OPEN ACCESS
International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-2 Issue-3, February 2013

Failure of Photovoltaic Modules under Lightning and Thunderstorms

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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.

Keywords: Lightning electromagnetic impulse, Lightning current arresters, Earth Termination System, Lightning protection level, Lightning flash count.

I. INTRODUCTION

The Photovoltaic (PV) systems are especially threatened by lightning discharges during thunderstorms because of the big space requirements of the photovoltaic generator. 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. 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[1] : 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. R1 – risk of loss of human life; R2 – risk of loss of service to the public; R3 – risk of loss of cultural heritage; R4 – risk of loss of economic value;

Manuscript published on 30 February 2013.
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Each risk is the sum of some risk components, which may be grouped according to the source of damage and the type of damage.

Risk components for a structure due to flashes to the structure itself: RA – component related to injury to living beings caused by touch and step voltages; RB – component related to physical damage caused by sparking inside the structure triggering fire or explosion; RC – component related to failure of internal systems caused by LEMP (lightning electromagnetic impulse). Risk component for a structure due to flashes near the structure: RM – 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: RU – 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; RV – 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; RW – component related to failure of internal systems caused by over voltages induced on incoming lines and transmitted to the structure. Risk component for a structure due to flashes near a service connected to the structure: RZ – component related to failure of internal systems caused by over voltages 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 (R1 to R4); – evaluation of risk R for each type of loss (R1 to R4); – evaluation of need of protection, by comparison of risk R1, R2 and R3 for a structure with the tolerable risk RT; – evaluation of cost effectiveness of protection by comparison of the costs of total loss with and

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}

without protection measures. In this case, the assessment of components of risk R4 for a structure shall be performed in order to evaluate such costs. Another approach is to compare the risk R4 with a tolerable risk defined by the PV plant owner. IEC EN 62305-2 reports representative values of the tolerable risk RT for loss of human life and loss of social or cultural values (see Table 1).

If protection measures are required (R > RT), 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 [1]:

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

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.

II. LIGHTNING PROTECTION OF STRUCTURES

Lightning protection is achieved in structures [2] by an external lightning protection system, sized to carry the anticipated currents without damage. Electrical continuity among metallic services (water lines, coaxial cable shields, power system neutral) is mandated. The IEC model can lead to very large surge currents in relatively small conductors.

The lightning surge [3] entering the air termination in figure 1 is typically a fast – rising, slow-falling unipolar impulse current with a rise time of 1 µs, a peak of 2kA < i < 200kA and a time to half value of 50 µs. Figure 1 also shows how this current splits up at the ground and suggests that a building with only a three wire electrical service will carry (50% / 3 = 16.7%) of the lightning surge current in each wire. The lightning g flash will cause such a large voltage rise on the Bonding Bar (typical 50 -100 kA into ETS x 20 Ω = 1000 – 2000 kV) that typical low-voltage wiring would puncture without protection. The IEC recommends instead that the current be mnaged through the use of suitably rated lightning current arresters (LCA) that will conduct at about 1kV, with each LCA carrying away 16.7% of the 100-to-200 kA current from Table 1. The figure 1 shows division of lightning current among a structure's earth Termination System (ETS)/Grounding and other services entering the structure, per IEC 61312 – 1 (1995).

Metallic conductors of sufficient ampacity (such as reinforced steel) are bonded electrically and an external connection above the concrete surface is made before concrete is poured. This gives a large surface area and low inductance, both minimizing the potential rise resulting from a lightning flash.

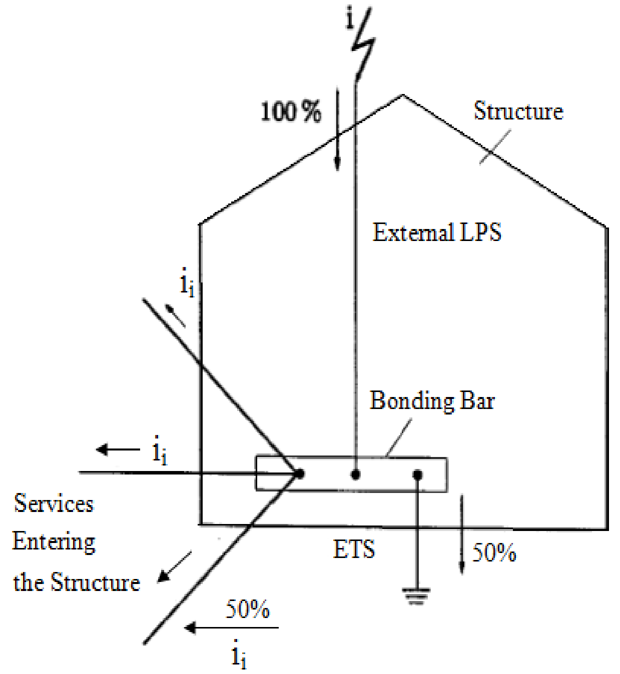

Figure 1: Division of Lightning Current among ETS (Earth Termination System/Grounding).

Made electrodes have a resistance that is calculated from the length of the electrode, its exposed surface area and the local resistivity of the soil ρ, in Ωm. One excellent equation covering a wide range of shapes from buried pipes through to flat surface, is :

$$R = \frac{\rho}{2\pi g}\ln\left(\frac{11.8g^2}{A}\right) + \frac{\rho}{l}$$

$$g = \sqrt{r_x^2 + r_y^2 + r_z^2}$$

Where A is the surface area of the electrode in contact with the soil, g is the geometric radius and l is the total length of wire in contact with the soil, a correction factor between a solid plate and wire grid of the same shape.

If the lightning protection system on a structure is hit by lightning, then the current flowing through the system and the resistance/impedance offered by the conductor path will determine the magnitude of the potential difference seen by the lightning conductors with respect to true earth. The lightning conductors can, instantaneously, have a potential magnitude of megavolts (1,000,000V) with respect to true earth. Before proceeding to design a lightning protection system, first carefully consider if the structure actually needs protection.

TABLE 2 Minimum Values For Rolling Sphere Radius And Mesh Size

Lightning Protection Level	Probability Level	Rolling Sphere Radius	Mesh Size	Peak Current	Peak Rate of Current Rise
I	99% (3kA)	20m	5 x 5 m^2	200 kA	200 kA/µs
II	97% (5kA)	30m	10 x 10 m^2	150 kA	150 kA/µs
III	91% (10kA)	45m	15 x 15 m^2	100 kA	100 kA/µs
IV	84% (16kA)	60m	20 x 20 m^2	100 kA	100 kA/µs

III. SURGE OVER CURRENTS ON LOW VOLTAGE SYSTEMS

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

In the case of direct flashes, the induced voltage *Uip* can be calculated with the following approximated equation for a structure without shielding:

$$U_{ip} = k_c \times L_M \times \frac{di}{dt}$$

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

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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.

Considering an external LPS [3] 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 I1 flowing near the longer side of the loop. In this latter case, the mutual inductance is calculated with equation (4):

TABLE 3 Expected Surge Over Currents 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 flash) Current shape 10/350 µs [kA]	Source of damage S4 (Indirect flash) Current shape 8/20 µs [kA]	Source of damage S2 (Induced flash) 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

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,

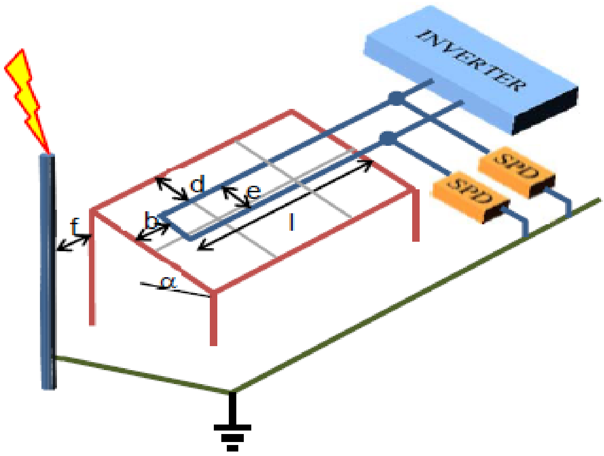

Figure 2 : Induced voltage for flashes to an isolated LPS

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

depending on the LPL [4] considered). The short circuit current can be calculated with equation (5), according to IEC 62305.

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

Where L_S is the self inductance of the loop: Under IEC 62305, the self inductance L_S can be expressed as below, where the terms are shown in figure 3.

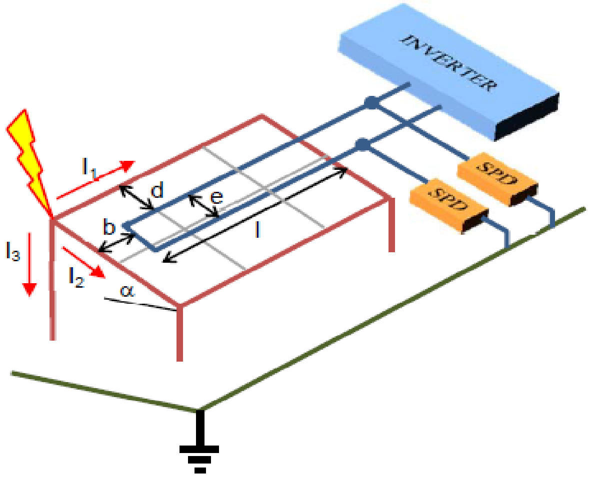

Figure 3 : Induced voltage for flashes to a natural LPS

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

Under these assumptions, the calculated values of the induced voltage *Uip* and of the short circuit current *Isc* are reported in Table II for unshielded loop with area of 50 m2 and considering kc = 1.

TABLE 4 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

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. In the case of flashes near the PV system (source of damage S2), the induced voltage *Uip*, required by the risk component RM, can be calculated using equation (2), with kc = 1. The mutual inductance (L_M) 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 *Rsp* and the structure dimensions:

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

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

where H and L are the height and the width of the structure, respectively. For source of damage S2, the surge over currents, according with IEC 62305-1, are given in table I as a function of the lightning protection level (LPL) [5].

IV. LIGHTNING FLASHES IN INDIA

Since lightning originates mainly from thunderstorm clouds [5], it is also likely that similar relationship should also prevail between these parameters [6]. The relationship can be examined using the monthly mean data of these parameters over ER and WR. Table 2 provides monthly mean values of Tmax ,Th and lightning flash count over ER and WR. We see that during January–February months, Tn over WR is higher than over ER. During the period April–September, we see that Tmax max over ER is

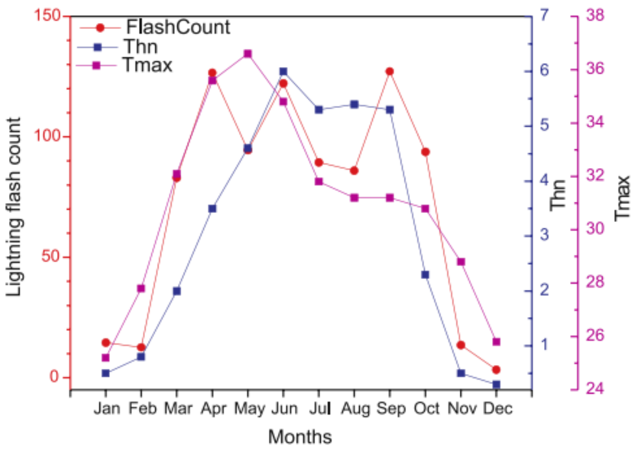

Figure 4 : Monthly mean maximum surface air temperature (T $_{max}$), number of thunderstorm days (Th_n), and lightning flash count over Eastern Region. Tmax results are reproduced from Manohar and Kesarkar higher than over WR. This observation suggests that WR undergoes more cooling relative to ER [10].

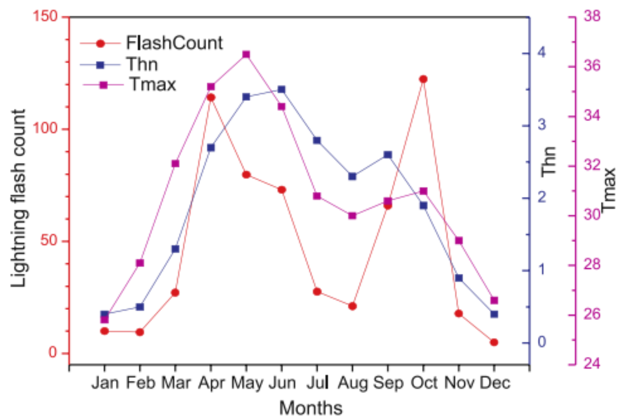

Figure 5 : Monthly mean maximum surface air temperature (T $_{max}$), number of thunderstorm days (Th_n), and lightning flash count over Western Region. Tmax results are reproduced from Manohar and Kesarkar (2003).

TABLE 5 VALUES OF RELATIVE COOLING IN TMAX, REDUCTION IN THN AND LIGHTNING flash COUNT OVER WR WITH RESPECT TO ER DURING APRIL–SEPTEMBER.

Months	Cooling in T_{max} ER minus WR (°C)	Reduction in Th_n ER minus WR (days)	Reduction in lightning flash count ER minus WR flash count (Number)
April	0.4	0.8	12.4
May	0.1	1.2	14.6
June	0.4	2.5	49.2
July	1.0	2.5	61.8
August	1.2	3.1	64.8
Sept.	0.5	2.7	61.2
Mean	0.6	2.1	44.0
CC T_{max} : Th_n	0.70	-	-
CC Th_n : Lightning	0.97	-	-
CC T_{max} : Lightning	0.75	-	-

TABLE 6 FAILURE OF BALANCE OF SYSTEM COMPONENTS

Category	# of events	Cost	Notes
Inverter	37%	59%	25% from 1 lightning storm
DAS	7%	14%	90% from 1 lightning storm
AC Disconnect	21%	12%	50% due to dirt accumulation
Module/J Box	12%	3%	60% due to failed blocking diodes
PV Array	15%	6%	45% from 1 lightning storm
System	8%	6%	All utility meters

The occurrence of thunderstorms and development of lightning in relation to temperature change of surface air, on monthly time-scales, has been a topic of long standing interest in many recent studies (Kandalgaonkar et al 2005b). These studies strongly suggest a close association between surface air temperature and development of thunderstorms.

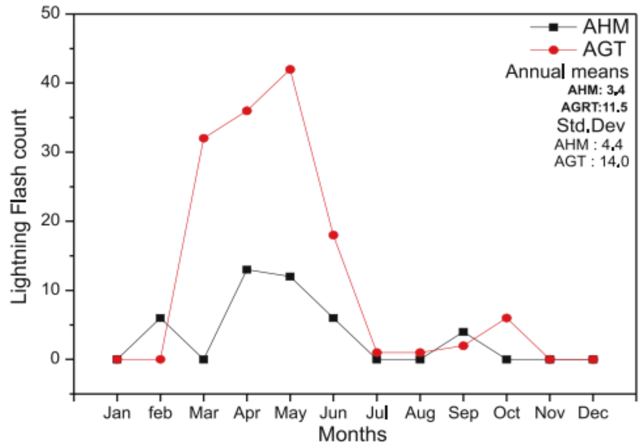

Figure 6 : Lightning flash count at Ahmedabad and Agatala

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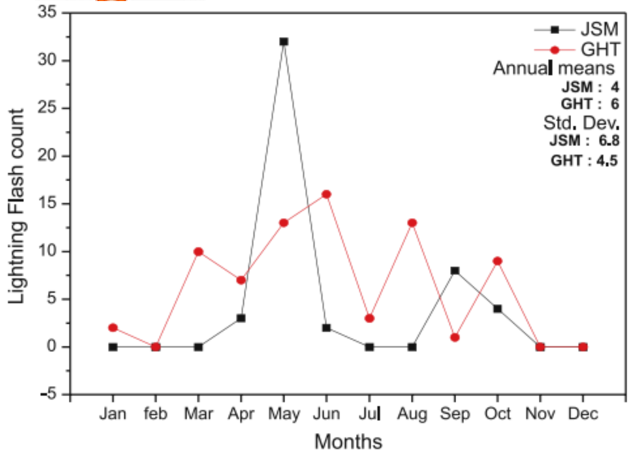

Figure 7 : Lightning flash count at Jaisalmir and Guwahati

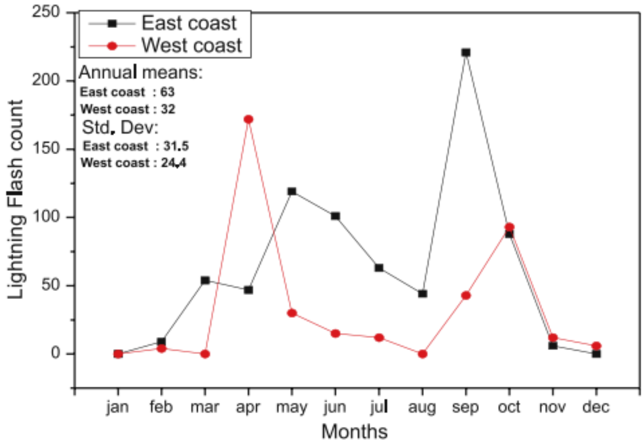

Figure 8 : Lightning flash count at East and West coast

Figures 6 to 9 shows the lightning flash count at various cities/places in India including the east coast in the bay of Bengal and the west coast in the Arabian Sea.

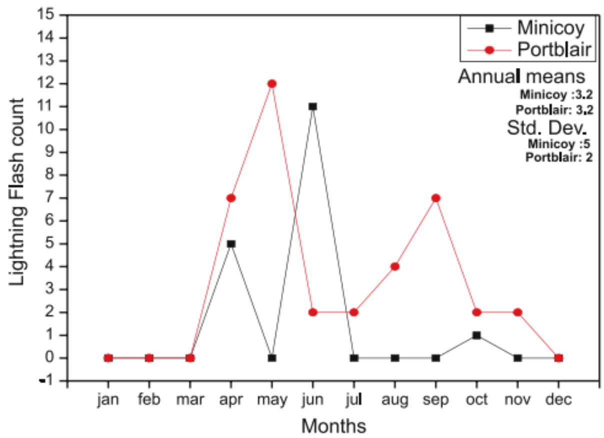

Figure 9 : Lightning flash count at Minicoy and Portblair

TABLE 7

ANNUAL MEAN LIGHTNING FLASH COUNT

Climate regime	Annual mean lightning flash count and no. of stations on which these are based			
	Flash count	Standard deviation	No. of stations	Normalized value of flash count, i.e., for 100 stations
Continental (ER)	361	173	40	903
Continental (WR)	240	132	40	600
Coastal (East coast)	63	32	6	1050
Coastal (West coast)	32	24	6	533
Off East coast	32	14	6	533
Off West coast	8	5	6	133
Hilly region of NE India GHT	6	4	1	600
Hilly region of NE India AGT	11	14	1	1100
Semi-arid zone of NW India AHM	3	4	1	400
NW India JSM	4	7	1	400
Oceanic MNC	3	5	1	320
Oceanic PBL	3	2	1	320

V. CONCLUSION

Insufficient protection reduces reliability, while excessive protection wastes money, making it vital to match the required protection level to the equipment or component being protected. 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 over current 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. The validity of above result may vary with geography of the location of study, but the generality remains that Th and lightning flash count variation is linked with surface maximum air temperature. The changes in the occurrence of thunderstorms dominate/control the variation in lightning activity. This result strongly supports the early results of Williams et al (2000) [7] and signifies the important role of thunderstorms in development of lightning over the tropics.

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