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Risk assessment and lightning protection for PV systems and solar power plants

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Abstract. Lightning strikes can affect photovoltaic generators and their exposed installation sites as well as the sensitive electronics of the inverter.
Therefore, it is necessary, to estimate the risk by lightning strikes, and to take these results into account for the design. IEC (EN) 62305-2 states procedures and data for the calculation of the risk resulting from lightning strikes into structures and for the choice of lightning protection systems.
Actually, the technical guidelines for installation suggest protecting with SPD's (surge protective device) both the DC and AC sides of the PV plant.
The aim of this paper is to estimate voltages due to lightning discharges and to determine the effective need of lightning protection measures on the basis of the risk analysis and the protection costs.

Key words

Lightning protection, PV system, surge, risk assessment, SPD

1. Introduction

Not only house owners install a PV system on their rooftop but also private operating companies make more and more investments in shared systems, which are erected on large-surface roofs, on traffic structures, or unused open areas.
Because of the big space requirements of the photovoltaic generator, PV systems are especially threatened by lightning discharges during thunderstorms.
The installation of PV modules on buildings does not increase the risk of a lightning strike, so that the request for lightning protection cannot be derived directly from the mere existence of a PV system. However, there may be an increased danger for the electric facilities of the building in the event of a lightning strike. This is based on the fact that, due to the wiring of the PV lines inside the building in existing risers and cable runs, strong conducted and radiated interferences may result from lightning currents.
In case of a solar power plant the aim is to protect both the operation building and the PV array against damage by fire (direct lightning strike), and the electrical and electronic systems (inverters, remote diagnostics system, generator main line) against the effects of lightning electromagnetic impulses (LEMP).

2. Risk evaluation according to standard IEC EN 62305-2

To determine whether a structure should be protected against lightning flashes, according to IEC EN 62305-2 [12], a risk evaluation has to be performed.

In this paragraph the general evaluation procedure is described. Then t will be applied to the particular situation in which the structure to be protected is a PV system. Four different sources of damage are recognized by the Standard:

- S1 – flashes to the structure;
- S2 – flashes near the structure;
- S3 – flashes to a service;
- S4 – flashes near a service.

Three basic types of damage which can appear as the consequence of lightning flashes are also distinguished:

- D1 – injury to living beings;
- D2 – physical damage;
- D3 – failure of electrical and electronic systems.

Each type of damage, alone or in combination with others, may produce the following types of loss, that have to be considered:

- L1 – loss of human life;
- L2 – loss of service to the public;
- L3 – loss of cultural heritage;
- L4 – loss of economic value.

For each type of loss, the relevant risk shall be evaluated (the risk is the value of the probable average annual loss); the risks to be evaluated in a structure are therefore the following:

- R_1 – risk of loss of human life;
- R_2 – risk of loss of service to the public;
- R_3 – risk of loss of cultural heritage;
- R_4 – risk of loss of economic value;

Each risk is the sum of some risk components, which may be grouped according to the source of damage and the type of damage.

<u>Risk components for a structure due to flashes to the structure itself:</u>

R_A – component related to injury to living beings caused by touch and step voltages;

R_B – component related to physical damage caused by sparking inside the structure triggering fire or explosion;

R_C – component related to failure of internal systems caused by LEMP (lightning electromagnetic impulse).

Risk component for a structure due to flashes near the structure:

R_M – component related to failure of internal systems caused by LEMP.

Risk components for a structure due to flashes to a service connected to the structure:

R_U – component related to injury to living beings caused by touch voltage inside the structure, due to lightning current injected in a line entering the structure;

R_V – component related to physical damage (fire or explosion triggered by sparking between external installation and metallic parts) due to lightning current transmitted through or along incoming services;

R_W – component related to failure of internal systems caused by overvoltages induced on incoming lines and transmitted to the structure.

Risk component for a structure due to flashes near a service connected to the structure:

R_Z – component related to failure of internal systems caused by overvoltages induced on incoming lines and transmitted to the structure.

According to IEC EN 62305-2, the following risk management procedure shall be followed:

– identification of the object to be protected and its characteristics;
– identification of all the types of loss in the object and the relevant corresponding risk R (R_1 to R_4);
– evaluation of risk R for each type of loss (R_1 to R_4);
– evaluation of need of protection, by comparison of risk R_1, R_2 and R_3 for a structure with the tolerable risk R_T;
– evaluation of cost effectiveness of protection by comparison of the costs of total loss with and without protection measures. In this case, the assessment of components of risk R_4 for a structure shall be performed in order to evaluate such costs. Another approach is to campare the risk R_4 with a tolerable risk defined byt he PV plan owner.

IEC EN 62305-2 reports representative values of the tolerable risk R_T for loss of human life and loss of social or cultural values (see Table 1).

Table 1: Typical values of tolerable risk R_T

Types of loss	**R_T [Years^{-1}]**
Loss of human life or permanent injuries	10^{-5}
Loss of service to the public	10^{-3}
Loss of cultural heritage	10^{-3}

If protection measures are required ($R > R_T$), they shall be selected according to the share of each risk component in the total risk R.

Each risk component can be evaluated by mean of an expression similar to the following:

$$R_X = N_X \times P_X \times L_X \qquad (1)$$

where:
N_X is the number of dangerous events per year;
P_X is the probability of damage to the structure;
L_X is the consequent loss.

3. Risks and risk components in a PV system

The risk of loss of human life (Risk R_1) generally is not relevant for the PV system both in the case of PV modules on buildings and in the case of solar power plant (SPP). It is because the fire hazard is negligible (PV structure is substantially incombustible); in solar power plants there are not presence of persons; PV modules on roof are usually installed on small buildings (with low risk of direct flashes).
The risk of loss of service to the public (Risk R_2) is not considered because, generally, the out of service of a SPP doesn't influence the public service.
At last, the only risk to be considered is the loss of economic value (Risk R_4) with its risk components R_B, R_C, R_V, R_w, R_M and R_Z.
In figure 1 the risk components for PV modules on buildings are indicated.

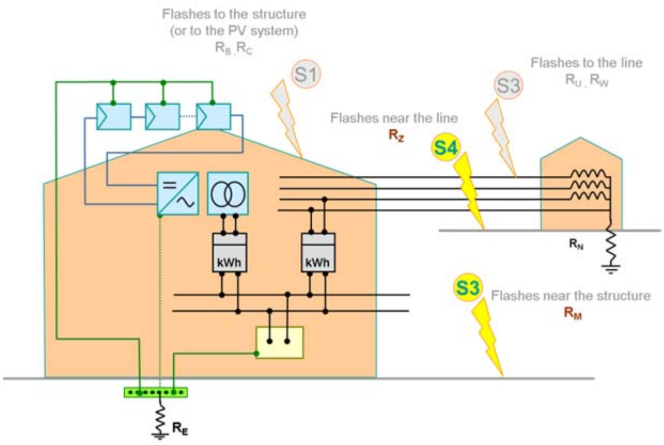

Fig. 1. Risk components for PV modules on buildings

In this case the most relevant risk components are $R_{w,}$ R_M and R_Z. To reduce the risk R_4 to a tolerable level the following protections could be adopted:

- a coordinated SPD system on the LV line entering the structure to reduce the components R_W and R_Z;
- a coordinated SPD system on the DC line of PV to reduce the components R_M.

Figure 2 shows the risk components for a solar power plant. In this case, beside the protection above mentioned, an external LPS could be installed.

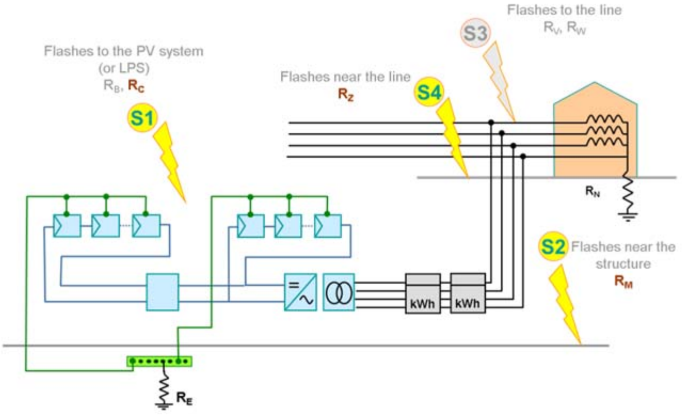

Fig. 2. Risk components for a solar power plant

4. Surge overcurrents on LV systems

For direct and indirect lightning flashes to connected power lines, the surge overcurrents, according with IEC 62305-1, are given in table I as a function of the lightning protection level (LPL) and the source of damage.

Table I: Expected surge overcurrents due to lightning flashes on low-voltage systems.

LPL	Direct and indirect flashes to the service		Flash near the structure
	Source of damage S3 (direct lash) Current shape 10/350 µs [kA]	Source of damage S4 (indirect flash) Current shape 8/20 µs [kA]	Source of damage S2 (induced current) Current shape 8/20 µs [kA]
I	10	5	0.2
II	7.5	3.75	0.15
III-IV	5	2.5	0.1

5. Induced voltage by direct flashes

In the case of direct flashes, the induced voltage U_{ip} can be calculated with the following approximated equation for a structure without shielding:

$$U_{ip} = k_c \times L_M \times \frac{di}{dt} \qquad (2)$$

where

- k_c is the repartition coefficient of the lightning current amongst the air-termination/down conductors (kc = 1 for one down conductor, k_c = 0.5 for two down conductors and k_c = 0.44 for 3 or more down conductors.
- di/dt is the steepness of the subsequent stroke lightning current (200, 150 and 100 kA/µs as function of LPL), which is the worst case for the open circuit voltage in the induced loop.
- L_M is the mutual inductance between the lightning current along the down conductor and the induced loop.

The mutual inductance can be calculated with the equation (3) for flashes on an external isolated LPS (fig. 3):

$$L_M = 0.2 \times m \times \sin\alpha \times \ln\frac{f+b+l}{f+b} \qquad (3)$$

Where "m" is the width of the loop to be equal to "e" for the differential mode calculation or to "e+d" for the common mode calculation.

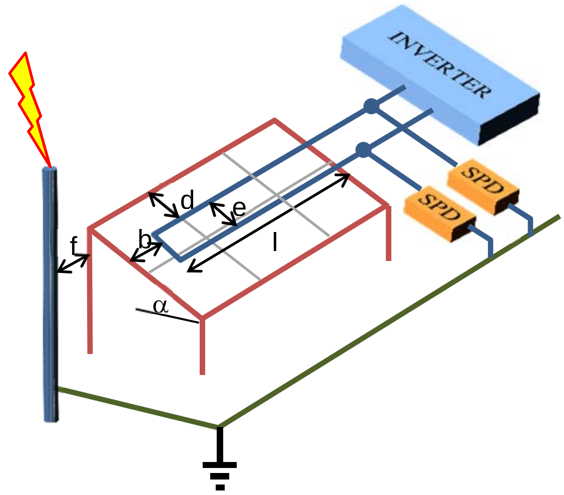

Fig. 3. Induced voltage for flashes to an isolated LPS

Considering an external LPS integrated into the PV metallic structure (natural LPS, fig. 4), the lightning current is divided in three path along the structure.
The higher induced voltage value is due to the current I_1 flowing near the longer side of the loop.

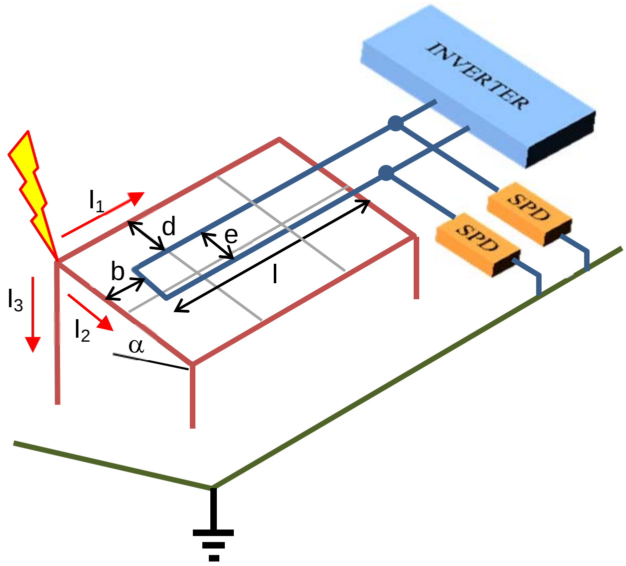

Fig. 4. Induced voltage for flashes to a natural LPS

In this latter case, the mutual inductance is calculated with equation (4):

$$L_M = 0.2 \times l \times \ln\frac{d+e+r}{d+r} \qquad (4)$$

Where "r" is the equivalent radius of the metallic support of the PV system.

The short circuit current flowing in the loop, in the worst case, is the current associated to the first short stroke of the lightning current (200, 150 or 100 kA, depending on the LPL considered). The short circuit current can be calculated with equation (5), according to IEC 62305.

$$\boldsymbol{I_{sc}} = \boldsymbol{k_c} \times \boldsymbol{I} \times \frac{\boldsymbol{L_M}}{\boldsymbol{L_S}} \qquad (5)$$

Where L_S is the self inductance of the loop:

$$L_S = 0.8 \cdot \sqrt{l^2 + e^2} - 0.8 \cdot (l + e) + 0.4 \cdot l \cdot \ln\left[\frac{\frac{2e}{r}}{\left(1 + \sqrt{1 + \left(\frac{e}{l}\right)^2}\right)}\right] + 0.4 \cdot e \cdot \ln\left[\frac{\left(\frac{2l}{r}\right)}{\left(1 + \sqrt{\left(\frac{l}{e}\right)^2}\right)}\right] \cdot 10^{-6}$$

Under these assumptions, the calculated values of the induced voltage U_{ip} and of the short circuit current I_{sc} are reported in Table II for unshielded loop with area of 50 m^2 and considering $k_c = 1$.
Of course, different values could be calculated with different assumptions. However, the values in Table II are representative of the expected induced voltages on PV loops due to direct flashes to the structure. Moreover the induced voltage can be disregarded when the loop conductors are routed in the same cable and are twisted or are shielded.

Table II: Induced voltage values for unit length of the loop and short circuit current as function of the LPL.

LPL	**Induced voltage per unit length** [kV/m]	**Short circuit current (10/350 µs)** [kA]
I	4	5
II	3	3.75
III-IV	2	2.5

6. Flashes near the PV system

In the case of flashes near the PV system (source of damage S2), the induced voltage U_{ip}, required by the risk component R_M, can be calculated using equation (2), with $k_c = 1$. The mutual inductance can be calculated with the following approximate equation:

$$L_M = 0.2 \times \frac{A}{s}$$

where A is the induced loop area and s is the distance between the point of strike and the centre of the structure. The distance s can be calculated as function of the rolling sphere radius R_{sp} and the structure dimensions:

$$s = (2 \times R_{sp} \times H - H^2)^{0.5} + \frac{L}{2} \qquad \text{for } H < R_{sp}$$

$$s = R_{sp} + \frac{L}{2} \qquad \text{for } H > R_{sp}$$

where H and L are the height and the width of the structure, respectively.

For source of damage S2, the surge overcurrents, according with IEC 62305-1, are given in table I as a function of the lightning protection level (LPL).

7. Conclusion

The need of lightning protection measures on PV systems must be evaluated on the basis of the risk analysis and the protection costs.
In the paper the procedures of risk assessment of the IEC 62305 series are applied to PV systems to calculate the surge overcurrent for the different source of damage.
Formulas and criteria for calculation of the induced voltage on the DC loops of the PV systems are also showed.

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