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FLASH DENSITY APPLIED TO LIGHTNING PROTECTION STANDARDS

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Abstract - This paper criticizes the lightning flash density concept to be used in lightning protection standards, namely in IEC 62305-2 (Lightning Protection - Risk assessment). The evaluation of the ground flash density (N_g) is not straightforward, though it is a crucial parameter related to the risk calculations. This is due to several reasons analyzed herewith. The selection of a corrected value of N_g related to the risk estimation of a given building or structure could be defined as proposed in this paper.

1 - INTRODUCTION

The lightning flash density N_g is generally viewed as the primary descriptor of lightning incidence, at least in lightning protection studies (see, for example, [1]) and standards, namely in the IEC 62305-2 international standard (Lightning Protection - Risk assessment, [2]).

The ground flash density has first been estimated from records of lightning flash counters (LFC) in several countries and, more recently, from records of lightning location systems (LLS) in many countries. It can also potentially be estimated from records of satellite-based optical or radio-frequency radiation detectors, but it is worth noting that satellite detectors cannot distinguish between cloud discharges (intra-cloud and cloud-to-cloud) and cloud-to-ground discharges and, hence, in order to obtain N_g maps from satellite observations, a spatial distribution of the fraction of discharges to ground relative to the total number of discharges is needed. IEEE 1410 [3] recommends, in the absence of ground-based measurements of N_g, to assume that N_g is equal to one third of the total flash density (including both cloud discharges and cloud-to-ground discharges) based on satellite observations [1, 4].

The evaluation of the ground flash density N_g is not straightforward, though it is a crucial parameter related to the risk calculations [1, 2]. This is due to the following reasons.

- Values of N_g result from LFC (lightning flash counters) and LLS (lightning location systems) data that so far are *not accurate* enough. The main problems are: detection efficiency, location accuracy (current LLS location error is in the range 500-1000 m), and misclassified events [7]; moreover, there is a lack of data in many regions of the world (see next section).
- Depending on the country, maps of N_g sometimes refer to either *maximum* values or *average* values in a selected area which can be variously estimated (from a few km^2 to hundreds of km^2); an ideal area as small as 2 km x 2 km should be considered.
- In some countries, there is some confusion between "*flash density*" maps and "*stroke density*" maps and there is a *flash multiplicity* with an average of 2 to 3 strokes per flash in negative lightning discharges, a typical average value of the *interstroke interval* being around 60 ms [4].
- Damages are generally attributed to the *first stroke* though they could be also due or even made worse by *subsequent strokes*.
- Moreover, almost one-half of all lightning discharges to ground, both single- and multiple stroke flashes, strike ground at more than one point with the spatial separation between the multiple terminations of individual cloud-to-ground flashes ranging from some tens of meters to 8 km; the *number of channels per flash* (number of *ground contacts* or *ground terminations* related to multiple channel terminations on ground) is not taken into account, though the average number of ground contacts is between **1.5** and **1.7** (observed in USA, Brazil, Western Europe, [1, 4]). Before obtaining more accurate results, it is practical to estimate the ground strike-point density by multiplying the ground flash density by a correction factor of 1.5 to 1.7 [7]. Recently, Météorage [22] showed that in France the mean number of ground strike-point was 1.74 per flash.

In mountainous regions, Rakov et al. [21] found another factor of **1.7** higher average value of the ground flash density than for a plain terrain area, the two areas being about equally covered by the lightning location system.

The "risk estimation" should also incorporate the possibility that many lightning events may occur in a very short time (due to the relaxation time of the measuring system, some of them could be ignored), resulting damages being worsened by such a concentration.

2 - KERAUNIC LEVEL AND LIGHTNING GROUND FLASH DENSITY

The number of *thunderstorm days* per year ($year^{-1}$) T_d or *keraunic level* is the average number of days per year when thunder can be heard. It is not a good parameter. Indeed, in temperate regions, a frontal thunderstorm can go away after some minutes or can stay during several hours in full activity. Sometimes thunder can be heard at unusually large distances, say, 40 km or even more, giving a strongly exaggerated impression of the lightning activity [5].

For example, in France, by means of the Météorage network of electric and magnetic field antennas, employing triangulation in real time, it was verified that the regions which were most often struck by lightning were the Southern Alps, the Pyrenees (especially Western Pyrenees) and the Massif Central where the number of thunderstorm days per year is greater than 30. In Belgium, a SAFIR-VAAISALA lightning detection system was installed by the Royal Meteorological Institute. It employs the method of electromagnetic interferometry and allows one to track thunderstorms in real time in the whole country [5, 24]. An average value of 15 thunderstorm days per year is accepted (average of values between 8 and 22 depending on the various regions of Belgium).

Inside the inter-tropical belt, in the Central of South-America (from Colombia and Peru to the Center-South part of Brazil), in Central Africa (from Guinea to Tanzania and South-Africa) and in Indonesia, the keraunic level can be larger than 100 per year. Following O. Pinto [6], on the African continent, the largest number of thunderstorm days would be in Kamembe, Rwanda, with 221 per year.

The keraunic level is an indicator of thunderstorm activity. It is not rigorous at all since it gives no indication of the number of lightning strikes to ground. That is why the keraunic level was replaced by the ground flash density N_g, number of lightning flashes to ground per kilometer squared per year ($km^{-2}.year^{-1}$). In temperate regions, Ng (expressed in $km^{-2}.year^{-1}$) is roughly one tenth of the keraunic level T_d (expressed in $year^{-1}$).

In France, this corresponds to $0.6\ km^{-2}.year^{-1} < N_g < 4.4\ km^{-2}.year^{-1}$ with an average value approximately equal to $2\ km^{-2}.year^{-1}$. In Belgium, from the LLS data from 2001 to 2011, we have $0.8\ km^{-2}.year^{-1} < N_g < 2.2\ km^{-2}.year^{-1}$ with an average value equal to $1\ km^{-2}.year^{-1}$ [24]. In Germany, measurements of the ground flash density made by the lightning location system BLIDS from 1999 to 2011 give values of N_g ranging from $0.6\ km^{-2}.year^{-1}$ to $3.0\ km^{-2}.year^{-1}$ [23], corresponding comparatively well to the long-term evaluations of the keraunic level. In Brazil, Indonesia, Florida, and Central Africa, N_g is much larger, up to $15\ km^{-2}.year^{-1}$.

Without any modern lightning detection system, the Royal Meteorological Institute in Belgium estimated that Kifuka, in the equatorial region of the Democratic Republic of Congo (at the time when this country was still Belgian Congo), close to Lake Kivu, was supposed to represent a world record with 156 flashes $km^{-2}.year^{-1}$ this value looks overestimated if we compare it with the highest value of 83 $km^{-2}.year^{-1}$ measured in Kamembe [6] .

There are many factors influencing lightning incidence. The following parameters are important to consider: *topographical* factors (soil humidity, thunderstorm corridors favoured by airstreams in valleys, lightning strikes on hillsides instead of mountaintops, etc.), *geological* and *orohydrographical* factors (faults, crevices, cracks, water layers, etc.).

These and other factors can be responsible for the observed inhomogeneity of spatial distribution of lightning ground flash density [4].

3 – LIGHTNING FLASH COUNTERS AND LIGHTNING LOCATION SYSTEMS

The *lightning flash counter* (LFC) is an antenna-based instrument that produces a registration if the electric (or magnetic) field generated by lightning, after being appropriately filtered (the center frequency is typically in the range from hundreds of hertz to tens of kilohertz), exceeds a fixed threshold level. The output of a LFC is the number of lightning events and/or time sequence of lightning events recorded at a given location. If the fraction of ground flashes in the total number of lightning flash counter registrations Y_g and its effective range R_g are known, lightning flash counters can provide reasonably accurate data on ground flash density. However, estimation of Y_g and R_g is not a trivial task [1].

Locating lightning discharges with reasonable accuracy requires the use of multiple-station systems, named *lightning location systems* (LLS). The principles of operation of multiple-station lightning locating systems are described, for example, in CIGRE Report 376 [7]. Various techniques are used to locate lightning. Lightning radiated electromagnetic fields are acquired by electric and magnetic field sensors in the VLF, LF and VHF frequency ranges.To locate ground strike points, either magnetic direction finders (MDF), time-of-arrival (TOA), or a combination of both techniques (MDF+TOA) is employed [1].

LLS systems are presently used in many countries to acquire lightning data that can be used for mapping N_g. Unfortunately, any LLS fails to detect relatively small cloud-to-ground flashes (particularly near the periphery of the network or some hundreds kilometers outside the antenna network) and fails to discriminate against some cloud flashes, unwanted in determining N_g. The corresponding system characteristics, the detection efficiency and the selectivity with respect to ground flashes, are influenced by network configuration, position of the lightning relative to the network, system sensor gain and trigger threshold, sensor waveform selection criteria, lightning parameters, and field propagation conditions. The interpretation of system output in terms of N_g is subject to a number of uncertainties [8], but multiple-station lightning locating networks are by far the best available tool for mapping N_g. More detailed information about LLSs is found in [7, 4]

It is important to note [4] that LLSs record strokes, not flashes, and therefore estimation of N_g from LLS data depends on the method to group strokes into flashes. Further, many lightning flashes produce multiple terminations on ground, so that the number of ground strike points is 1.5 to 1.7 times larger than the number of flashes (see section 1). Here, it must be distinguished between multiple terminations on ground for a single stroke (a pretty rare event), which is usually detected from the LLSs as one ground strike-point, and a termination on ground for a subsequent stroke deviated from the termination of the previous stroke, which is usually detected from the LLSs as a further ground strike-point.

This performance should be taken into account in estimating lightning incidence to areas when performing risk calculations, for example, [2]. Finally, the accuracy of N_g mapping depends on the number of events per grid cell, which in turn depends on the grid cell size and period of observations [9]. It is recommended that the number of events per grid cell be at least 80 [9] or 400 [3].

4 – ROUGH ESTIMATION OF THE GROUND FLASH DENSITY

If no measurements of the ground flash density N_g for the area in question are available, this parameter can be roughly estimated from the annual number of *thunderstorm days* T_d, also called the keraunic level. Apparently the most reliable expression relating N_g and T_d is the one proposed by Anderson et al. [10]::

$$N_g = 0.04\ (T_d\ )^{1.25} \qquad (4.1)$$

This expression is based on the regression equation relating the logarithm of the five-year-average value of N_g measured with CIGRE 10 kHz lightning flash counters at 62 locations in South Africa and the logarithm of the value of T_d as reported by the corresponding weather stations. The range for T_d was from 4 to 80, the range for N_g was from about 0.2 to about 13 km^{-2} $year^{-1}$, and the correlation coefficient between the logarithms of N_g and T_d was 0.85.

Another characteristic of lightning activity that can be used for the estimation of N_g is the annual number of *thunderstorm hours* T_h. The relation between N_g and T_h proposed by MacGorman et al. [11] is

$$N_g = 0.054\ (T_h\ )^{1.1} \qquad (4.2)$$

Although T_h is a parameter potentially more closely related to N_g than T_d, the long-term annual number of lightning-caused outages of power lines that have similar geometrical and electrical characteristics and are located in areas with different long-term values of T_d and T_h do not show a better correlation with T_h than with T_d [12]. Both T_d and T_h are generally based on human observations at weather stations [4].

The observed variation in ground flash density from one region to another in the United States, and in many other countries, is more than two orders of magnitude.

Many flashes strike ground at more than one point. Most measurements of lightning flash density do not account for multiple channel terminations on ground. When only one location per flash is recorded, while all strike points separated by distances of some hundreds of meters or more are of interest, as is the case where lightning damage is concerned, *measured values of ground flash density should, in general, be increased* [4].

5 – GROUND FLASH DENSITY FOR LIGHTNING PROTECTION STANDARDS

In the risk calculation, Lightning Protection standards require the assessment of annual number N of dangerous events [2]. This number of dangerous events due to lightning flashes influencing a structure to be protected depends on the thunderstorm activity of the region where the structure is located and on physical characteristics of the structure.

To calculate the number N, one should multiply the lightning ground flash density N_g by an equivalent collection area of the structure, taking into account correction factors for the physical characteristics of the structure.

In countries where no LFC or LLS are installed, no map of N_g is available. In this case, lightning protection national standards generally apply an empirical formula relating the lightning flash density N_g to the keraunic level T_d ; in temperate regions N_g can be estimated by

$$N_g = 0.1\ T_d \qquad (5.1)$$

The value of the ground flash density N_g ($km^{-2}.year^{-1}$) should be available from ground flash measurements with LLS and/or LFC. Nevertheless, we mentioned above that these networks are not yet accurate enough, commercials announcing efficiencies as high as 98%, though we pretty know that the detection efficiency (DE), the location accuracy (LA) and the misclassified events probably induce at the best a total efficiency not greater than in 70 to 80%. Moreover low peak currents are never recorded and we mentioned that most measurements of lightning flash density do not sufficiently account for multiple channel terminations on ground.

We should include such distinctions in the concept of "risk estimation" (better than "risk calculation"). A first rough proposal to include these physical events could be to multiply N_g values (obtained from LFC and LLS measurements) by a factor of **2** for usual situations (flat grounds where the "effective height" could be considered as equal to the "geometrical height"; structures not taller than 60 m). This factor 2 will be proposed in the German [23]standard and in the Belgian one on values recorded from the LLSs. France will adopt a similar factor that will be directly provided by Météorage; this factor will be included in the standard printed maps. In the Netherlands, the Dutch National Committee advises to impose a value of 2.5 $km^{-2}.year^{-1}$, higher than the highest value recorded on the whole country, when the designer does not know the value of N_g in the structure location, from the LLS mapping.

Let us not forget (see section 4) that the accuracy of N_g mapping depends on the number of events per grid cell, which in turn depends on the grid cell size and period of observations [9]. It is recommended that the number of events per grid cell be at least 80 [9] or 400 [3]. A grid cell size should then be defined (example: 2 km x 2 km).

In a lightning protection standard, what is important is not the ground flash density itself, but the *ground strike-point density* that we call N_{sg}.

The choice of a specific value of N_{sg} related to the risk estimation of a given building or structure, applicable to the international and national lightning protection standards, could be defined as follows: "*choose the estimated maximum value of N_g on the ground flash density map of the region involved (on the condition that these values were confirmed during a period covering at least the last 10 years) in a circular area of 10 km radius around the building or structure and*, when estimating the lightning risk assessment, *multiply this number by a factor of 2".*

$$N_{sg} = f\, N_g\,, \qquad (5.2)$$

where the proposed factor f is equal to 2. Let us note that, when the LLS systems will directly give the ground strike-point density such a correction factor will not be needed.

This proposal, applicable to structures less than 60 m high, could be discussed during the Conference.

Moreover we would like to recommend that, inside IEC TC81, a new working group on Lightning Location Systems (LLS) shall be set up. Indeed so far no common rule exists giving requirements neither for the LLS performances nor for the elaboration of the measured data. In order to make reliable and homogeneous the values obtained from the LLS systems in various countries using such systems, a new international standard is needed. This standard shall promote the harmonization of the national specifications and practices concerning the LLS systems, in order to give a common and acknowledged validity to ground flash density values available in various countries so that the risk evaluation would be harmonized as well not only as a procedure (IEC 62305-2 standard [2]) but also for its results. This standard should specify the requirements and tests to be performed for lightning location systems independently of the technology used for the hardware relevant to (1) the performance of the hardware such as the detection efficiency of the LLS system, the location accuracy, the quality of the measured data; (2) the data processing such as the data sample to be used, the grid cell size, etc.

6 – LIGHTNING GROUND FLASH DENSITY AND TALL STRUCTURES

Indeed the same structure can strongly increase the value of N_g, especially for tall grounded vertical objects (h > 60 m) that produce relatively large electric field enhancement near their upper extremities so that upward-moving connecting leaders from these objects start earlier than from the surrounding ground and, therefore, serve to make the object a preferential lightning termination point [1,4].

With increasing height of an object an increase in the number of lightning discharges is observed with an increasing percentage of upward initiated flashes. Objects with heights ranging from 100 to 500 m experience both types of flashes, upward and downward. The high number of lightning events to elevated towers makes those objects preferential for direct lightning current measurements. Instrumented towers and rocket-triggered lightning are the most widely used possibilities to perform direct measurements of lightning current waveforms [4].

To account for the observation of increased lightning activity to towers of moderate height (less than 100 m) on high mountains a so called "effective height" that is larger than the physical height of the object is assigned to the structure. The effective height accounts for the additional field enhancement at the tower top due to the presence of the mountain. Pierce [13] and Eriksson and Meal [14] proposed two statistical and empirical methods to estimate the effective height of tall objects, based on experimental observations of the lightning incidence to a given tower. According to Eriksson [15], the total number of flashes N_{all} to a tall structure is given by :

$$N_{all} = N_g\, 24\, h^{2.05}\, 10^{-6} \qquad (6.1)$$

where h is the structure height in meters and N_g is the ground flash density in $km^{-2}.year^{-1}$ in the region where the object is situated. An equation for proportion of upward flashes P_u as a function of structure height was proposed by Eriksson and Meal [14] as:

$$P_u = 52.8\, ln(h) - 230 \qquad (6.2)$$

The effective height depends on both mountain height and tower height. Zhou et al. [16] proposed a method to estimate the effective height based on a model taking into account the overall geometry (structure plus mountain), the electric field distribution around the mountaintop, and the upward flash inception criterion proposed by Rizk [17]. They called it the "Rizk-model method". Variations of the upward positive leader speed and mountain base radius have been identified as most influencing parameters in estimating this effective height.

New approaches to estimate the number of upward flashes from tall structures based on the analysis of the data provided by lightning location systems (LLS) were presented recently by Smorgonskiy et al. [18, 19] and Ishii et al. [20].

The problem of estimating N_g in the formulation of the assessment of annual number N of dangerous events on tall structures should be studied more carefully in a near future, particularly for wind turbines when they are rotating as observed in different studies carried out namely in Japan. The factor to be applied to the number of upward leaders generated at the tip of a blade at rest when the blades are rotating should probably be as high as 2.5.

7 - CONCLUSIONS

The evaluation of the ground flash density (N_g) is a crucial point related to the risk calculations especially in the Lightning Protection standards [2]. Data from LFC and LLS are not yet accurate enough; moreover there is sometimes some confusion between stroke density, flash density and ground strike-point density. Waiting for a better detection efficiency and a better location accuracy of LLSs, taking into account all unknown or non-precise parameters, and wishing to stay in a safety situation, we suggest to multiply the ground flash density (obtained from LLS) by a factor of 2 in the standards focusing on the lightning risk assessment. We also recommend to work on a new international standard, through IEC TC81, treating the performance of various lightning location systems.

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