Type 2 a.c.: Type 1
		No	At least 16 mm^2 copper	d.c.: Type 1 a.c.: Type 1
No external lightning protection; ground wire terminal	Analysis of requirement of building regulations or risk management	–	At least 6 mm^2 copper	d.c.: Type 2 a.c.: Type 2

cable length to the inverter is more than 10 m, an additional equipotential bonding with protective devices must be installed near the inverter. The connection to the equipotential bonding must be made with at least 6 mm^2 copper parallel to the d.c. lines. If partial lightning currents occur, grounding must be carried out with at least 16 mm^2 copper (Table 3). Metal cable routing and cable support systems reduce magnetic coupling to a minimum. The cables of the PV system must always be routed tightly and parallel. The reduction in the area between the lines reduces the inductively coupled overvoltage.

a. Selection of SPD according to the protection level

The d.c. side of photovoltaic systems can have different operating voltages, depending on the system. Values up to 1500 V d.c. are currently possible. Accordingly, the terminal devices also have different dielectric strengths. To ensure effective protection of the system, the protection level U_P of the SPD must be lower than the dielectric strength of the system to be protected. At least 20% safety distance should be maintained between the dielectric strength of the system and the U_P. The energy coordination between SPD type 1 or SPD type 2 and the device input must be observed. If arresters are already integrated in the terminal device, then the coordination between

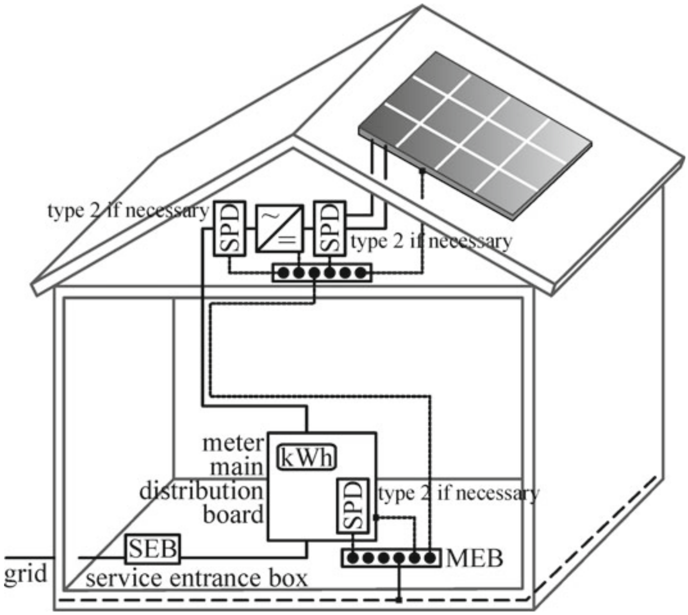


Fig. 8 PV system on building without external lightning protection (situation A) [7, 13]

SPD type 2 and the input circuitry of the terminal device is usually already taken into account by the manufacturer.

The surge protection concept for a PV system on a building without external lightning protection (situation A) shows Figs. 8 and 9. Here, dangerous overvoltages are inductively coupled into the PV system by close strikes of lightning or act on the consumer system from the supply grid via the house connection.

Each d.c. input (Maximum Power Point Tracker MPPT) of the inverter must be equipped with a type 2 surge protective device. IEC 61643-32 [11] provides for an additional type 2 d.c. SPD on the module side for distances of more than 10 m between inverter input and PV generator. If PV inverters and other electronic components, such as a.c.-coupled battery storage systems, are not more than 10 m away from the installation location of the SPD at the grid connection point (low voltage feed-in), they are adequately protected. For longer cable lengths, an additional type 2 SPD must be used. The use of an SPD type 1 + type 2 (combined lightning current and surge arrester) is recommended at the mains connection point (low-voltage main distributor).

If inverters with data and sensor lines for yield monitoring have wired communication interfaces, suitable IT surge protective devices are required.

Figure 10 shows the surge protection concept for a PV system with external lightning protection and with sufficient separation distance between the PV system and the external lightning protection (situation B). The primary protection objective is to avoid personal injury and damage to property, in particular building fires, caused

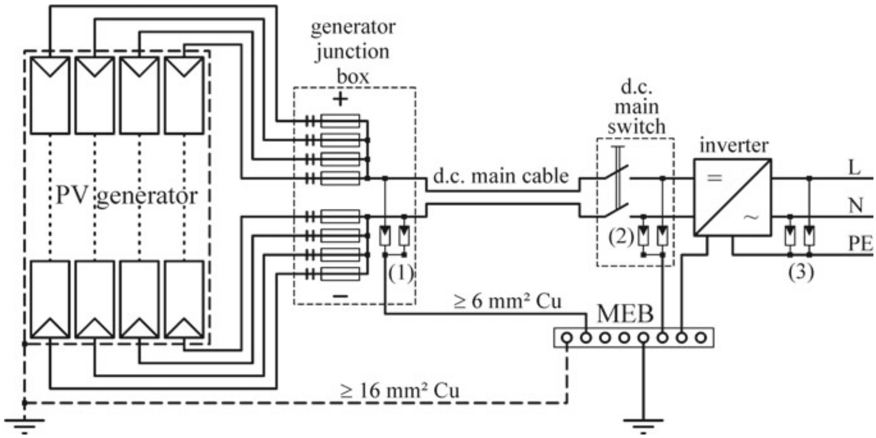


Fig. 9 Surge protection for a PV system without LPS (example with TN system). The surge arresters (2) in front of the inverter are recommended for long d.c. main lines (10 m). Surge arresters (2) and/or (3) are often already integrated in the inverter. The surge arresters (1) in the generator junction box can be dispensed in smaller PV systems with input-side varistors inside the inverter

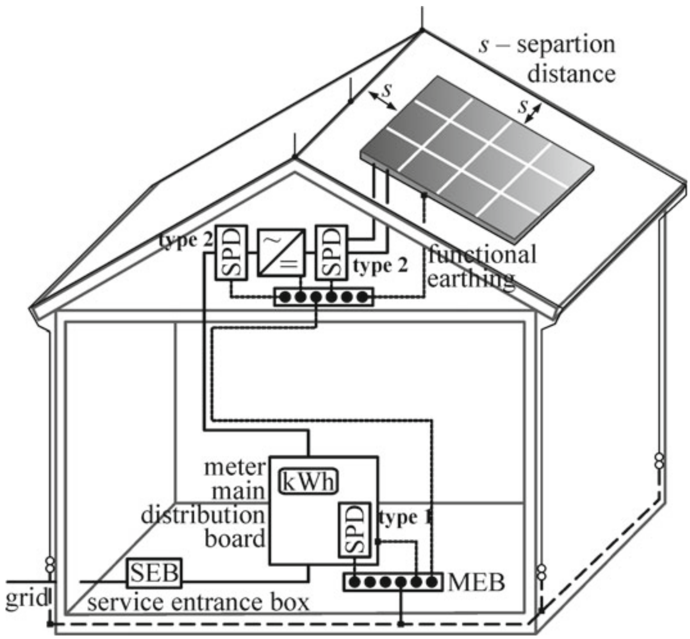


Fig. 10 PV system on building with external lightning protection while maintaining the separation distance (situation B) [6, 7]

by lightning. The PV system must not impair the function of the external lightning protection. In addition, it itself must be protected against a direct lightning strike; it must be installed in the protected space of the external lightning protection. Air termination devices, e.g. air-termination rods, form this protected space and prevent direct lightning strikes into the PV modules and the wiring. The protected space can be determined using the protective angle method (Fig. 14) or the rolling sphere method (Fig. 14) in accordance with [9]. It must be ensured that the separation distance is maintained between all electrically conductive parts of the PV system and the external lightning protection. At the same time, a core shadow, e.g. by sufficient distance of the air-termination rods to the PV modules, must be avoided.

An essential component of a lightning protection system is lightning equipotential bonding. It must be carried out for all conductive systems and cables fed into the building from outside. Lightning equipotential bonding is achieved by directly connecting all metal systems and indirectly connecting all live systems to the earthing system via SPD type 1 lightning arresters. The lightning equipotential bonding should take place as close as possible to the building entrance in order to prevent partial lightning currents from entering the building. The mains connection point must be equipped with a multi-pole SPD type 1 (combined lightning current and surge arrester). For cable lengths less than 10 m between the SPD, the inverter and other electronic components, such as an a.c.-coupled battery storage system, there is sufficient surge protection. For longer cable lengths, the installation of additional SPD type 2 upstream of the devices to be protected is mandatory. The d.c. side of the inverter must be protected with an SPD type 2 PV arrester. This also applies to transformerless devices. If the inverters are equipped with wired data lines, e.g. for yield monitoring, surge protective devices must be installed for data transmission.

In buildings with a PV system and external lightning protection, if the separation distance is not maintained (situation C), the following protection concept can be applied. If the roof skin is made of metal or if it is formed by the PV system itself, the separation distance cannot be maintained from an installation point of view.

The metal components of the PV mounting system must be connected to the external lightning protection with a lightning current carrying connection of at least 16 mm^2 copper or equivalent. This means that lightning equipotential bonding must now also be carried out for the PV cables fed into the building (Fig. 11). The d.c. cables must be equipped with a PV-SPD type 1 or PV combined arrester. Lightning equipotential bonding must also be carried out in the low-voltage supply. If the PV inverter and e.g. the battery storage system are more than 10 m away from the SPD type 1 required there for the grid connection point, a further SPD type 1 or combined arrester must be used. If yield monitoring is planned, suitable surge protection devices must also be provided for the wired data lines.

If the separation distance cannot be maintained, DC cables can be shielded and routed down to ground level outside the building (see Fig. 12). In this case, the cable shield has to be connected to the air-termination system at the high-point and to the earthing system at the base-point immediately before entering the structure. The cable shield must be designed to carry lightning currents and must be integrated into the lightning equipotential bonding as described in [14].

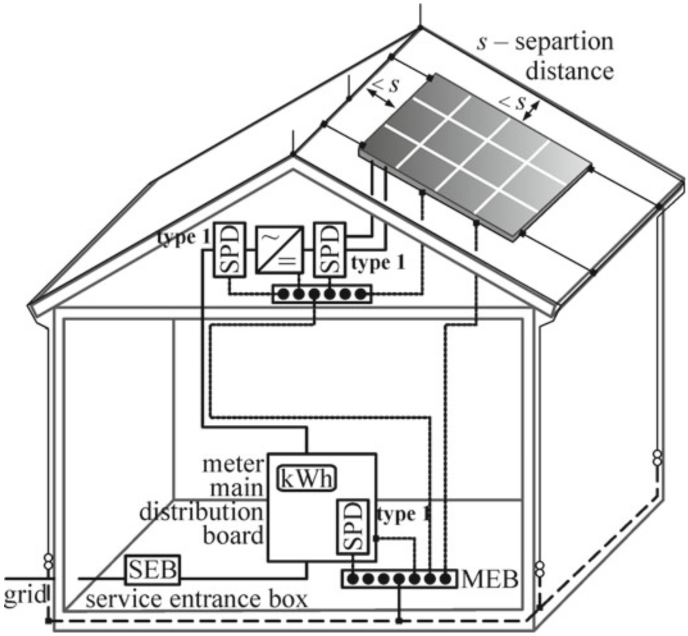


Fig. 11 PV system on building with external lightning protection without maintaining the separation distance (situation C) [6, 7]

It should be noted that the separation distance *s* between the PV components (e.g. modules) and metal parts carrying lightning current such as the external lightning protection, rain gutters, roof windows or antenna systems has to be maintained (Figs. 13 and 14).

b. Roof-mounted PV systems with module inverters

Module inverters (micro inverters) require a different surge protection concept. The d.c. cable of a module or a module pair is connected directly to the small inverter. The module d.c. cables must be laid avoiding unnecessary conductor loops, but direct inductive couplings into such small d.c. structures usually have only a low energetic destruction potential. In systems with module inverters, the extensive wiring of the PV system is carried out via the a.c. side (Fig. 15). If the module inverter is located directly on the module, then the wiring with surge protective devices can only be carried out on the a.c. side.

- Buildings without external lightning protection require SPD type 2 for alternating or three-phase current in the immediate vicinity of the module inverters and at the low voltage feed-in.
- Buildings with external lightning protection and maintained separation distance require SPD type 2 in the immediate vicinity of the module inverter and SPD type 1 with lightning current carrying capacity at the low voltage supply.

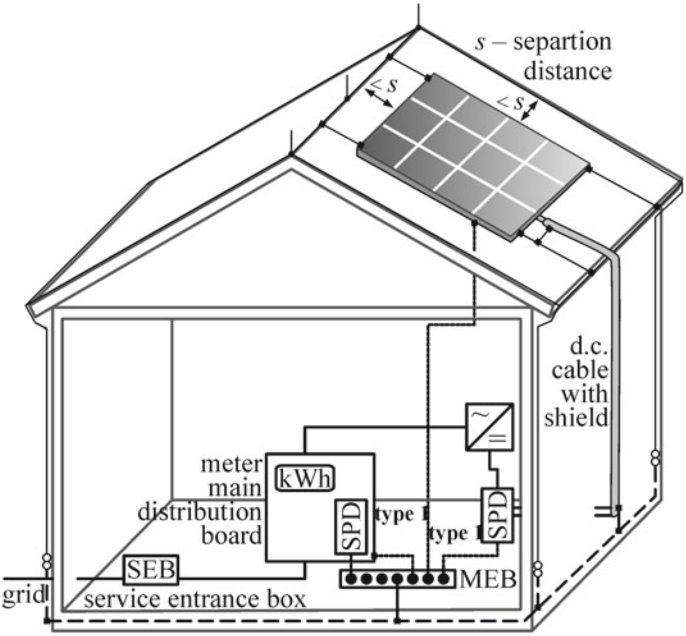
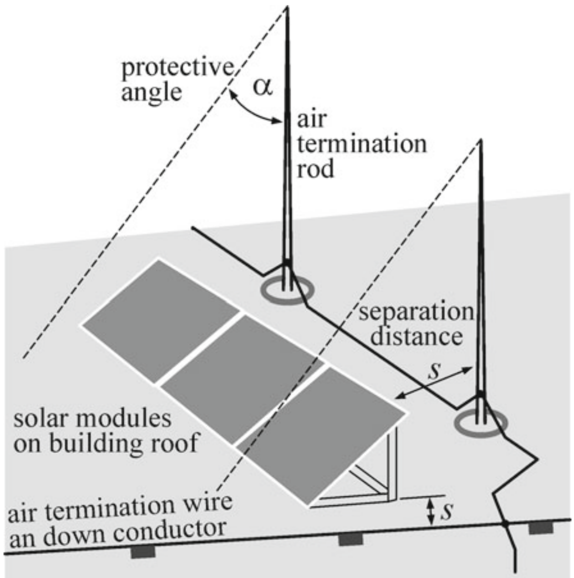


Fig. 12 PV system on building with external lightning protection without maintaining the separation distance (situation C) and using d.c. cable with shield capable for carrying lightning current [7, 13]

Fig. 13 Determination of protected space by protective angle method and PV modules in protected space of air-termination rods taking into account the separation distance [6, 7]



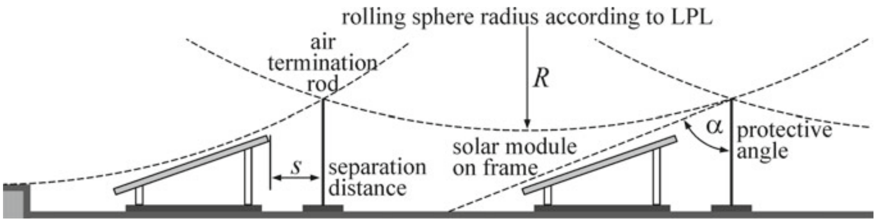


Fig. 14 Protected space by means of rolling sphere method or protective angle method [2, 6, 7]

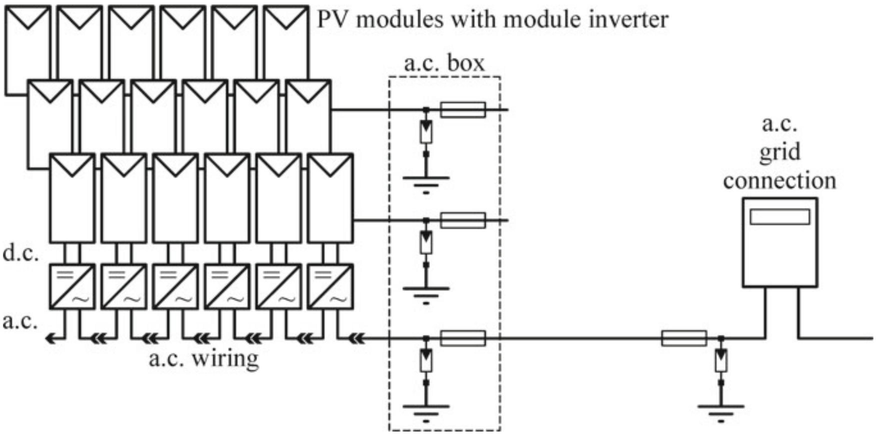


Fig. 15 Building without external lightning and surge protection for module inverters in the connection housing of the cabling provided by the customer

- Buildings with external lightning protection and without maintaining the separation distance require SPD type 1 in the immediate vicinity of the module inverters and at the low voltage supply.

Module inverters from all manufacturers have equipment monitoring systems. If the data is modulated onto the a.c. lines via the module inverters, surge protection must be provided on the separate receiver units (output, data processing). The same applies to wired interface connections and their power supply to downstream bus systems, e.g. Ethernet, ISDN [2].

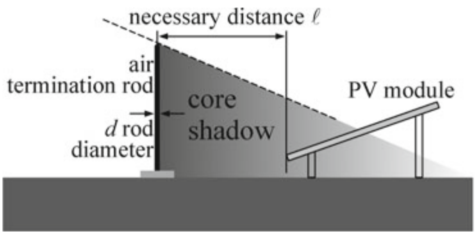
4 Specialities of PV Systems

i. Core shadow on solar cells of solar generators and construction of air terminations

The air terminations of the external lightning protection are necessary. An uncontrolled lightning strike into the PV system would result in the flow of lightning currents in the electrical system and lead to serious damage within the system. When installing the external lightning protection, care must be taken to avoid relevant shadowing of the solar cells, e.g. by air-termination rods. Diffuse shadows, such as those formed by air-termination rods or air termination wires far away, are insignificant in terms of plant and yield. Core shadows, on the other hand, are characterized by clearly defined darkened contours on the surface behind them, causing power losses and unnecessary stress on the cells and the associated bypass diodes, and should be avoided. A sufficient distance prevents the formation of core shadows. The core shadow of an air-termination rod is reduced as the distance to the module increases. At distances greater than in Fig. 16, only a diffuse shadow remains. The necessary distance is predictable; it is in a fixed ratio to the diameter of the air-termination rod. The core shadow of an air-termination rod with 10 mm diameter has scattered into a diffuse shadow after 1.08 m. The shadow of the air-termination rod is not visible. [6] in Annex A and [7] deals with the calculation of the core shadow.

ii. Special surge protective devices for the d.c. side of photovoltaic systems

In PV systems with central inverters, fuses are used to protect against reverse currents, whereby the maximum current occurring depends on the current irradiation. Under certain operating conditions, reverse current fuses only respond after a few minutes (Fig. 17). Surge protective devices in generator junction boxes must therefore be designed for the possible total current, consisting of operating current and return current, and disconnect automatically in the event of overload without forming arcs [11, 13].



$\ell = 108 \times d$

rod diameter d	necessary distance ℓ
10 mm	1.08 m
16 mm	1.73 m
20 mm	2.16 m

Fig. 16 Distance from air-termination rod to module free of core shadows

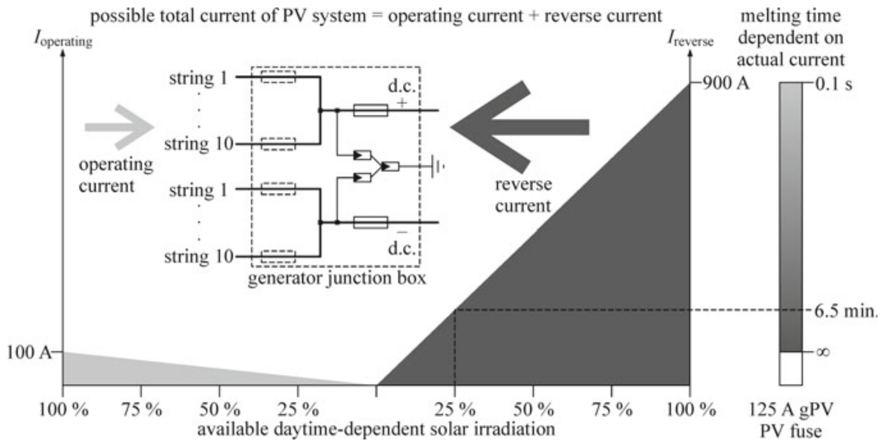


Fig. 17 PV system with d.c. maximum current of 1000 A and daytime-dependent prospective short-circuit current at the PV surge protective device [2]

The U/I characteristics of photovoltaic power sources differ significantly from those of conventional direct current sources. They have a non-linear characteristic with constant current behaviour (Fig. 18) and are the cause of the long maintenance of ignited arcs. This peculiarity not only results in a larger design of PV switches and PV fuses, it also requires suitable surge protective devices with a specially adapted disconnecting device. These PV-SPD must be capable of extinguishing PV-d.c. follow currents. Safe operation, even in the event of overload of SPD on the d.c. side, is required in [6, 7, 11]. On the d.c. side of PV systems, special SPD suitable for PV must always be used, which can handle PV currents with PV characteristics and high d.c. system voltages and thus avoid an increased fire risk [2].

The maximum continuous operating voltage of the d.c.-SPD must be selected in such a way that it is higher than the open circuit voltage of the PV generator, which is to be expected at maximum solar radiation on a cold day in winter.

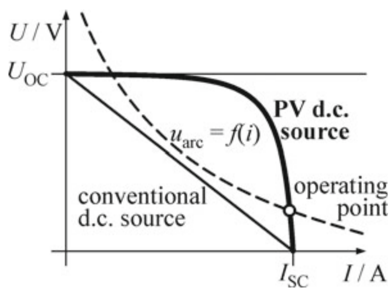


Fig. 18 Characteristic curves of conventional d.c. source and PV generator as well as U/I characteristic of electric arc

b. **Protection of Wind Turbines**

5 Limitation of Wind Turbines to be Considered

In the following, the individual wind turbine (WT) or a wind farm consisting of several wind turbines as well as onshore and offshore wind turbines are considered.

6 Importance of Lightning Protection for Wind Turbines

There is an unbroken trend towards the use of renewable energies such as wind power [15]. This results in an enormous market potential not only for the power industry, but also for the suppliers of the power industry and the electrical trade, worldwide. The wind power industry continues its impressive growth. In 2018, more than 20,000 new wind turbines with a capacity of more than 50 GW were installed worldwide [16]. The importance of wind turbines is obvious. The reliable availability of power is an important factor in the growth rates of this electricity market [3].

Wind turbines (WT) are exposed to lightning strikes as they are free-standing, slender and, in particular, tall structures. Wind turbines are often exposed to direct lightning due to their exposed position and height. Several studies have shown that wind turbines of the multi-megawatt class are exposed to at least 10 direct lightning strikes per year. The high investment costs must be amortized in a few years due to the feed-in tariff, i.e. downtimes due to lightning and overvoltage damage and the associated repair costs must be avoided. Comprehensive lightning and surge protection is therefore necessary.

With the increasing size of wind turbines and thus the increasing length of rotor blades, lightning protection measures are becoming more and more important. Therefore, the rotor blades installed today are equipped with lightning protection consisting of several receptors along the rotor blade, which are guided via a metallic wire (down conductor) to the blade root, from where they are connected to the earthing system [17, 18]. The great importance of effective lightning and surge protection is, however, not only derived from the rapidly increasing number of wind turbines, but, due to the rapid increase in overall height, the danger to modern wind turbines from lightning strikes has increased considerably. The danger of being struck by lightning increases quadratically with the height of the structure. Megawatt wind turbines with their blades reach an overall height of up to 150 m and more today (Fig. 19) and are therefore particularly at risk [4, 5].

Lightning strikes are unavoidable with all larger wind turbines. Most lightning strikes hit the rotor blades especially in the blade tip area. The result is considerable damage. The initial view that rotor blades made of non-conductive glass fiber composite material could do without a lightning protection did not prove to be true in practical operation. For this reason, the demands for effective lightning protection

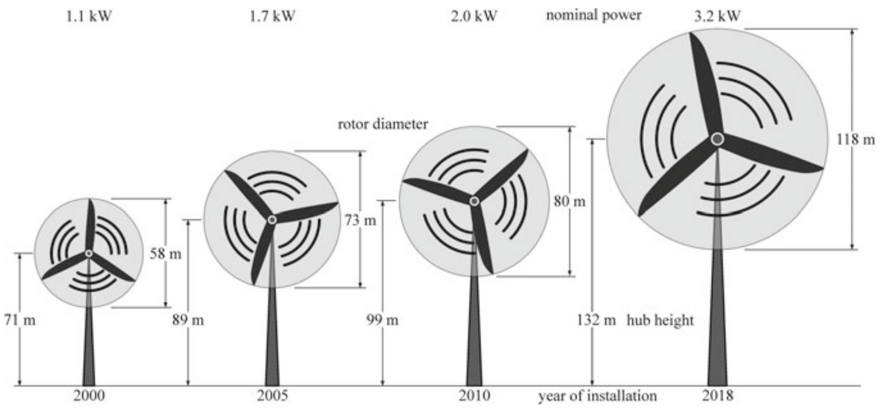


Fig. 19 Increase in overall height of onshore wind turbines in recent years

became louder and louder as wind turbines became more widespread and larger, especially among insurers. Today, a lightning protection system (LPS) is a matter of course for all new rotor blades [19, 20]. The carbon fiber is characterized both by the longest tearing length and by a high modulus of elasticity. The stiffness of carbon fiber components is comparable to that of steel constructions. The fatigue strength properties are good. Only the still high price of carbon fiber speaks against it. Carbon fiber is therefore often used in combination with glass fiber material for particularly stressed areas. Carbon fiber has practically no corrosion problems, but when used for rotor blades it requires special precautions for lightning protection, because the electrical conductivity is not high enough. Down conductors in the rotor blades with transitions to the shaft and to the tower, specially designed for current conduction, as well as an effective (low-impedance) foundation earth electrode allow damage to be limited. For this purpose, e.g. metal caps are attached to the blade tips and large-surface copper mesh is placed under the blade surface in order to conduct lightning currents without major damage [19].

In measuring and control circuits, on the generator as well as on supply facilities, etc., the system is protected against overvoltage damage by powerful coarse and fine protection devices, which can be caused by voltage increases on the generator or by direct or indirect lightning strikes. Direct lightning strikes usually result in major damage. The main components of modern wind measuring systems are wind sensors [18], wind measuring mast and measuring computer, which allow fully automatic and maintenance-free operation. Prerequisites for this are their weatherproof design, internal lightning protection and an efficient power supply [17].

The electrical safety devices include the aviation obstacle lighting with day and night marking and the fire alarm system. Depending on the location, a warning device for the danger of icing or even an electric resistance heating for the defrosting of the rotor blades may be required. The safety devices must be protected by lightning and surge protection so that their function is also ensured in the event of lightning strike

[17]. The central module of a wind turbine houses the power distribution, the control system for charging the batteries and the switching and protection devices.

The rolling bearings of a wind turbine must be protected against the flow of high electrical currents, in particular lightning currents. A lightning strike can otherwise cause very expensive bearing damage, especially to the blade bearings and in the tower head bearing. This measure is of particular importance for the generator bearing arrangement. In the event of a short circuit, there is a risk that the rolling bearings will become unusable due to fusion craters and corrugation formation.

Wind turbines are not particularly fire-prone plants such as vehicles or aircraft with large quantities of flammable fuel on board. Nevertheless, experience has shown that fires can also occur in wind turbines, which in some cases have led to the complete destruction of turbines. Combustible building materials, insulating materials and operating materials are also present in wind turbines. For example, the large-area cladding of the nacelle made of glass fiber composite material is flammable. Fires are primarily triggered by lightning strikes (Fig. 20) and electrical short-circuits; extinguishing the fire in these tall structures is often hopeless. Lightning protection, which is first and foremost fire protection, is therefore of great importance today.

i. Lightning environment of wind turbines

At 50 onshore wind farms in Germany, each with 1–21 wind turbines from 120 to 200 m in height, observations were made on localized earth flashes. A period of 10 years around 2010 with 5 years before and 5 years after the installation of the wind farms was investigated [22].

Fig. 20 Burning wind turbine as result of a lightning strike [21] (NDR)

- negative flashes: significant increase in number (+64% on average), no noticeable change in amplitude and slight shift towards larger amplitudes after construction of wind farm
- positive flashes: increase in number (+29% on average), noticeable change in amplitude and significant shift in lightning current amplitudes towards higher values after construction of wind farm

In addition, 2 offshore wind farms in the German North Sea were considered.

- negative flashes: significant increase in number compared to onshore wind farms and small increase in amplitude after construction
- positive flashes: increase in number and noticeable increase in amplitude after construction

Overall, it can be seen in the exceedance probability distributions that the area with higher positive lightning current amplitudes shifts towards the CIGRÉ characteristic for positive first strokes and the middle area of negative flashes shifts towards the CIGRÉ subsequent stroke characteristic after construction of the wind farms.

For the dimensioning of lightning protection measures, it must be taken into account that for objects with a height greater than 60 m and lightning-exposed position, in addition to cloud-to-earth flashes, earth-to-cloud flashes, so-called upward lightning, as well as side flashes must also be taken into consideration. The upward flashes occur above all in winter with charges even higher than 300 °C. It therefore makes sense to set higher requirements for air termination and down conducting systems. The reason for this is that the charge is the cause of fusion on turbine components and thus has a decisive influence on the maintenance of down conducting systems, e.g. spark gaps. As an example, the lightning charge in Japan reaches values of 600 °C due to upward flashes during winter thunderstorms [23].

Studies in Japan, North America but also in Central Europe have shown that wind turbines are exposed to a large number of upward flashes due to the strong increase in height. Operating experience shows that especially in areas where winter thunderstorms are to be expected, the normative maximum value described in [24] for the charge of the flash $Q_{flash} = 300$ °C does not reflect the actual possible load. For this reason, the charge value was doubled to $Q_{flash} = 600$ °C for such systems. This value then also forms the basis for the tests of the melting out on rotor blades and rotating components. The increase of the current parameters for the first positive surge current to 20 MJ/Ω, which roughly corresponds to a lightning current of 280 kA 10/350 μs, is also being discussed. This increased pulse current is anchored in an additional national annex to the Japanese standard as a normative threat variable. This current parameter is often used as a test parameter by international wind power manufacturers, especially for offshore applications. IEC 61400-24 [25] states that there is currently no evidence that the lightning current parameters for offshore turbines deviate significantly from the parameters for onshore turbines. Therefore, the standard requires that these threat values also be used for offshore wind turbines [23].

Table 4 Relationship between percentage of upward lightning and winter lightning activity [23]

Winter lightning activity	Percentage of upward lightning (%)
High	80–99
Medium	40–90
Low	20–50
None	10–40

The risk analysis in [25] is not used to assess whether a lightning protection system (LPS) is necessary and according to which lightning protection level (LPL) it is to be designed. It is determined that wind turbines must be protected against lightning and that the lightning protection must be dimensioned according to LPL I as standard. The risk analysis according to [25] is mainly used to estimate the frequency of dangerous events and especially the number of direct impacts into the wind turbine. The effect of flashes with several impact points on the earth is taken into account by doubling the values of the earth flash density according to [26].

It should be emphasized that winter thunderstorm activities must be taken into account when estimating lightning frequencies. Field experience shows that lightning damage to wind turbines occurs especially in areas with increased winter thunderstorm activity. Table 4 shows that, depending on the degree of winter thunderstorm activity, such winter lightning flashes can represent the absolutely dominant damage scenario. It should also be noted that the percentage of upward flashes may be even higher for wind farms constructed in mountainous terrain or at high altitudes above sea level.

7 Lightning and Surge Protection for Wind Turbines

The design of the protection concept is based on [25], the standards of the [8, 9, 14, 24] and the guidelines of (Germanischer Lloyd) [25] and [27] recommend that all subcomponents of the lightning protection system (LPS) of a wind turbine (WT) be protected according to the lightning protection level LPL I, unless a risk analysis can prove that a lower LPL is sufficient [8]. A risk assessment can also show that different sub-components are assigned different protection levels. IEC 61400-24 [25] recommends a complete lightning protection concept as the basis for lightning protection.

The LPS of a WT consists of the external lightning protection and the surge protection measure (SPM) to protect the electrical and electronic equipment. When planning the protective measures, it is advantageous to divide the WT into lightning protection zones (LPZ). The lightning protection of wind turbines includes the protection of two subsystems which are only found in WT: the rotor blades and the mechanical drive train. The complex problems of the protection of rotor blades and rotating parts or bearings require detailed investigation and are manufacturer and type specific.

i. Lightning protection zones concept

The lightning protection zones concept is a structuring measure to create a defined electromagnetic compatibility (EMC) climate within an object. The defined EMC climate is specified by the interference immunity of the electrical equipment used. The lightning protection zones concept therefore contains the protective measure of reducing the conducted and field-bound interferences at interfaces to agreed values. For this reason, the object to be protected is divided into protection zones [28] (Fig. 21).

The determination of the zones LPZ 0_A, i.e. the system parts which may be exposed to direct lightning strikes, and LPZ 0_B, which is assigned to those system parts which are protected against direct strikes by external air terminations or air-termination devices integrated in system parts, such as in the rotor blade, is carried out by the rolling sphere method. According to IEC 61400-24 [25], the rolling sphere method is not applicable to the rotor blades themselves (moving parts). Figure 23 shows the principle application of the rolling sphere method and Figs. 22 and 28 the possible division of a WT into different lightning protection zones. The division into lightning protection zones depends on the structure of the WT. They should take their structure into account. However, it is decisive that the lightning parameters acting from outside

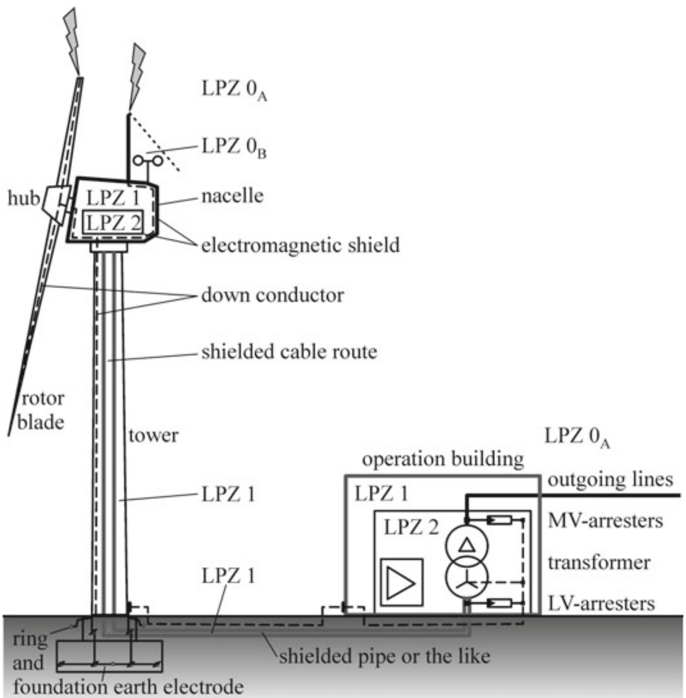


Fig. 21 Lightning protection zones concept for wind turbine—lightning protection and earthing system (Germanischer Llyod)

in the lightning protection zone LPZ 0_A are reduced at all zone boundaries by suitable shielding measures and the installation of surge protective devices to such an extent that the electrical and electronic devices and systems located within the WT can be operated without interference.

The lightning protection system (Fig. 22) must protect the mechanical components against damage and protect the electrical and electronic components against destruction and overvoltage.

a. Electromagnetic shielding measures in wind turbines

The nacelle should be constructed as a self-contained metal shield. Within the nacelle, a volume with an electromagnetic field considerably weakened on the outside is achieved. A tubular steel tower, as it is often used in large wind turbines, can be regarded as an almost perfect Faraday cage for electromagnetic shielding.

In concrete hybrid towers, the function of the galvanic cage must be ensured by means of reinforcement steel as well as earthing and through-hole bonding of the individual components. The switch and control cabinets in the nacelle and, if available, in the operating building should also be made of metal. The connecting cables should be provided with an outer screen capable of carrying lightning currents or be routed in a closed metal cable duct. In terms of interference protection, shielded cables are only effective against EMC couplings if the shields are connected to the

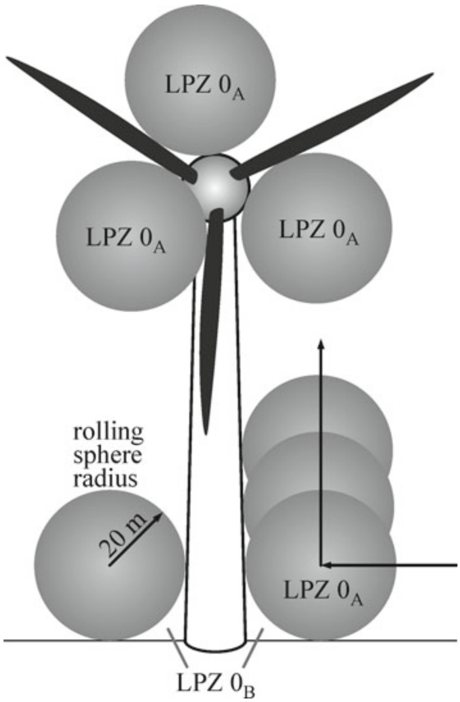


Fig. 22 Rolling sphere method at wind turbine

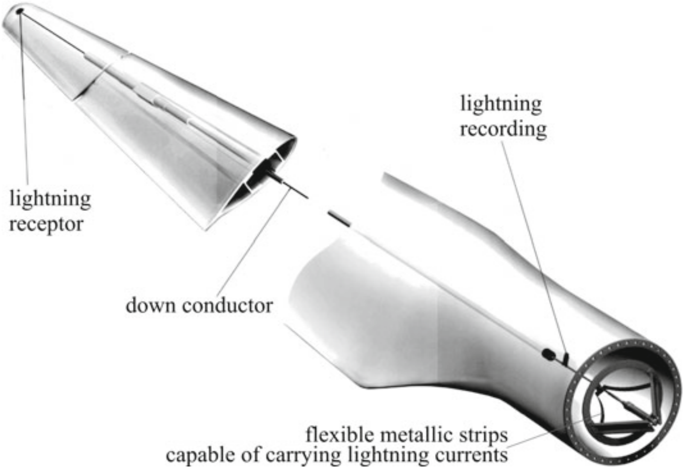


Fig. 23 Example for the lightning protection of a rotor blade [19]

equipotential bonding on both sides. The shields must be contacted with all-round connection terminals.

Magnetic shielding and cable routing should be carried out in accordance with [14]. Shielding measures include, for example, metal braiding on nacelles with glass fiber reinforced plastic (GRP) coating, a metal tower, metal switch cabinets, metal control cabinets, shielded connecting cables with lightning current carrying capacity (metal cable duct, shielded pipe or similar) and cable shielding.

ii External lightning protection for wind turbines

The external lightning protection has the task of intercepting direct lightning strikes, including strikes on the WT tower, and diverting the lightning current from the strike point to earth. Furthermore, it serves to distribute the lightning current in the ground without causing thermal or mechanical damage or dangerous sparking which could cause a fire and endanger persons. The potential points of strike into a wind turbine can be determined using the rolling sphere method, except for the rotor blades (Fig. 23). Lightning protection level (LPL) I is recommended for WT. A rolling sphere with a radius $R = 20$ m is therefore rolled over the WT to determine the strike points. Wherever the sphere touches the WT, potential lightning strike points and thus air terminations are required.

The external lightning protection measures include air-termination and down-conductor devices in the rotor blades, air-termination devices to protect the nacelle superstructures, the nacelle and the hub, use of the tower as an air termination (for side flashes) and down conductor as well as a foundation earth electrode in combination with a ring earth electrode as an earthing system.

The nacelle construction should be part of the LPS to ensure that lightning strikes the nacelle either hit natural metal parts capable of withstanding the stress or an air-termination device designed for that purpose. Nacelles with a GRP sheath or the like should be fitted with an air termination and down conductors forming a cage around the nacelle (metal mesh). The air termination, including the exposed conductors in this cage, should be capable of withstanding lightning. Other conductors in Faraday's cage should be designed to withstand the portion of the lightning current to which they may be exposed. According to IEC 61400-24 [25], air terminations for the protection of measuring instruments etc. on the outside of the nacelle should be designed in accordance with the general regulations in [9] and down conductors should be connected to the cage described.

Natural components made of conductive materials, which always remain in or on the WT and are not changed, e.g. lightning protection of the rotor blades, bearings, machine frames, hybrid towers, may be used as part of the LPS. If WT are made of a metal construction, it can be assumed that this fulfils the requirements for external lightning protection of LPL I. The prerequisite is that the lightning is safely intercepted by the lightning protection of the rotor blades and can be diverted to the earthing system via the natural components such as bearings, machine carriers, tower and/or bypass systems, e.g. open spark gaps or carbon brushes.

a. Air termination and down conductor on wind turbines especially on rotor blades

As can be seen from Figs. 23 and 28, the rotor blades, the nacelle with superstructures, the rotor hub and the WT tower can be struck by lightning. If these are all able to safely catch the maximum expected lightning surge current of 200 kA and conduct it to the earthing system, they can be used as natural components of the external lightning protection of the WT.

If the rotor blades or their spars are made of steel, they form an ideal lightning air-termination and down-conductor device and do not require any further lightning protection devices. In the past, rotor blades made of glass fiber material were manufactured without special lightning protection measures. With the increasing spread of wind turbines, however, the number of damages caused by lightning strikes rose sharply. In the insurance statistics, these cases of damage were at times at the top of the list, so that economic pressure arose to limit this type of damage. Rotor blades today therefore without exception have special lightning protection devices. The lightning protection system of the entire wind turbine consists of metal connections, copper brushes and elastic copper strips at the critical transition points which divert the lightning current into the earthing system of the foundation. (Germanischer Llyod)

For the lightning protection of the rotor blades, metallic receptors are often inserted into the GRP blade tip and sometimes also into the sides of the rotor blades as shown in Figs. 21 and 22, which represent defined strike points for the lightning. In the simplest case, this is a screwed-in and therefore easily replaceable metal part. From the receptor, thick metallic wire or rope is routed to the blade root as down conductor inside the rotor blade. There this conductor is connected to the rotor hub with flexible metallic strips. When lightning strikes, it can be assumed that the lightning strikes the tip of the blade or the receptor and then takes its way via the lightning conductor inside the blade to the earthing system via the nacelle and the tower [19].

With regard to the lightning protection measures to be foreseen, [29] provides some general information, particularly with regard to rotor blades. For wind turbines erected in areas with high winter thunderstorm activity, such as the west coast of Japan, continuing lightning currents have been recorded which clearly exceed the total charge of 300 As required for LPL I (up to more than 1000 °C). Multiple lightning strikes during the lifetime at the same rotor blade end (receptor) are a realistic threat scenario. In this case, it must be taken into account that the charge of the lightning current that is decisive for material melting and ablation at the arc root point has an accumulating effect [30] (Fig. 24).

b. Earthing system for wind turbines

The earthing system of a wind turbine must combine several functions, such as personal protection, lightning protection and the improvement of EMC. Information on material (Fig. 23) is absolutely necessary for the distribution of lightning currents and to prevent destruction of the WT. The earthing system must also protect people from electric shock.

In the event of lightning strikes, the earthing system must discharge any high lightning currents into the ground and distribute them there without causing dangerous thermal and electrodynamic effects. It is generally important that an earthing system is set up for a WT, which is used both for lightning protection and for earthing the power supply grid.

Ring earth electrode and the reinforcement in the foundation must be connected to the tower construction. The reinforcement of the tower foundation should always be used for earthing of WT. The grounding of the base of the tower and the service building should be connected by a grounding mesh in order to obtain the largest possible grounding system. In order to avoid high step voltages in the event of a lightning strike, potential-controlling, corrosion-resistant ring earth electrodes should be laid in the ground around the base of the tower for the purpose of personal protection (Fig. 25).

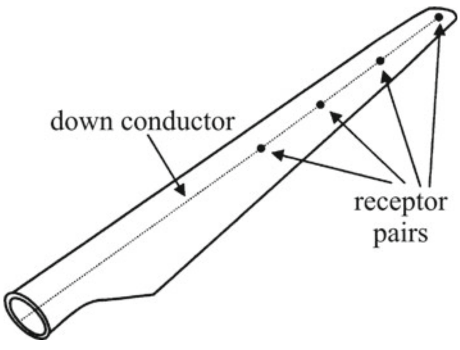


Fig. 24 Metal receptors on the surface of rotor blade and connected to down conductor inside the blade [4]

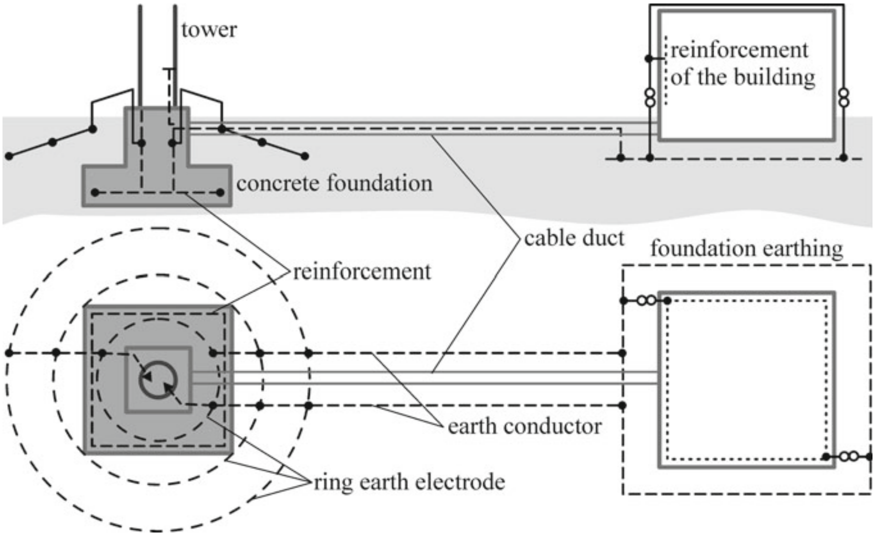


Fig. 25 Meshed network of earthing systems of a wind turbine [2]

A foundation grounding system is advantageous from both a technical and an economic point of view and is required in the technical connection conditions of the distribution grid operators. The foundation earth electrode is considered a component of the electrical system and fulfils essential safety functions. Metals for earth electrodes must comply with the materials listed in [9]. The behavior of the metals with regard to corrosion in the ground must always be observed. Round or strip steel, which can be either galvanized or non-galvanized, must be used as the material for the foundation earth electrode. Round steel must have a diameter of at least 10 mm, for strip steel the dimensions have to be at least 30 mm × 3.5 mm. It must be taken into account that this material is covered with at least 50 mm of concrete to protect it from corrosion. In addition, a connection must be made between foundation earth electrode and main earthing bar (MEB) in the WT. Corrosion-resistant connections must be made via fixed earthing points or connection lugs made of high-alloy stainless steel (Material No. 1.4571). A ring earth electrode made of stainless steel (Material No. 1.4571) must also be laid in the ground.

c. Earthing system for onshore wind turbines

For the earthing systems of an onshore WT with integrated medium-voltage system, which has to fulfil many tasks, many standards must be observed during installation. As a rule, a foundation earth electrode is used. The foundation earth electrode is considered a component of the electrical system and fulfils essential safety functions. The foundation earth electrode must be designed as a closed ring and arranged in the foundation of the tower.

The lightning protection earthing has the task of safely taking over the lightning current from the down conductors and diverting it into the ground. From the point of view of lightning protection, a single, common earthing system of WT is advantageous for all purposes (e.g. medium voltage system, low voltage supply, lightning protection, electromagnetic compatibility, telecommunications and control systems). For this purpose, the foundation of the WT made of reinforced concrete should be used primarily as foundation earth electrodes. They result in the most effective earth electrode with a low earthing resistance and represent an excellent basis for equipotential bonding.

The design of earthing systems must meet the following requirements:

- mechanical strength and corrosion resistance
- control the highest fault current (usually calculated) from a thermal point of view
- ensure safety of persons with regard to voltages at the earthing system occurring during the highest earth fault current or lightning surge currents (touch and step voltages).
- ensure function for complete lifetime of WT.

Consequently, the following parameters are important for the design of the earthing system:

- properties of the surrounding soil
- type of neutral-point connection and resulting short-circuit currents in the event of a fault.

In an installation where different nominal voltages are used, the requirements for each voltage level must be met. The medium-voltage earthing system should also be used for lightning protection. The earthing resistance recommended in the lightning protection standard [9] is less than or equal to 10 Ω.

A connection between foundation earth electrode and main earthing bar (MEB) is to be established in the WT via a connection part. In the case of reinforced foundations, as used at WT, the round or strip steel is placed on the lower reinforcement layer. It must be safely connected to the reinforcement at intervals of 2 m in an electrically conductive manner.

Figure 26 show the example of an earthing system of a WT where the foundation is designed as a circular ring. In the foundation a foundation earth electrode is installed as a ring and 2 further inner rings. The radial connecting lines between the 3 rings are continued to the center of the circle on a cross clamp. The rings and the connecting lines are connected to the reinforcement by means of clamp connections. From the internal inner ring, connection lugs are led to one earthing fixed point each, which is used to connect the earthing system with the equipotential bonding bar in the tower. There are also connection lugs for connection to the tower down conductors. Outside the foundation, a ring earth electrode is installed at a typical distance of 1 m from the outer edge of the foundation. Connecting leads run from the ring earth electrode to the outer inner ring and the connection of depth earth electrodes is optionally possible at the ring earth electrode.

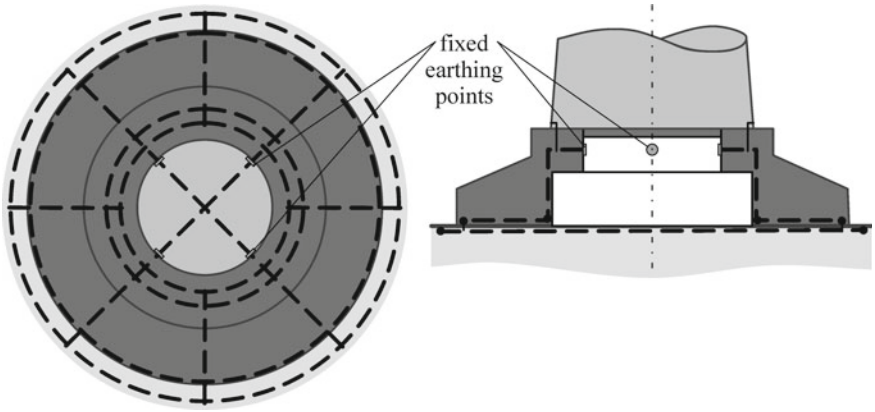


Fig. 26 Plan view of foundation (left) and section of foundation with earthing system (right) [2]

Due to the growing hub heights of wind turbines, concrete towers as well as hybrid towers consisting of a lower concrete tower and an upper steel tube tower are increasingly being erected. Since these towers also contain the earthing system, they must also be considered as part of the electrical system.

For concrete towers with reinforcing steel, the reinforcement can be used for the lightning down conductor if it is ensured that 2–4 parallel vertical connections with sufficient cross-section are available, which are connected horizontally to each other at the top and bottom as well as at intervals of 20 m. Connected in this way, the reinforcing steel offers an effective weakening of the magnetic field and a reduction of the lightning current within the tower. The tower is to be regarded as a primary protective earth conductor (PE) and as an equipotential connection. Due to the tower height direct lightning strikes into the tower construction are to be expected, and this circumstance is to be considered with the construction of the tower. External lightning protection equipment may be considered for use on concrete towers, but should always be connected to the tower's reinforcement steel. For the connection between the individual tower elements, fixed earthing points can be used in conjunction with bridging ropes. It must be ensured that all components used can carry the lightning current.

With tubular steel towers, all requirements, in particular the lightning current carrying capacity according to LPL I with lightning currents up to 200 kA, are fulfilled due to the existing cross-section and the completely metallic design. All metallic components used in the tower must be integrated into the equipotential bonding system. Conductor systems have to be connected to equipotential bonding at each end, at intervals of 20 m and on each platform. Components such as tensile ropes, hoisting ropes and rail systems must be connected at both ends to an equipotential bonding system.

iii. Internal lightning protection for wind turbines

The internal lightning protection must be designed correctly, as the system voltages of the WT are increasing more and more. The trend is towards 690 and 1000 V for TN systems in order to keep the cable cross-section small in large plants [28].

In addition to earthing and equipotential bonding, internal lightning protection measures include spatial shielding and separation distance, cable routing and cable shielding as well as the installation of coordinated surge protective devices (SPD).

a. Protection of cables at transition from lightning protection zones

For the safe operation of electrical and electronic devices, protection against conducted interferences at the interfaces of the lightning protection zones (LPZ) must be implemented in addition to shielding against field-bound interferences (Figs. 27 and 28). At the transition LPZ 0_A to LPZ 1 (classically also referred to as lightning equipotential bonding) protective devices must be used which are able to discharge considerable partial lightning currents non-destructively. These protective devices are referred to as SPD type 1 lightning current arresters and are tested with surge currents of the waveform 10/350 μs. At the transition LPZ 0_B to LPZ 1 and higher, low energy surge current pulses as a result of voltages induced by external processes or overvoltages generated in the system itself, e.g. switching overvoltages, must be controlled. These protective devices are referred to as SPD type 2 surge arresters and are tested with surge currents of waveform 8/20 μs.

According to the lightning protection zone concept, at the interface between LPZ 0_A and LPZ 1 or between LPZ 0_A and LPZ 2, all external cables and lines with SPD type 1 must be included in the lightning equipotential bonding without exception. This applies to both power and communication cables. For each additional zone interface within the volume to be protected, an additional local equipotential bonding must be set up, in which all cables and lines that penetrate this interface

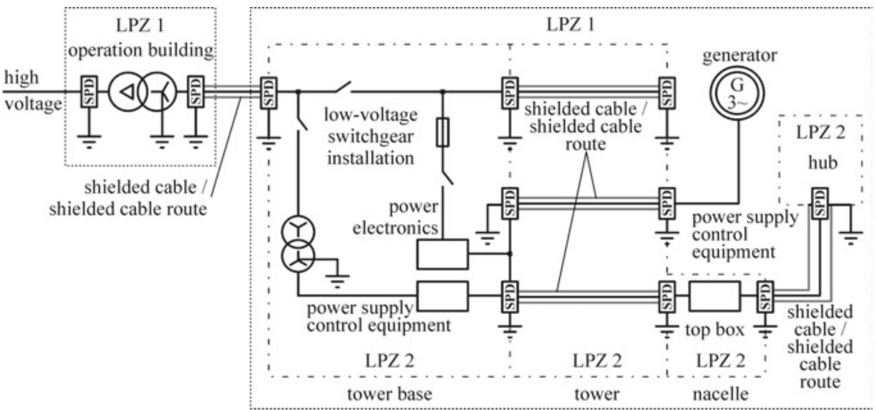


Fig. 27 Use of SPD at the LPZ boundaries of wind turbine with an operating building [2]

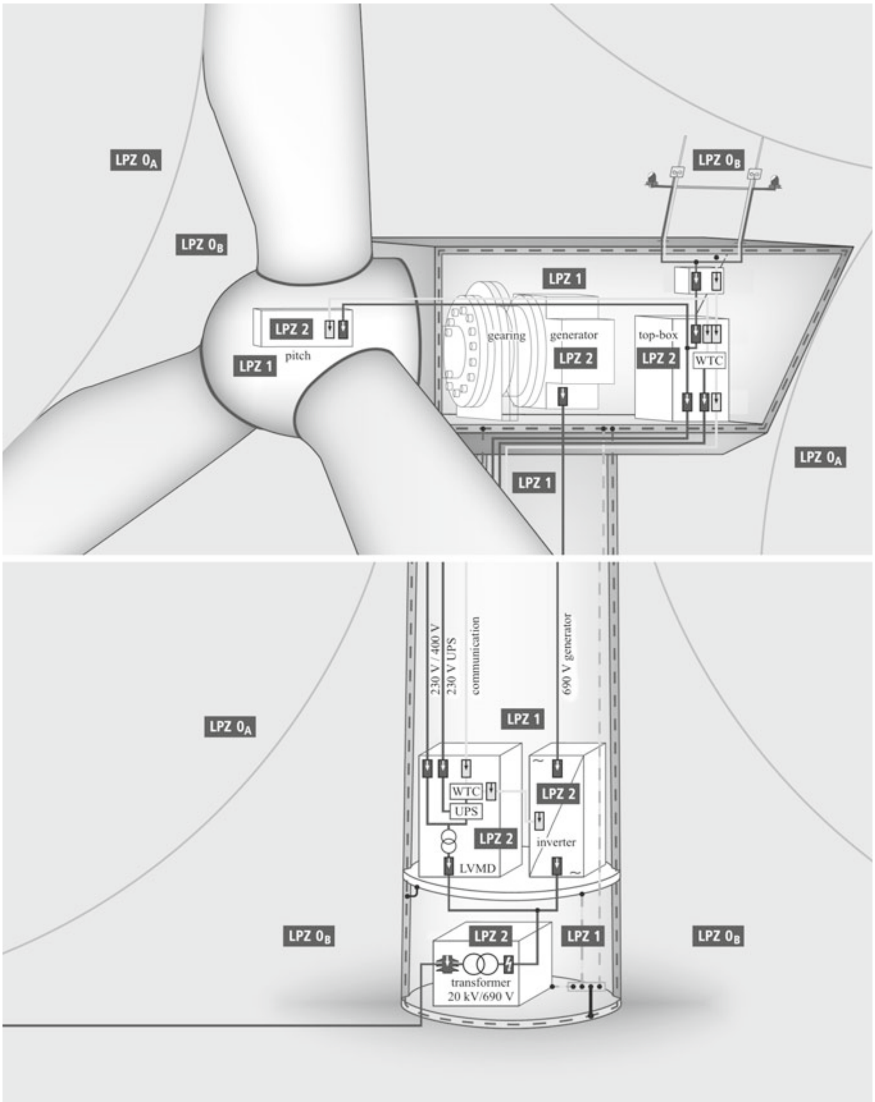


Fig. 28 Lightning and surge protection of a wind turbine [2] (WTC—wind turbine control, UPS—uninterruptible power supply, LVMD—low-voltage main distribution board)

must be included. SPD type 2 and/or type 3 must be installed at the transition from LPZ 0_B to LPZ 1 and at the transition from LPZ 1 to LPZ 2 and at all other internal zone transitions. The task of SPD type 2 and type 3 surge arresters is both to further reduce the residual interference of the upstream protective stages and to limit the overvoltages induced in the WT or generated there.

b. Protection of electrical power systems

The transformer of the WT can be accommodated in different places, in the separate switching house, in the tower base, in the tower or in the nacelle. In very large WT, for example, the unshielded 20 kV cable is fed into the tower base to the medium-voltage switchgear, consisting of a vacuum circuit breaker, a mechanically interlocked busbar disconnector, an outgoing earthing switch and a protective relay. The medium-voltage cables then run from the medium-voltage switchgear in the WT tower to the transformer, which can be located at the base of the tower or in the nacelle (Fig. 27). The transformer supplies the control cabinet in the tower base, the control cabinet in the nacelle and the pitch system in the hub with a TN-C system (L1, L2, L3, PEN conductor). The electrical equipment in the nacelle is supplied with a.c. low voltage from the control cabinet in the nacelle. All electrical equipment installed in the WT have a rated impulse withstand voltage corresponding to the rated voltage of the system. This means that the SPD to be installed must have at least the specified protection level, again in accordance with the rated voltage of the system. The SPD used to protect the 400/690 V supply, for example, must have a protection level of at least $U_P \leq 2.5$ kV and the SPD used to protect the 230/400 V supply, for example, must have a protection level of $U_P \leq 1.5$ kV to protect sensitive electrical and electronic equipment.

The protected area includes power and information technology equipment such as:

- power supply hub; pitch system in hub; signal cables nacelle—hub
- protection of the aviation obstacle lighting on the sensor mast in LPZ 0_B; protection at the respective zone transitions (LPZ 0_B to 1, LPZ 1 to 2)
- signal cable weather station and control cabinet in the nacelle; nacelle superstructures
- control cabinet in the nacelle; voltage supply
- protection of the generator, the transformer, the mains filter, and of the measuring equipment; the MV transformer supply is protected by medium-voltage arresters; these must be adapted to the medium-voltage grid to its grid configuration and voltage
- power supply of the control cabinet at the base of the tower (TN-C system)
- main supply TN system (SPD type 1 with high follow current limitation required)
- protection of the inverter on both sides of the inverter (mains and machine side) as well as on the generator; if double-fed asynchronous generators are used, an arrester combination with increased dielectric strength (continuous voltage up to 1000 V and surge currents up to 40 kA 8/20 μs) must be used on the rotor side
- signal cables in the control cabinet at the base of the tower.

c. Surge protection for information technology installations

Surge arresters for protecting electronic equipment in telecommunications and signal processing networks against indirect and direct effects of lightning strikes and other transient surges are described in accordance with [31] and installed at the zone boundaries according to the lightning protection zone concept [32]. In the case of arresters consisting of several stages, it must be ensured that the various protection stages are coordinated with each other. Information technology cables are often fed into the WT and the control cabinets are connected from the base of the tower to the nacelle via fiber optic cables. The cabling of the actuators and sensors from the control cabinets, on the other hand, is carried out using shielded copper cables. The fiber optic cables do not need to be equipped with SPD, as interference from an electromagnetic environment cannot occur, unless the fiber optic cable has a metal sheath, which must then be included in the equipotential bonding directly or via SPD.

In general, the following shielded signal lines must be connected:

- signal lines (4–20 mA interfaces), which lead from the sensors of the weather station into the control cabinet, come from the LPZ 0_B, run into the LPZ 2 and are best protected with combined arresters; shield grounding is carried out by means of shield connection terminals for permanent and low-impedance shield contacting of the protected and unprotected side of the SPD; if wind measuring devices (anemometers) are equipped with a heater, this must be protected with a suitable energy-coordinated combined arrester
- signal lines running between the nacelle and the pitch system in the hub; SPD suitable for high frequencies must be used
- signal lines for the pitch system, wiring of the signal lines depends on the sensors used, which may have different parameters depending on the manufacturer; wiring should be on both sides, in the pitch system and in the controller
- signal lines to the inverter; signal lines to the fire extinguishing system

d. Condition Monitoring

The subject of plant availability at WT is becoming increasingly important, especially for offshore wind farms. Condition monitoring of the lightning current and surge arresters for preload is important. Through the targeted use of condition monitoring, service calls can be planned and costs saved. In addition, SPD function monitoring with a potential-free contact is usually possible. The signal to replace the SPD in the next service interval is transmitted to the turbine controller via the telecommunication contact.

8 Specialities of Wind Turbines

i. Direct lightning strike in wind turbine

Since wind turbines are very high, they can trigger lightning when exposed to a thunderstorm electric field. In fact, a wind turbine could be a better trigger for lightning than a stationary tower of similar height [4]. In the presence of an electric background field, all pointed structures at earth level form corona, even at high towers corona discharges are generated (Fig. 29a). Corona discharges create a space charge area around the top, and this space charge can screen the top of the tower from an electric field. As the electric field generated by the storm cell slowly increases, the corona discharge increases and continues to screen the tip from the increasing strength of the electric field. So, to create a connecting upward leader from the tip, the field must grow very rapidly to overcome the screening effect of the corona. In a slow-growing field, the corona generated at the tip prevents the formation of a connecting upward discharge. In wind turbines, however, these space charges cannot accumulate at the tips because they are displaced by the rotation of the blades. When a rotor blade is parallel to the ground, the electric field at its tip is rather small and increases rapidly as the blade turns upwards towards the cloud (Fig. 29b). The electric field is greatest when the blade is perpendicular to the ground and away from the ground (Fig. 29c). The electric field at the tip of the rotor blade oscillates while the blade rotates in the background field. As the rotor blade rotates, the electric field at its tip increases rapidly without forming a significant amount of corona space charge. Without screening the tip from the electric field, the conditions for starting upward leaders in the electric background field are achieved that no stationary tower of similar height would have produced [4].

Wind turbines operating with a rotating rotor thus offer more favorable conditions for lightning strikes.

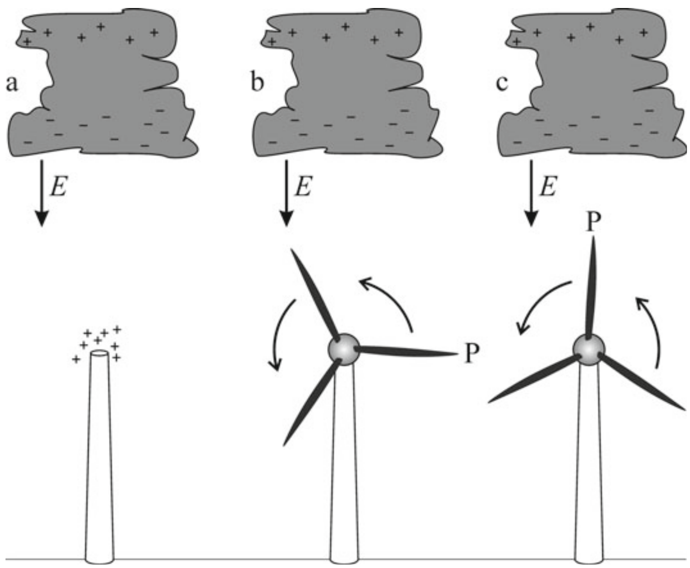


Fig. 29 Due to the constant electric background field, charges are accumulated at the upper head of the wind turbine (**a**). The electric field intensity at the tip of the horizontal rotor blade (P in **b**) increases during rotation and reaches its maximum when the blade is vertical (P in **c**) [4]

ii. Temporary overvoltages

In the event of faults in the power generation system, e.g. short circuits, temporarily high mains voltages can occur due to the continued presence of the propulsion, the rotation of the hub. The surge arresters in the area of the generator and the inverter must have a correspondingly high continuous voltage strength in order not to be damaged. This applies in particular to SPD type 2 on varistor basis without serial spark gaps which could be overloaded.

iii. Lightning caused cross overvoltages at tower top

Metal towers, towers with reinforcement or extensive coaxial metal elements of the tower structure have a very good magnetic shielding effect for electrical cable systems inside the tower. Nevertheless, high lightning surge voltages occur at the upper end of the tower between cables and the tower when lightning impulse currents are diverted via the tower. Therefore, surge protection measures at the top of the tower are absolutely necessary. Measures for lightning equipotential bonding and in particular SPD must therefore be used at the top and bottom of the tower to safely prevent dangerous sparking.

iv. Lightning current peak values at tower base

Due to large tower heights and long rotor blades, travelling wave effects occur with steep lightning impulse currents because the wind turbine behaves like an electrical line with comparatively high characteristic impedance (tower 150–250 Ω). At the base of the tower, this line is terminated with low impedance by the earthing system. This can lead to an increase in the current peak values at the base of the tower. However, this travelling wave behavior is only pronounced with very steep lightning impulse currents, with negative subsequent strokes or also with negative first strokes with a very short front. Surge arresters used at the base of the tower should therefore be powerful SPD type 1 lightning current arresters for LPL I, which can dynamically control the higher current peak values. Higher specific energies than for typically used type 1 SPD are not to be expected due to this effect, since no peak value increase occurs with slowly rising high-energy positive first lightning current.

v. Strike frequency and side flashes on wind turbines

According to the latest evaluations, there are usually more strikes on wind turbines than would be expected according to the height. At least 8–9 strikes per year per wind turbine instead of 2–3 strikes per year are to be expected. This refers to a single wind turbine, even if it is located in a smaller or larger wind farm.

With wind turbines as high structures, side flashes are not only possible, but more likely. Similar to the lightning protection of normal high buildings, it is also necessary to protect the areas above 80% of the hub height against side flashes at WT, i.e. to integrate air-termination devices and the connection to down conductors or to ensure that natural components are resistant to strikes. This applies in particular to the nacelle including existing weather measurement equipment, communication technology, etc. Strikes below 80% of the hub height occur with a significantly lower probability and with significantly smaller lightning current amplitudes, so that protective measures can usually be omitted there.

vi. Wind turbines with guyings

For very high wind turbines, with nacelle heights greater than approx. 200 m, 3 or 4 guy ropes (made of steel) are used for mechanical stabilization. Due to the rope cross-sections required to achieve mechanical strength, all partial lightning currents can be safely controlled. However, direct strikes into these guy ropes are also possible, although lower lightning current parameters occur. The effects at the root points of strike, in particular melting with severing of partial wires, are only permissible to the extent that no impermissible weakening or even tearing of the ropes is possible.

vii. Personal safety

It should be noted that the erection of WT may take several days and that persons are particularly exposed to the risks of lightning strikes during this time. In the documentation of the wind turbine, safe areas have to be indicated which must be visited in the event of a thunderstorm. In this context, the term "personal safety distance" was introduced. This minimum distance can be calculated according to the calculation of the separation distance according to [9]. If this minimum distance is maintained, uncontrolled flashovers to persons staying in the designated safety areas are to be prevented.

viii. Lightning current measuring devices in wind turbines

There are recommendations for the use of monitoring systems that provide information on lightning strikes into the WT. This enables the preventive maintenance of systems to be optimized and downtimes to be minimized. Such lightning current measuring devices are particularly important for lightning protection of rotor blades. Undetected lightning strikes in rotor blades and possibly associated serious consequential damage can thus be avoided. Therefore, such monitoring systems are not only capable of recording the relevant lightning current parameters, but also indicate which rotor blades have been struck directly by lightning. Continuing lightning currents have a special influence on the loading of the lightning protection of rotor blades and rotating components. Measuring systems should also be able to detect continuing currents without superimposed or subsequent pulse currents, so-called ICC-only lightning currents, since such lightning flashes of such current waveforms cannot be detected by lightning location systems.

c. **Protection of Railway systems**

9 Limitation of Railway Systems to be Considered

With regard to lightning protection and surge protection, the following section considers stations with railway installations and buildings, railway facilities, especially for passenger transport, electrical railway control technology and the rail network with track installations, overhead lines and signaling systems (railway infrastructure). In particular, electrified (electrically operated/powered) railways are considered [33, 47].

The lightning and surge protection discussed below primarily considers passenger traffic, including freight traffic.

10 Importance of Lightning Protection for Railway Facilities and Railway Systems

Railway station buildings, overhead lines, moving and stationary trains are often the highest facilities in the immediate vicinity and are therefore endangered by direct lightning strikes. In addition, overhead contact lines, rails and electrical signal lines represent long, large-scale loops into which high pulse voltages and pulse currents can be coupled by electromagnetic induction at close lightning strikes.

Lightning protection systems are required for immobile railway installations, as these are structures for which the necessity exists by law. This is because they are structural installations, such as railway stations, for a larger number of people. Last but not least, crowds of people are a particular problem with lightning strikes.

Railway networks are considered to be exposed to the effects of lightning, since many km to many 100 km of lines and thus many strikes occur each year (often routes through different regions with different lightning densities).

Rail-bound transport ensures mobility and has an important function as a sustainable means of transport for passengers and freight. The development of safe and highly available transport routes has given the railways a constantly growing significance. As a result, the railway infrastructure will be massively renewed and expanded over the next few decades. As the railway network stretches over large distances, its size and exposed location make it an ideal target for the effects of atmospheric discharges, e.g. in the form of direct lightning strikes. Thus, buildings, installations and electronic equipment of the railway are considerably endangered by lightning strikes and the resulting electromagnetic disturbances.

Damage is caused by direct lightning strikes in overhead contact lines, rails, masts and buildings (Fig. 28). This results in the following protection goals:

- personal protection
- fire protection

- protection against mechanical damage
- protection of power supply, radio systems and control and command technology (CCT)
- protection of electronics and digital interconnection systems
- ensuring plant availability.

A further threat are railway-specific overvoltages, e.g. caused by switching operations or continuous influencing voltages in adjacent line cables.

Railway stations are not just places where countless people pass by every day. They also offer attractive areas for shopping, eating and enjoying other services. Within these complex infrastructures, solutions ensure a trouble-free flow of electricity and data. These solutions meet the highest safety standards with tested systems for fire protection, lightning protection and surge protection. In buildings where many people spend a lot of time, three protection objectives must be achieved: Limiting the speed of fire, securing escape and rescue routes, maintaining the function of important safety and electrical systems.

No railway operator can afford a lightning-related technical device or system failure. Effective protection is guaranteed by correctly installed lightning protection systems. Damage is also frequently caused by electrical surges, which can be triggered by a nearby lightning strike or by switching in large electrical systems.

Thus lightning and surge protection should include protection for stations and railway buildings as well as for the railway network and signaling equipment.

i. Railway environment

The railway environment is dominated by the overhead structure, which forms a huge lightning antenna. In rural areas this overhead structure is a main target for lightning strikes (Fig. 30). An earthing cable on the masts ensures that the entire structure is at the same potential. Every third to fifth mast is connected to the traction return rail, the other rail is used for signaling. In d.c. traction areas the masts are isolated from the ground to avoid electrolysis, while in a.c. traction areas the masts are in contact with the ground. Sophisticated signaling and measurement systems are mounted on

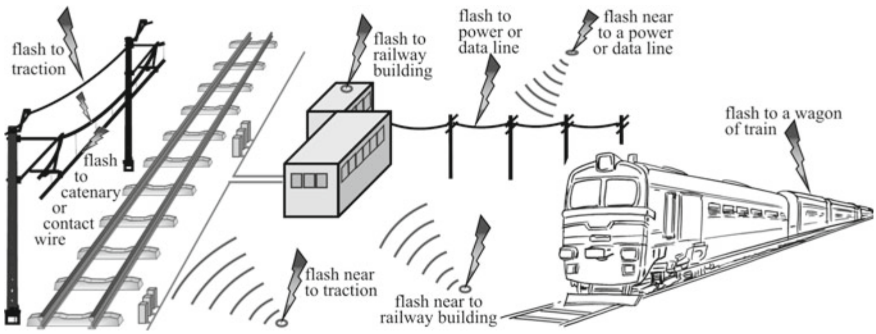


Fig. 30 Points of lightning strikes as sources of damage of railway systems [34]

or near the rail. These devices are exposed to lightning strikes in the rail which are absorbed by the overhead construction. Sensors on the rail are connected via cables to track-side measuring systems which are connected to earth. This explains why rail-mounted devices are not only exposed to induced overvoltages, but also to conducted direct lightning surges [36].

ii. Minimize downtime and operational disturbances with lightning protection

For railway technology to run reliably, many highly sensitive electrical and electronic systems must function reliably. However, this continuous availability of the systems is at risk. Lightning strikes or electromagnetic interferences damage or destroy cables, control components, assemblies or computer systems and in most cases lead to operational faults and time-consuming troubleshooting. This means delays in rail traffic and high follow-up costs.

Causes of damage, losses and rail operation downtimes are:

- Direct lightning strikes: Lightning strikes the overhead contact line, the rail or a mast. Malfunctions or rail operation downtimes are usually the result.
- Indirect lightning strikes: Lightning strikes an adjacent building or the ground. Now lightning surges spread via the cables or are inductively coupled in, damaging or destroying unprotected electronic components.
- Electromagnetic interferences: Overvoltages can occur if different systems, e.g. a railway traffic light bridge, the high-voltage road and the railway overhead line, influence each other due to their spatial proximity.
- Causes within the railway system: A further danger is switching operations or triggering fuses. They can also generate overvoltages and cause damage.

With a consistent, optimized concept for lightning and surge protection, cost-intensive malfunctions can be reduced and system downtimes minimized.

iii. Specific railway facilities in the lightning and surge protection concept

The following railway facilities are to be protected by an integrated lightning protection zone concept:

- electronic and digital signal boxes; control and safety technology systems
- level crossing protection systems ensure safety at intersections of road and rail traffic
- point heating systems should guarantee trouble-free railway operation even in ice and snow
- d.c. rail systems are used worldwide in metropolitan area in local public transport. d.c. rail systems such as trams, suburban trains and underground trains are gaining in importance and are being actively expanded.

As modern control and command technology (CCT) is increasingly digitalized and equipped with highly sensitive electronics, it is now more susceptible to faults than in the past. The consequences of system failures due to lightning strikes or overvoltages can lead to delays in rail traffic, often associated with high costs. Availability, even during thunderstorms, can be increased with a carefully planned lightning and surge protection concept.

iv. Measuring systems and signaling elements for railway

Various rail-bound measuring systems are used to monitor the condition of the wagon fleet and the undesirable loads in the rail structure. Some of these systems are hot bearing detectors, hot brake detectors, wheel profile measurement system, weighing or wheel impact measurement, inclined bogie detector, track measurement, vehicle identification system, weighbridge, etc. The following measuring elements are important and must be available for an effective signaling system, track circuits, axle counters, turnout detection and associated power supplies.

The environment for railway signals consists of a variety of different types of devices with complex connections distributed along a railway line and located in exposed locations. The railway line and the structures around it tend to receive lightning strikes [35].

In the vicinity of railway signaling, lightning and/or surges occur, enter or are passed into the signaling system by one or more of the following devices and processes:

- power supply points, e.g. 240 V a.c. or 120 V a.c., derived from overhead line systems, e.g. 33 kV/11 kV/2.2 kV transmission/distribution systems
- e.g. 240 V a.c. or 120 V a.c. power supply air cables (in rural areas)
- e.g. 240 V a.c. or 120 V a.c. power supply cable
- overhead line 1500 V d.c. contact wire structure in the electrified area
- rail and track connections to signaling sites
- cables for signaling control and display circuits (connected to field devices)
- communication lines
- communication equipment on high masts
- consequence of earth potential rise (EPR)
- induction into the power supply, communication, control wiring, etc.

Typically, the wiring standards and arrangements allow the transmission of very high overvoltages and currents through the signaling system.

In the environment of railway signaling there are various earthing systems. These earthing systems are: signal ground, electrical 240 V earth, electrical high-voltage ground, public/municipal 240 V multiple earth neutral (MEN) ground and communication ground. (TN 030 2018).

11 Lightning and Surge Protection for Railway Facilities and Railway Systems

The progressive automation of operational processes has already covered entire railway systems. There are high demands on the availability and reliability of the railway systems used. System failures, e.g. at an electronic interlocking or parts thereof, affect the railways not only locally, but also nationally. Since the operation of the railways must also be guaranteed during thunderstorms, both the operator and the industry of the rail suppliers are asked to deal with transient surges caused by switching operations and lightning discharges [37].

- Railway buildings: Lightning protection level (LPL) III generally applies to buildings frequented by the public and LPL II to buildings with extensive information technology equipment. When selecting a lower lightning protection level or dispensing with a lightning protection system, risk assessment must be carried out and documented.
- CCT systems: The highest lightning protection level I generally applies. Surge protection in railway technology ensures a safe and trouble-free infrastructure.

i. External lightning protection for railway systems

External lightning protection systems with air terminations, down conductors and earthing system shall be planned and installed. Separation distances must be calculated, documented and observed individually. Preferably foundation earth electrodes shall be erected. If no foundations are laid, earth electrodes shall be designed as rod earth electrodes or ring earth electrodes. In existing installations without foundation earth electrodes with CCT systems installed, ring earth electrodes shall be retrofitted or, if this is not possible, rod earth electrodes. Earthing systems of neighboring buildings of the railway should be included in the earthing concept. For building distances of up to 3 m, the earthing systems must be connected to each other (Fig. 31). At distances of up to 20 m, influences must be demonstrably considered. The total earthing resistance should not exceed 10 Ω. Railway tracks are not suitable as lightning protection earthing systems. However, the tracks must be integrated into the equipotential bonding system in an appropriate manner.

For new installations, the reinforcement of the entire building must be included in the equipotential bonding. For buildings in reinforced concrete construction, the reinforcement should preferably be used as down conductor system. The prerequisite for this is that the reinforcement, including its joints and connections, is capable of carrying lightning currents. Concrete module buildings without external lightning protection must have lightning current carrying reinforcements included in the equipotential bonding. The lightning current carrying capacity of foundations, building walls and ceilings must be confirmed.

External lightning protection for components of the outdoor railway systems is generally not required. If possible, the protected space of overhead catenary or contact wires or bridges should be used (Fig. 32).

In the outdoor area, the aim is to lay the signal cables and install signal systems in the protected space of the overhead lines or the traction and/or conductor rails. Lightning strikes in traction circuits or building (Fig. 30) lead to voltage craters, which can cause insulation damage to cables laid in their vicinity. Minimum distances between signal cables and earthing systems (mast foundations, building earth electrodes, etc.) must therefore be observed. Signaling equipment such as interlocking buildings,

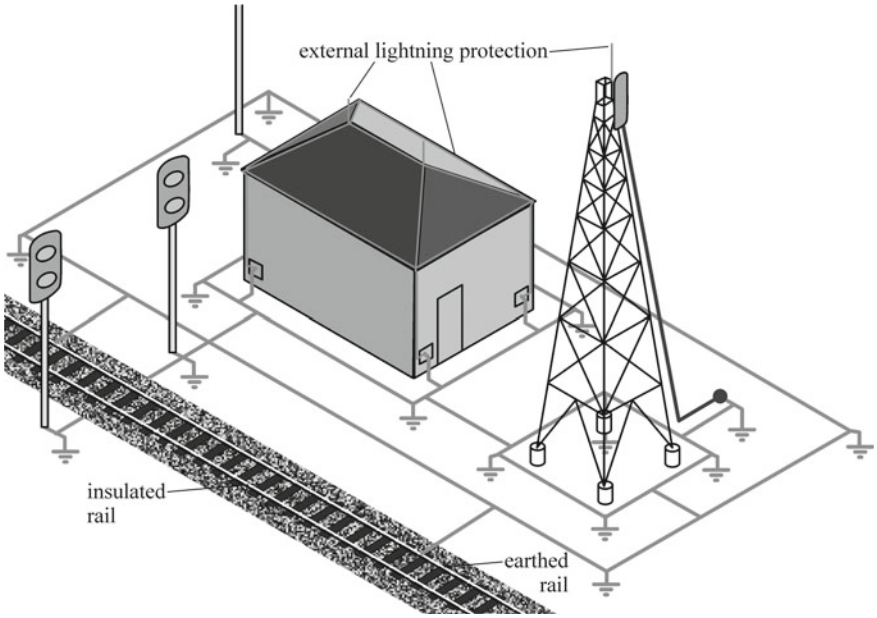


Fig. 31 Railway earthing and external lightning protection

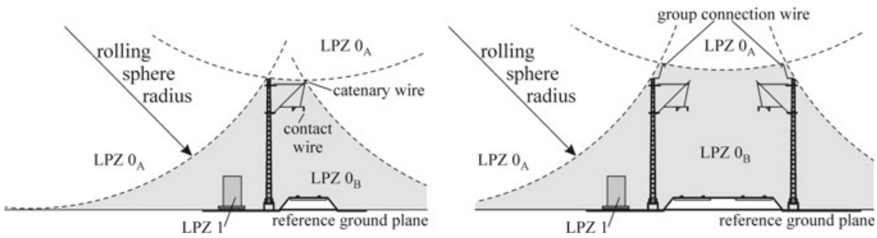


Fig. 32 Lightning protection zones of traction systems [34]

switchgear houses, signals or cable systems must always be installed at less exposed locations.

ii. Internal lightning protection for railway systems

A comprehensive protection of buildings and electrical or electronic systems against the effects of lightning electromagnetic pulses (LEMP) can be achieved by LEMP protection measures system (LPMS). It consists of the individual combination of

- earthing and equipotential bonding measures
- lightning protection measures for magnetic and spatial shielding
- cable routing and shielding measures as well as
- measures for energetically coordinated protection by SPD [38].

The following applications show the use of surge protective devices (SPD) in parts of railway systems. It should be noted that protection concepts for railway systems should always be agreed between the operator of the railway system, the planner, the system supplier as well as the client (general contractor) and the responsible experts. The question of the scope of lightning and surge protection measures shall be answered by a risk analysis in accordance with [8]. The decision cannot only be made according to economic aspects. The protection of persons always has a higher priority than the protection of installations or material assets and must therefore be considered.

The following descriptions mainly refer to future signaling systems, such as electronic interlockings (EI), railroad crossings (RRX), electrically located points and all telecommunications systems.

With a view to improving availability and reducing damage caused by lightning and surge voltages, signaling systems will in future always be designed in LPL I. An individual risk assessment and the associated calculations are no longer required.

Air-termination devices and down conductors on buildings with signaling equipment with a floor area of less than 10 m^2 or an enclosed space of less than 25 m^3 can be dispensed with, but not with other measures such as surge protection by means of SPD. Equipotential bonding should be provided for all electrical railway systems. It is always necessary to set up a lightning equipotential bonding system covering all trades. All active electrical conductors should preferably be included in the equipotential bonding at the entrance to the building via SPD indirect with low impedance. Electrically passive conductors, such as cable shields, must be earthed directly.

In signaling systems, the special requirements arising from functional safety must be taken into account (safety integrity level SIL 4).

Overvoltage protection in indoor systems must always be implemented. All SPD may only be used if there is proof of safety from the CCT system manufacturer. It must be ensured that the SPD has no retroactive effect on the signaling system. The safety verification must take into account the behavior of this SPD in the unaffected case as well as in the influenced case (e.g. inductive influence by travel and short-circuit currents in the overhead line and the traction return current paths or lightning effects) with CCT systems free of earth faults or earth-faulted systems and also with failures or faults of the SPD. SPD must be installed in circuits galvanically connected to outdoor components, e.g. signals, points or axle counters.

The implementation of EMC measures shall be taken into account. In practice, for shielding measures, existing metal facades and reinforcements of walls, floors and ceilings on or in the building are often used to form shielding cages, which are ideally combined to form shielding cages, e.g. in the case of control and command technology concrete buildings. Cable shields must be earthed on both sides. For floor openings of shielded cables, their shields must be connected to the meshed equipotential bonding. Current-carrying cable shields in outdoor installations must be earthed on both sides. Otherwise, it must be noted that continuous influencing voltages of up to 250 V and short-term influences of up to 1500 V must be expected. To reduce induction loops, cabling in interlocking buildings should be separated into cable ducts according to cable categories. All CCT external cabling must be introduced into the building at a central point. Other trades may have their own central entrances.

Main equipotential bonding and earthing bars, e.g. MEB, shall be located close to lightning protection zone boundaries. Equipotential bonding rails shall be accessible and shall be located in close proximity to sub-distribution boards or cable termination racks. Suitable earthing fixed points shall be available. The track system shall only be connected to MEB at one single position. For new installations, TN-C-S systems with insulated PEN conductors and central earth connection, TT systems or IT systems shall be installed. TN-C systems are not suitable.

a. Standard and backup power supply

For standard 50 Hz power supply systems, such as electronic interlockings, lightning protection is provided by combined lightning current and surge arresters SPD Type 1. This SPD is capable of discharging lightning currents up to 100 kA (10/350 μs) several times. Even at high short-circuit currents of up to 50 kArms, the occurring mains follow currents are significantly reduced. Selectivity to upstream overcurrent protection devices (fuse) up to 20 A gL/gG is achieved. This enables maximum system availability, which ensures the functionality of the electrical power supply system for the operator of the railway system.

In various railway system applications, the traction power supply system is increasingly being used as a supply system for other systems, such as signaling systems or even as a backup power supply. The overhead line voltage up to 25 kVrms 50 Hz is converted into low voltage of e.g. 2 × 230 V by means of transformers. The short-circuit currents vary between 3 and 20 kArms depending on the location. Since there are different loads and thus different powers of the lightning current arresters used, especially in railway systems with operating frequencies of 16.7 Hz, the applicability of protective devices should be documented in the test report of an independent test laboratory.

b. Turnout control for local public transport railways

The electronic turnout control is used in local traffic railways. It safely controls turnouts for various drive technologies in signaling systems and turnout areas. These turnout controls can be flexibly adapted to the railway operator's requirements and comply with safety integrity level SIL 3 according to [39]. In addition to the safety level with signal control, turnout control and monitoring system, the evaluation unit of the track switching device and, if necessary, an isolating transformer unit for the power supply are installed in an external cabinet. The surge protection devices are SPD of category D1 according to [15]. They are capable of safely discharging lightning currents up to 5 kA 10/350 μs. In addition, the SPD selected for this application offer energetically coordinated surge protection for the parts of the system using combined lightning current and surge arresters. Both lightning currents and currents inductively coupled into the periphery, e.g. in turnout operating devices, signal transmitters, key switches, are safely controlled.

c. Railway power supply systems—application of surge arresters for medium-voltage systems

Electrified alternating current railways form a dense network that leads to a large equivalent collection area for direct and indirect lightning strikes. Surge arresters for medium-voltage systems are used to minimize the effects of such sources of damage on the traction current network and the associated systems.

In order to select the correct MV surge arrester for the application, the energy absorption capacity, the maximum continuous voltage in the rail network and the ambient conditions on site must be taken into account [40]. A class 3 surge arrester used on a supply transformer in a 25 kVrms/50 Hz traction power supply system and also used every 10–20 km, for example on high-speed lines, provides surge protection. Classification in line discharge class 3 offers sufficient energy absorption capacity. This allows the surge arresters to withstand local loads without damage over a long period of time. When further designing the MV surge arresters, it must be taken into account that the maximum non-permanent voltage U_{max2} occurring in the railway system is defined, which must only occur for a limited period of time and not longer than five minutes. The continuous voltage U_c of the surge arrester must be selected in accordance with $U_c \geq U_{max2}$.

Arresters for d.c. rail systems are also based on the above selection criteria. MV surge arresters for d.c. rail networks can effectively protect them against the effects of lightning strikes [41, 42]. An example for 3 kV d.c. traction is shown in Fig. 33.

Tested surge arresters are to be used in the low and high voltage range.

d. Track circuits and open earthing of railways

In alternating current (a.c.) circuits, track circuits are used for signaling occupied or free track sections. The insulation of one or both rails is required (Figs. 33 and 34). In the event of a fault, the insulation of the tracks of a track section creates a hazard

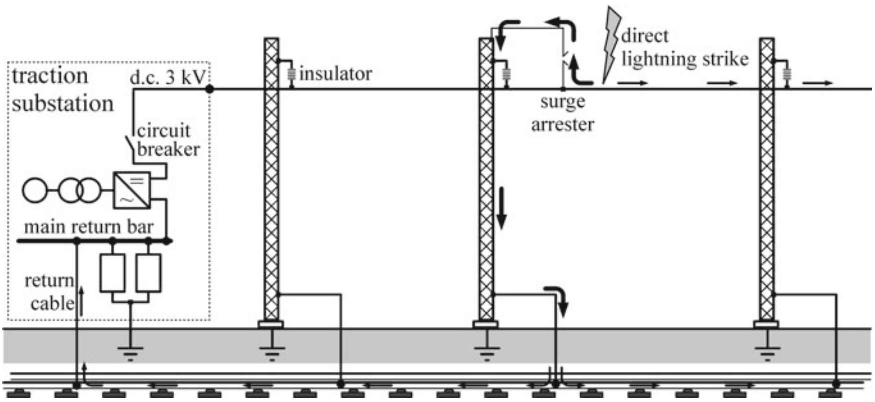


Fig. 33 Lightning current distribution in the case of connection to one rail [34]

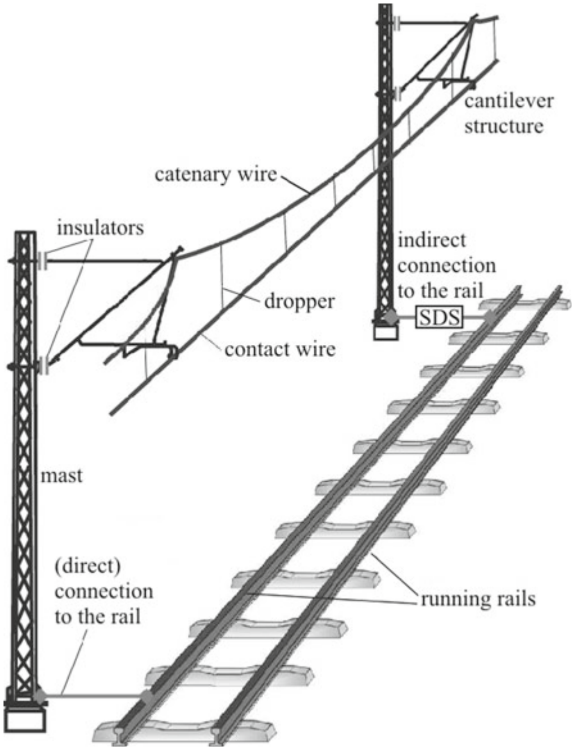


Fig. 34 Lightning protection zones of traction systems [34, 37]

potential for persons through indirect contact. According to [43, 44], the busbars with alternating current circuits are generally earthed. For railway earthing systems, [43, 44] must be observed. It defines the requirements for protective measures for electrical safety in fixed installations connected to a.c. and d.c. railways. However, [43, 44] also contains the requirements for all installations which are threatened by power supply systems of electric railways. It includes the requirements for the protection of persons and installations.

The protection against accidental contact must be ensured by rail earthing (Fig. 34). The track earthing implies the connection between conductive parts and the track earthing. The rails represent the earth. They are used as reverse circuits and are deliberately connected to earth in alternating current circuits. The orbital earth contains all conductive parts connected to it. A distinction is made between direct railway earthing, direct connection between conductive parts and railway earthing, open railway earthing and indirect connection of conductive parts with railway earthing by means of voltage limiters or short-circuiters, e.g. track circuits insulated on one side, direct current circuits with insulated tracks.

The protective devices used must ensure the protection of persons and property both in the event of an interruption of the overhead contact line and in the event of a lightning strike. Voltage limiting devices (SDS) are used for this purpose (Fig. 34).

These provide safe equipotential bonding both under lightning current load and under loads caused by a permanent short-circuit connection in the case of short-circuit currents due to the high-current-resistant welding of the SDS electrodes. If the SDS is short-circuited and its electrodes are therefore welded, this SDS must be replaced by the railway operator's maintenance personnel. Experience has shown that lightning strikes, unlike malfunctions, are the most common cause of electrode welding.

Based on this result, lightning current resistant SDS are required, which avoid a permanent welding of the electrodes when discharging lightning currents. With lightning current resistant SDS, a safe potential equalization is only temporarily established for the duration of the lightning flash. If, however, a short-circuit current load occurs, the safety of persons and material assets, as with an SDS that is not resistant to lightning current, is guaranteed by safe welding of the electrodes [37].

e. EMV of railways and lightning protection

The signal and train protection systems of modern railways are highly automated. Digital electronics can realize a high degree of intelligence and flexibility in the control functions and is increasingly used in railway systems. However, due to the low destruction energies associated with modern electronics, there are more concerns about reliability and safety. Before the advent of modern electronics, key components in signal and control networks were electromechanical and largely insensitive to electromagnetic disturbances such as transient events caused by lightning strikes. Therefore, the design of signal and control networks at that time was not always carried out according to the strict rules of electromagnetic compatibility. Later, individual subsystems in the network were replaced by units with modern electronics and new functions such as automatic train stop (ATS), automatic train control (ATC) etc. were added. These developments made the signal and control system more susceptible to lightning transients.

During thunderstorms, the railway systems are exposed to electromagnetic pulses (LEMP), either by direct lightning strikes on any part of the overhead contact line or by the induced voltages generated in the overhead contact line by nearby lightning strikes. A part of the lightning energy reaches the electronics and causes disturbances and destruction.

The main objective is to provide effective lightning protection to avoid or minimize traffic congestion and thunderstorm delays. The system to be protected should include the rails and overhead contact line system above the conductive earth, track circuits, amplifier and auto transformers, buried communication cables near the tracks, etc. The system to be protected should also include the tracks and overhead contact line system above the conductive earth.

The following system components must be included in the lightning equipotential bonding indirectly via isolating spark gaps:

- systems with cathodic corrosion protection and stray current protection measures
- earthing systems of high voltage installations above 1 kV, if impermissibly high earthing voltages can be carried off

- railway earth for alternating current and direct current railways (railway tracks may usually only be connected after approval).

f. Low voltage SPD for a.c. and d.c.

When it comes to dimensioning common a.c. systems, there is a wide range of SPD on offer. These can be TN or TT systems, fed networks from the overhead railway line, emergency standby power system with mobile diesel aggregates or special IT systems, e.g. for transmission lines with different voltage levels. As a rule, they are easy to plan on the basis of the manufacturer's documentation. Basic aspects must be observed when dimensioning SPD in a.c. systems. In the railway sector, further aspects must be taken into account. Above all, the railway earthing affected by reverse current and the resulting influences should be included in the planning when selecting SPD. A long-term influence of 250 V a.c. and a short-term influence of 1500 V a.c. should be assumed. Thus in railway networks a strict separation of the system against the railway earth should be established, either by spark gaps or by SPD with gas arresters connected to earth. The use of such SPD also ensures that no leakage currents occur between the active conductors.

In the railway sector there have always been direct current (d.c.) systems with typical voltage levels of 48/60 V d.c. for telecommunications and CCT and 36/48 V d.c. for railroad crossing protection systems. However, new railway projects require new system architectures. In future, the voltages used will also be implemented as d.c. systems. Here, CCT 400 V d.c. are the most important. Power buses, which are led from the track field concentrator into the field to the field element connection box, or also the CCT system 48 V d.c. level (own requirements). When planning d.c. systems, existing a.c. SPD are often used. This is also possible in many areas. In certain cases, however, the framework conditions should be examined more closely. Particularly due to the photovoltaic boom of recent years and the recognition by many manufacturers that special technologies or circuit designs are necessary for d.c. systems, it is advisable to discuss the applications in detail with experts or companies.

g. SPD for telecommunications and control and command technology

In addition to safeguarding the power supply side, the areas of telecommunications and control and command technology (CCT) must also be taken into account. In general, the selection of information technology SPD depends on considerations similar to those of power technology SPD:

- lightning protection zones at the installation site and their arrangement
- compliance with product- or application-specific standards
- adaptation to ambient conditions, installation conditions
- mounting type and environment.

In contrast to the selection of SPD in power systems, which usually have uniform conditions with regard to voltage and frequency, there are different types of signals to be transmitted in control and command technology systems with regard to

- voltage (e.g. 36, 48, 60 V)
- current (e.g. 0–20, 4–20 mA)
- signal reference (balanced, unbalanced)
- frequency (d.c., Low Frequency, High Frequency)
- signal type (analog, digital).

Each of these electrical quantities of the useful signal to be transmitted can contain the information actually to be transmitted. For this reason, the useful signal must not be inadmissibly influenced by the use of SPD, e.g. in control and command technology systems. Therefore, some aspects have to be considered for the selection, which are roughly described in the following [45].

CCT systems are supplied from the local supply or from the internal network of the railway operator or from stationary or mobile emergency power supply systems. Lightning and overvoltage protection must be effective for all operating states. Even in systems without external lightning protection, protection against partial lightning currents must be implemented in the main power supply for reasons of availability. When feeding in with or without isolating transformer, SPD type 1 must be used directly at the building entrance. According to the lightning protection zone concept, sub-distributions must always be equipped with SPD. The lightning protection zone boundary between indoor and outdoor installations is formed by the cable termination frame. Dimensioning of the SPD must take into account, for example, the system voltage, additional influencing voltages or short-term influencing voltages from the railway system. SPD in CCT systems must always be built up from series connection of varistor (MOV) with gas discharge tube (GDT) between each signal wire and earth (Fig. 34), in particular to ensure absence from feedback. Reliability against feedback and protection of the system must be proven (Fig. 35).

These SPD must have a rated discharge surge current of 3 kA 8/20 μs in accordance with category C2. The SPD protection level (<1.5 kV) must be well below the insulation strength of the equipment and the insulation strength between the signal wires and earth.

h. Protection of mobile radio systems for railways and SPD for antenna systems

SPDs for antenna cables differ in particular according to their suitability for coaxial, symmetrical or waveguide systems, depending on the physical design of the antenna

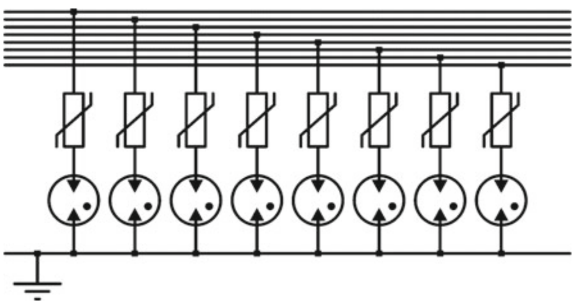


Fig. 35 Each signal core with series connection of MOV and GDT wired

cable. In coaxial and waveguide systems, the outer conductor can usually be connected directly to the equipotential bonding.

Remote radio head (RRH) technology is not only used for commercially used mobile radio applications. This technology is also used in digital authority radio (BOS) systems, e.g. in police and rescue services or in railway communications, where high reliability and system availability are top priorities.

i. Protection for data communication systems

Data communication systems are available for various railway infrastructures, whether for high-speed trains or local public transport. They usually consist of an antenna installed on a mast, a power source and a modem. These devices are essential to ensure the safety of rail transport. It is therefore necessary to make every effort to avoid malfunctions of these systems. The risk of direct and indirect lightning damage to installations must be taken into account. Lightning can strike antennas directly, but can also affect other external elements, an overhead line, a traction substation, etc., causing surges and induced partial lightning currents.

To protect against direct lightning effects, the installation of lightning air-termination rods together with a metallic lightning down conductor, a rod earth electrode as a simplified earthing system and an equipotential bonding bar is proposed. Under certain conditions defined in the international standard [9], the metallic mast can serve as a natural down conductor. It will also be necessary to establish equipotential bonding with the metal parts of the system (Fig. 31).

To protect against indirect lightning strikes, the installation of coaxial SPD to protect coaxial cables and the installation of a SPD type 1 + 2 to protect power lines is recommended. Grounding kits are also used for the coaxial cables.

j. Influence on electrical railway systems in the event of lightning strike

The railway systems are usually struck by lightning on the overhead line (Fig. 30). Statistical studies have shown that the number of lightning strikes on a substation is very low compared to overhead contact lines. Normally, a lightning strike on a contact line leads to very local damage. And usually, for economic reasons, only important safety devices and connection terminals to substations are protected. In view of this, the choice of surge arrester (SA), technology, design, installation and location are important to minimize incoming surges in the substation. But this surge arrester may not be sufficient to protect the entire substation, and more SA tuned to the first one are needed. Surge protective devices (SPD) on power lines and communication/control lines are also required. Response shows that telecommunications and signaling systems are the most frequently destroyed.

k. Earthing the computers

A common problem exists with all measurement or information systems that use computers to perform data analysis and other functions. Typically, computer enclosures are grounded via the power cord and computers' 0 V (reference line/PE) is also grounded. This situation usually violates the principle of making the measuring/information system float to protect it from external lightning strikes. The only way to overcome this dilemma is to feed the computer via an isolating transformer and separate the computer frame from the system cabinet in which it is mounted. Electrical connections to other devices will again lead to an earthing problem, for which a fiber optic connection is proposed as the solution. The key word is the consideration of the overall system and the search for a holistic solution.

12 Specialities of Railway Facilities and Railway Systems

i. Lightning protection of persons

During thunderstorms, platforms, stops and stations offer protection for commuters and travelers. Earthing of roofed systems is particularly important. If the lightning finds a way into the ground in this area, it can lead to increased touch and step voltages and thus to fatal injuries. Other faults, such as a broken overhead contact line, can also result in inadmissibly high touch voltages and thus endanger people.

In context with external lightning protection, lightning-induced touch and step voltages in the station area must be minimized by suitable measures such as standing surface insulation or potential control.

It must be taken into account that panic in crowds is possible with direct impact in station buildings.

a. Protection of persons near overhead wires

In the event of a lightning strike into an overhead line, the lightning current flows through the various masts closest to the point of strike into the ground. The risks at these masts are the same as with lightning down conductors, touch voltages and step voltages. It is generally accepted that people within a radius of 3 m of the masts are in a dangerous situation without protective measures. Although the protection of technical personnel can be considered through technical or organizational measures (thunderstorm warning and lightning information systems), it is difficult to consider evacuating/clearing a platform during thunderstorms. Studies have helped to define the risks, their probability of occurrence and the personal protection measures to be taken for masts. These are usually insulation of the line connecting the overhead contact line and possibly its traction SPD, and equipotential bonding. It can also be an insulation of the earthing system [46].

Rails and overhead lines can introduce partial lightning currents into station areas.

b. Passengers in railway wagons

Persons in railway wagons, especially passenger wagons, are well protected against lightning (Fig. 27).

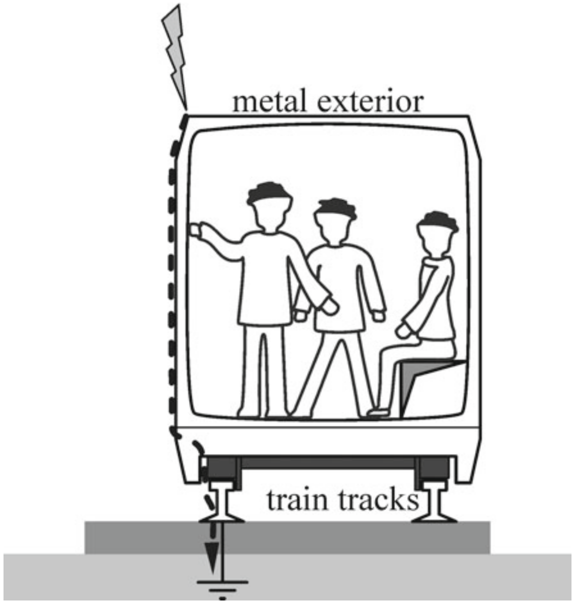


Fig. 36 Railway passenger wagon during lightning strike

The metal shell of a train forms a so-called “Faraday cage” which blocks electric fields and lightning currents in this shell and protects passengers from lightning strikes, currents and high potential differences. When lightning strikes, this cage conducts the electrical current through the outer shell of the train, not through the cabin, and lightning current flows through the steel wheels to the steel rail. The train is earthed through the track (Fig. 36).

When lightning strikes a train, the electrical charge in the metal surface of the wagon flows to the tracks and thus to the ground. Since the outside conducts the lightning current outside the enclosed space and no current flows through the interior, the passengers inside are safe.

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