PROTECTION OF PV SYSTEMS FROM LIGHTNING EFFECTS IN ITALY

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Abstract – Photovoltaic systems occupy large areas, usually on the top of buildings, and so they are particularly exposed to the direct and indirect effects of lightning.

Direct effects take place when an atmospheric discharge strikes directly on a part of a PV plant. Indirect effects, on the contrary, consist mainly in overvoltages and overcurrents which are caused by the Electro-magnetic fields generated in the circuits by lightning that fall on the surroundings.

Different types of lightning are taken into account as well as their variations in terms of annual frequency and intensity.

After a description of the problem, specific precautions to be adopted against lightning effects are discussed in the paper, also by considering the approach of the Italian CEI (Electrotechnical Italian Committee) and IEC (International Electrotechnical Committee) which have emanated specific standards concerning lightning protection.

A few examples will illustrate the opportunities offered nowadays by technology to protect PV plants from the risks of direct and/or indirect effects of lightning.

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1. GENERAL CONSIDERATIONS ON LIGHTNING

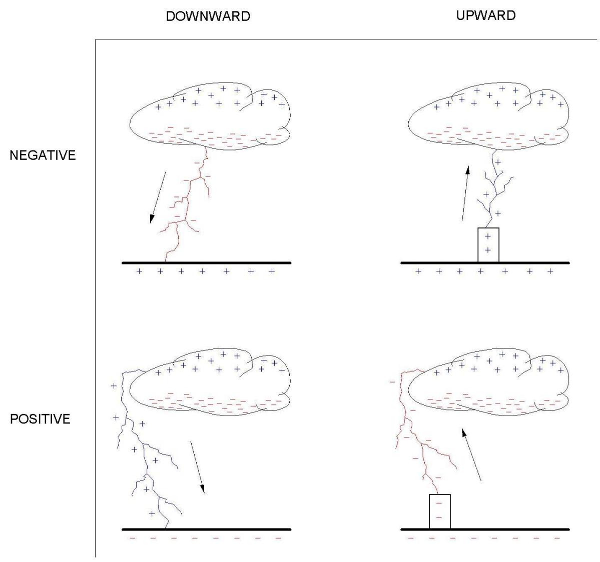
The clouds that usually bring about strikes are cumulus and rain-clouds. Frequently these take origin from cold fronts and may grow up to 10 ÷ 15 km from a few km of distance from the ground.

Inside these big clouds a number of electrically-charged zones may form because of the strong currents made of humid air, consequent to the heating and evaporation of the lower layers, further than by the presence of liquid and solid (ice) particles. The movement of these particles releases a huge amount of electrons, which produces positive and negative charges.

The polarity of a lightning, positive or negative, corresponds (by convention) to the part of the cloud that exchanges electric charges. Usually, negative charges take place on the lower part of the cloud and positive on the upper one. This means that actually about 90% of lightning are negative.

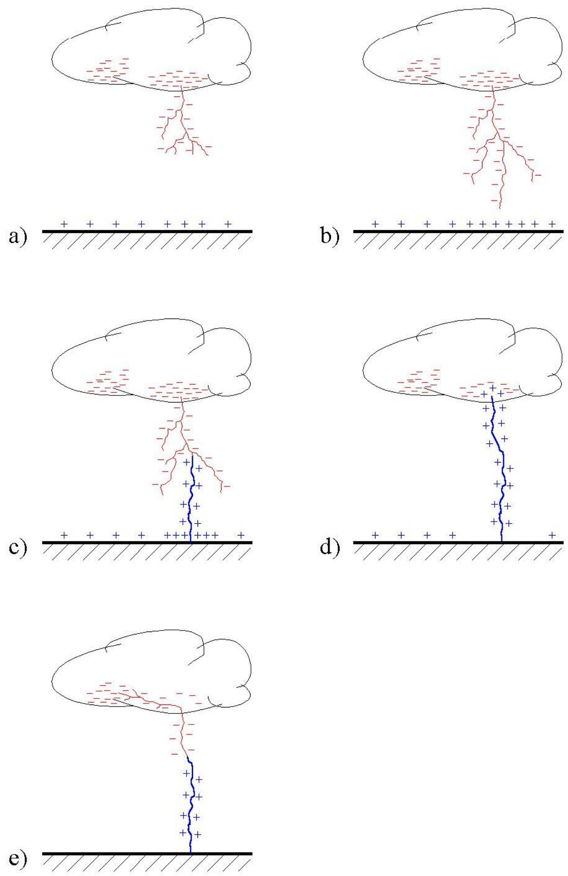
In general, negative lightning are formed by a number of close strikes. Positive lightning are formed by only one big strike.

The formation of lightning between the cloud and the ground begins when the electric field exceed the electric rigidity of the air (about 500 kV/m). Electrons are accelerated in the direction of the electric field and propagate their discharge toward the ground. Subsequently, from the ground (roofs. pinnacles, trees and other projecting spots) may form a counter-discharge that intercept the ionised channel caused by the descending discharge.



When the two charges meet, the ionised channel expands and the velocity of the charges may reach 1/3 of the light speed. The associated delivery of energy causes a bright light and a thunder.

Lightning may also happen from cloud to cloud, or inside a single cloud, when differently charged zones interact.



2. THE LIGHTNING CURRENT

From an electric point of view, an atmospheric discharge consequent to a lightning is faced by using a simplified model where every impulse is approximated by the same shape and downward lightning are formed by a first strong but slow strike, followed by a number of weaker but more rapid strikes.

Each strike has characteristics that usually are in accord with the following table:

Parameter	Min value	Average value	Max value
Current [kA]	3	35	200
Charge [C]	1	8	350
Energy I^2t [kAs]	6	60	10000
Slope *di/dt* [kA/µs]	10	40	200
Crest time Tc – first strike [µs]	2	5	20
Crest time Tc – other strikes [µs]	0,2	1	5
Halv. time Te – first strike [µs]	30	75	200
Halv. time Te – other strikes [µs]	6	30	150
Interval between strikes Δt [ms]	7	30	150
Total duration [ms]	30	180	1000

The lightning current causes overvoltages on circuits and equipment by means of three types of coupling: resistive, inductive and capacitive (this last is usually negligible).

The average number of lightning Nd that strike a structure is given by:

$$N_d = N_t \cdot A_d \cdot 10^{-6} = N_t \cdot C \cdot A \cdot 10^{-6} \quad \text{[Lightning/year]}$$

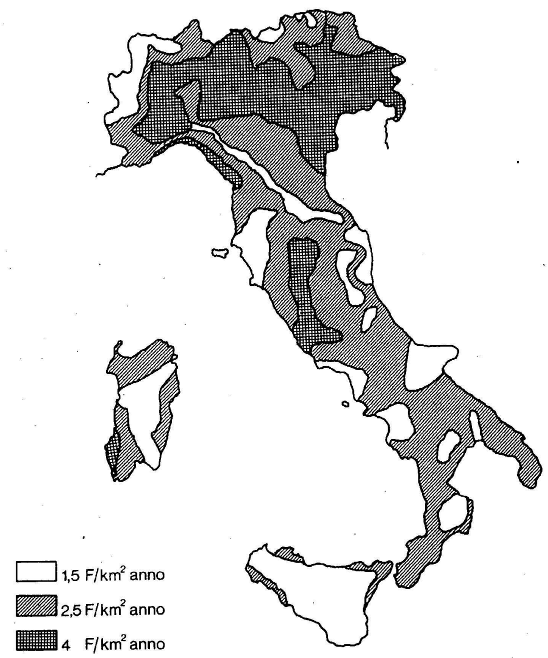
where:

Nt is the number of lightning per km2 per year in the region (see figure);

Ad is the collection surface (in m2) of the structure;

A is the collection surface (in m2) of the isolated structure;

C is the environmental coefficient, from 0.25 to 2 (0.25 when higher structures in the surroundings are prevailing, 0,5 when lower structures in the surroundings are prevailing, 1 when there are not structures in the surroundings, 2 on the top of a hill).

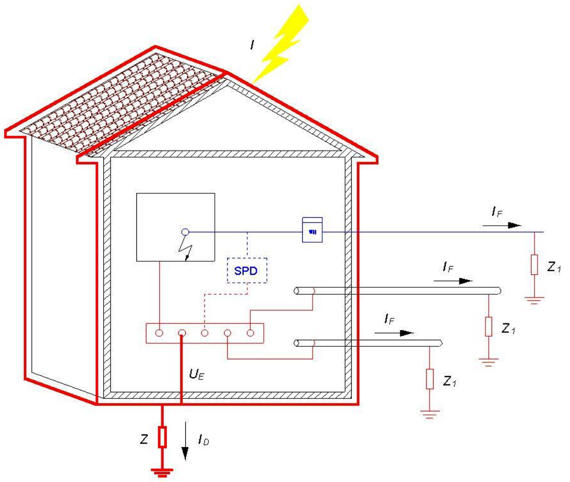


From 1994 CESI has installed in Italy the "*Sistema Italiano Rilevamento Fulmini*" (SIRF) that is able to localise the points of impact of lightning with the ground and to record all relevant parameters (amplitude, polarity, number of strikes). The system is based on the use of a number of probes for measuring the Electro-magnetic field generated by lightning, which are located mostly in the Italian territory and partially in the surrounding countries (Austria, France and Switzerland).

3. EFFECTS OF LIGHTNING ON STRUCTURES AND PLANTS

3.1 Resistive coupling

Faults are caused by the difference of potential between the local earth and the far earth.



$$I_D = \frac{Z_1}{n_1 Z + Z_1} I \qquad I_F = \frac{Z}{n_1 Z + Z_1} I$$

The earth potential raises to: $U_E = Z \cdot I$

Shielding of the power line may be effective.

3.2 Self inductance (L_a)

The two lines have a common point.

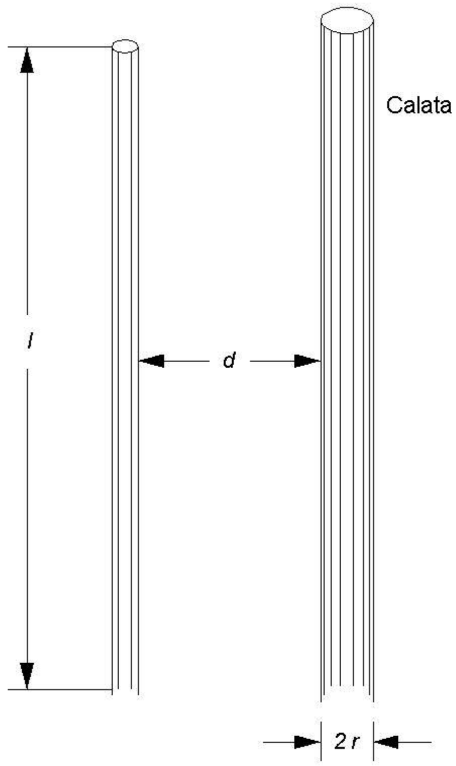
$$U = -\frac{d\Phi}{dt} = -L\frac{di}{dt}$$

$$L_a = 0{,}2 \cdot l \cdot \ln(d/r) = L_{au} \cdot l$$

Usually is L_a = 1 ÷ 1.5 μH/m

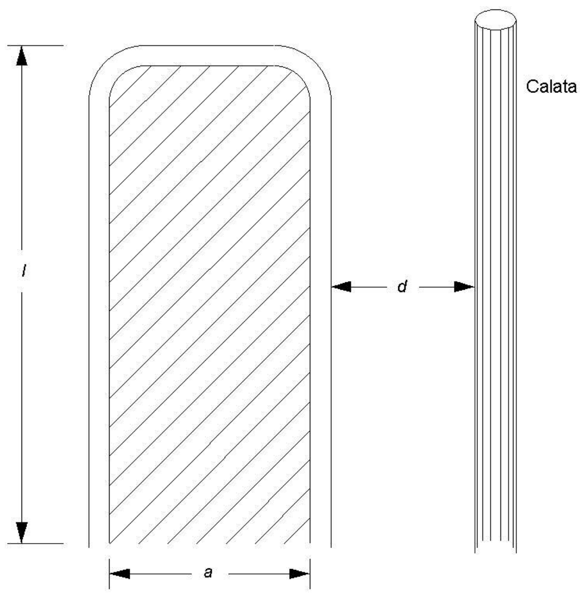
$$Z_{au} = \frac{L_{au}}{I} \cdot \frac{di}{dt} \quad \text{if} \quad di/dt = I/T_C \;\rightarrow\; Z_{au} = \frac{L_{au}}{T_C}$$

Roughly it is T_c = 2.5 μs (first strike) and 0.25 μs (further strikes) and so Z_{au} = 0.5 Ω/m (first strike) and 5 Ω/m (further strikes).



3.3 Mutual inductance (L_m)

The two lines do not have a common point.



$$U = -\frac{d\Phi}{dt} = -L\frac{di}{dt}$$

$$L_m = 0{,}2 \cdot l \cdot \ln\left[(d+a)/d\right] = L_{mu} \cdot l$$

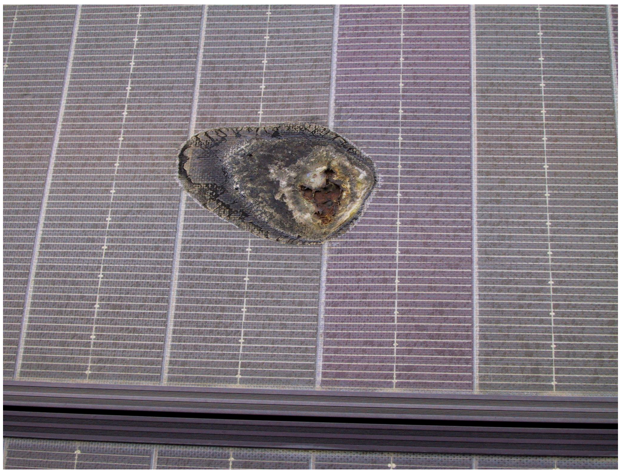
$$U = L_m \frac{di}{dt} \cong L_m \frac{I}{T_C}$$

A mitigation of the mutual inductance may be obtained by shielding.

Type of cable	K_s
Not shielded	1
Shield section area S ≤ 5 mm^2	0,2
Shield section area S > 5 mm^2	0,02
In canal or metallic tube	0,0005

4. MEASURES AGAINST THE EFFECT OF LIGHTNING

Photovoltaic plants may be struck directly by lightning (unlike but not impossible event, see the figure) or, more usually, must face overvoltages generated by lightning that fall close to the plant.



If calculations show a danger of direct strike, the plant must be protected by a suitable LPS (Lightning Protection System) along with the structure or building that support it.

The safeguard of equipment from the effects of overvoltages need the knowledge of the maximum allowable voltage (pulse) for the insulation inside them.

Four zones (I, II, III and IV) have been singled out by international standards in order to make easier the co-ordination of the equipment's insulation.

Zone	**Pulse insulation**	**Equipment**
I	1.5 kV	Electronic equipment supplied by LV transformer
II	2.5 kV	Traditional LV equipment supplied by normal LV sockets
III	4 kV	Distribution panels, automatic switch, cables
IV	6 kV	Energy meters and remote measurement devices installed in the delivery point of energy

Class II insulation PV modules (i.e. double insulation) are tried with a 6 kV pulse generator.

The protection devices against overvoltages are called SPD (Surge Protection Devices). These components reduce their impedance when an overvoltage occur and in this way they suppress, or at least mitigate, the voltage pulse.

Basically, there are two classes of SPD, the first one is based on the current discharge between two electrodes in air or gas, the second one (varistors) are based on the impedance variation of the zinc-oxide when the electric field exceed a certain value.

In photovoltaic application, actually only zinc-oxide varistors are used, because they restore the initial conditions when the overvoltage disappears. This is particularly true for the DC side of the plant.

SPDs are classified in three classes (I, II and III) by IEC standards and in four classes by DIN standards (A, B, C and D).

Application	**Impulse Tc/Te**	**IEC code**	**DIN code**
On LV overhead lines. They may stand the lightning current	-	-	A
Arrival of energy lines. They may stand the lightning current	10/350 μs	I	B
Secondary energy lines	8/20 μs	II	C
Installation in equipment to be protected	8/20 μs	III	D

Class I SPD are able to stand up to 50 kA pulses, class II SPD may reach 10 15 kA and class III SPD usually do not exceed a few kA.

Class II SPD varistors are frequently used in DC sections of PV plants. They usually have an internal fuse in order to be protected by faults. When the fuse trips a small window in the front part of the device turns its colour in order to signal the fault. Most inverters incorporate class II or III SPDs in correspondence of their external connections.

5. MITIGATION OF OVERVOLTAGES ON PV PLANTS

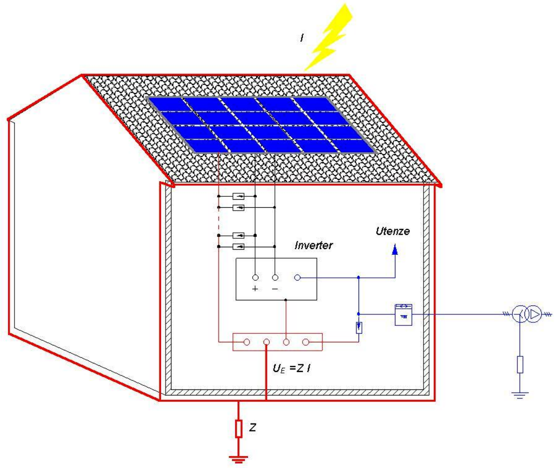
5.1 Safety clearance given

A suitable use of a number of SPD, placed very close to the PV modules may avoid damage by assuring an equipotential bonding among poles.

Also the use of internally-protected inverters close to PV modules may be effective. Anyway for this configuration the lightning current cannot flow along the PV plant.

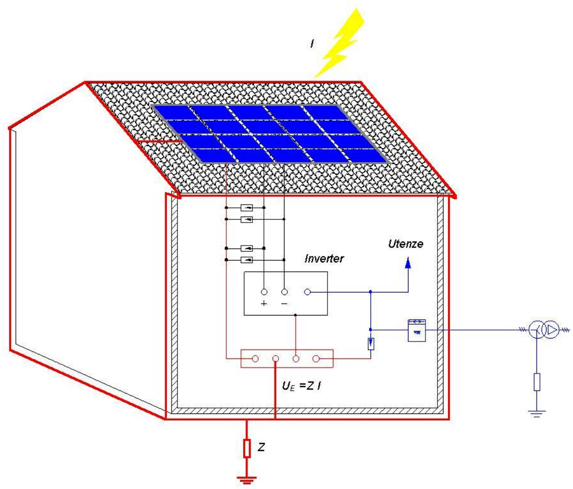
Also inductive coupling may be dangerous for components as well as direct coupling to LPS. Voltages may raise to tents of kV in case of mutual inductance and to hundreds of kV in case of self-inductance.

If SPDs are not sufficiently close to the PV generator, the risk of insulation damages in one or more modules can be a real concern.



5.2 Safety clearance not given

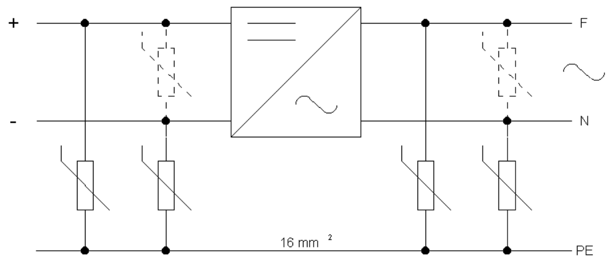
When it is not possible to keep a sufficient clearance (0.2 1 m, depending from the building type) between the PV generator and the LPS, may be advisable to make a direct connection. In this way the occurrence of dangerous sparking is avoided but the potential of the PV generator rises to the air-termination voltage that may reach tents or hundreds of kV.



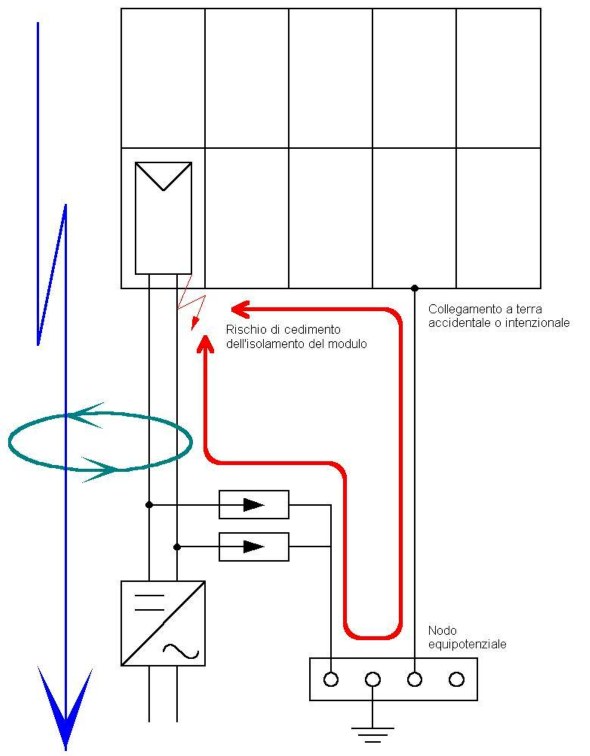
results may be in many cases unpredictable.

When it is possible to keep a sufficient clearance between the PV generator and the LPS, it is better to avoid any connection. In this way overvoltages may be resistive or inductive but one is almost completely sure that the lightning current cannot come into the building.

5.3 Placement of SPDs in and inverter



5.4 Possible damage of the insulation in a PV module by self or mutual inductance



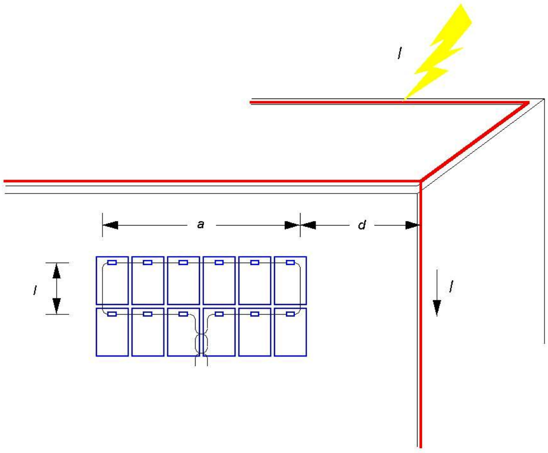
6. EXAMPLE OF MUTUAL INDUCTANCE ON A PV GENERATOR

The mutual inductance may occur on every part of the PV plant but the PV generator is the section where this phenomenon most likely appear.

We consider a simple PV generator with 1200 × 600 mm modules at a distance d = 5 m to the down-conductors and a lightening with a slope di/dt = 140 kA/µs for subsequent strikes. In this way we obtain (see the figure) a = 3.6 m, l = 1.2 m and

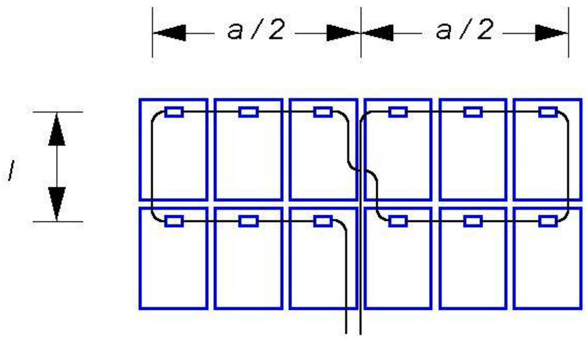
$$L_m = 0{,}2 \times 1{,}2 \times \ln\,[(5+3{,}6)/5] = 0{,}13\ \mu\text{H}$$

U = 0,13 × 140 10^3 = 18,2 kV



The value 18.2 kV is over the maximum allowable voltage that normally equipment can stand and so it is necessary to reduce it to a more reasonable one by using SPDs and/or by cabling differently the PV generator.

For instance, it would be possible to use a cross-cabling which divides in two the PV generator and partially suppresses the overvoltages with an opposite sign.



In this way we obtain:

L_{m1} = 0,2 × 1,2 × ln [(5+1,8+1,8)/(5+1,8)] = 0,056 µH

U_1 = 0,056 × 140 10^3 = 7,84 kV

L_{m2} = 0,2 × 1,2 × ln [(5+1,8)/5] = 0,074 µH

U_2 = 0,074 × 140 10^3 = 10,36 kV

U_1 and U_2 have different signs and so the resulting overvoltage U = 2,52 kV is significantly less than the previous one.

REFERENCES

Standards

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CEI 81-3 *"Medium values of the numbers of lightnings to earth of italian cities, issued alphabetically"*

CEI 81-4 *"Lightning protection of structures – Assessment of the risk of damage due to lightning"*

CEI 81-8 *"Electrical installations of buildings – Application guide for the selection and installation of the Surge Protective Devices"*

EN 61173 *"Overvoltage protection for photovoltaic (PV) power generating systems - Guide"*

IEC 62305-1 "*Protection against lightning – Part 1: General principles*"

IEC 62305-2 "*Protection against lightning – Part 2: Risk management*"

IEC 62305-3 " *Protection against lightning – Part 3: Phisical damage of structures and life hazard*"

IEC 62305-4 " *Protection against lightning – Part 4: Electrical and electronic systems within structures*"

IEC 62305-5 " *Protection against lightning – Part 5: Services*"

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