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PROBABILITY OF DAMAGE OF ELECTRICAL AND ELECTRONIC SYSTEMS DUE TO INDIRECT LIGHTNING FLASHES – INVESTIGATION OF DATA FROM GERMAN INSURANCE COMPANIES

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Abstract - In the presented paper data collected from the field related to damage statistics of electrical and electronic apparatus in households are reported and investigated. These damages (total number approx. 74000 cases), registered by five German insurance companies in 2005 and 2006, were advised by customers as caused by lightning overvoltages. With the use of stochastical methods it is possible, to reassess the collected data and to distinguish between cases, which are with high probability caused by lightning overvoltages, and those, which are not. If there was an indication for a direct strike, this case was excluded, so the focus was only on indirect lightning flashes, i.e. only flashes to ground near the structure and flashes to or nearby an incoming service line were investigated.

The data from the field contain the location of damaged apparatus (residence of the policy holder) and the distance of the nearest cloud-to-ground stroke to the location of the damage registered by the German lightning location network BLIDS at the date of the damage.

The statistical data along with some complementary numerical simulations allow to verify the correspondence of the Standards rules used for IEC 62305-2 with the field data and to define some correction needs. The results could lead to a better understanding whether a damage reported to an insurance company is really caused by indirect lightning, or not.

1 INTRODUCTION

Lightning flashes to ground near a structure or direct or nearby an incoming line (termed “indirect flashes” in the following) cause mainly failure of electrical and electronic systems within structures so that in some cases the risk due to indirect flashes may be greater than the risk due to direct flashes. In the case of a flash near a structure the overvoltage is the result of the inductive coupling of the lightning electromagnetic pulse (LEMP) with possible loops formed by the internal circuits; in the case of a flash direct or near a line the overvoltage results by the electromagnetic (including galvanic) coupling with line conductors. The probability and the expected frequency of damage depend on the lightning current parameters’ (amplitude and steepness of first and subsequent strokes) probabilistic distributions, on the lightning cloud-to-ground density, on the average number of subsequent strokes in a flash, on the height and consequently on the equivalent area of the structure and on the distance of the striking point from the induced circuit, as well as on the loop circuit dimensions, on the type of conductors forming the circuit, on the withstand characteristics of the apparatus to be protected and on protection measures installed to reduce the electromagnetic field coupling with the loop circuit.

In the presented paper data collected from the field related to the damage statistics of electrical and electronic apparatuses are reported. These damages were registered by German insurance companies in 2005 and 2006 in different households’ structures and installations. With the use of stochastical methods it is possible, to reassess the collected data and to define cases, which are with high probability caused by lightning overvoltages. The results of the stochastic model are compared with the frequency of damage distributions obtained by using the analytical method proposed in [1, 2] which is the basis for the IEC Standard rules [3]. This gives the possibility to better understand and analyze the statistical data from the field.

This paper is support and update of a previous paper [4], giving a more detailed description of the statistical investigation, the comparison of the results from the statistics and from the numerical simulations, and the final stochastical model.

2 DEFINITIONS GIVEN IN LIGHTNING PROTECTION STANDARDS

If a lightning flash strikes a structure directly, it is probable to a very high degree, that damages of electrical and electronic apparatuses occur (This source of damage is defined as S1 according to IEC 62305-2). If a lightning flash strikes the ground nearby the structure (S2) or an incoming line to the structure directly (S3) or nearby (S4), the probability of damage of an electrical and electronic apparatus is remarkably lower. In case of nearby strikes overvoltages occur due to magnetic induction into wire loops. In case of strikes to or nearby an incoming line, partial lightning currents may be the result (S3) or again magnetically induced overvoltages (S4). However, due to the large area of influence of a single flash (some 100 m up to a few km), the frequency of damage of electrical apparatus is much higher caused by indirect flashes (S2, S3, S4) than caused by direct flashes (S1).

The international standard IEC 62305-2:2006 [3] defines as the risk of damage R:

$$R = N \cdot P \cdot L \tag{1}$$

where:

- N is the number of dangerous events per annum (caused by lightning flashes);
- P is the probability of damage to a structure or to the content inside the structure;
- L is the consequent loss, i.e. the quantitative assessment of the damage (effect, consequence, extent, amount of loss).

L describes the consequent loss, which is not of interest for this investigation (the amount of the damage advised by the policy holder was registered, but not used here). P describes the probability of a certain damage, in this investigation nearly exclusively overvoltages are the source of the damages.

In addition to eq. (1) the product N⋅P can be used to describe the number of damaged apparatuses, independent on any consequences. This parameter is defined as the frequency of damage F:

$$F = N \cdot P \tag{2}$$

In the IEC Standard [3] it is assumed, that under defined circumstances an overvoltage as a consequence of a lightning flash exists, which the connected electrical or electronic apparatus is either able to tolerate, or not. Therefore, it is either a damage (P = 1), or not (P = 0). For a risk analysis, which should mainly support the decision, whether a structure should be equipped with a lightning protection system (and if yes, which protection measures), this result is surely sufficient.

However, for a comparison of this result with data sets of real damages, a more detailed approach is necessary. As an example, a direct flash to a structure is examined. Here, according to [3] the probability of damage for electrical and electronic apparatuses caused by overvoltages is clearly P = 1 (if no protection measures are installed, e.g. surge protective devices: $P_C = 1$). In reality it must be noted, that even in this worst-case scenario not all electrical and electronic apparatuses are damaged, i.e. the probability of damage for a single apparatus is clearly P < 1.

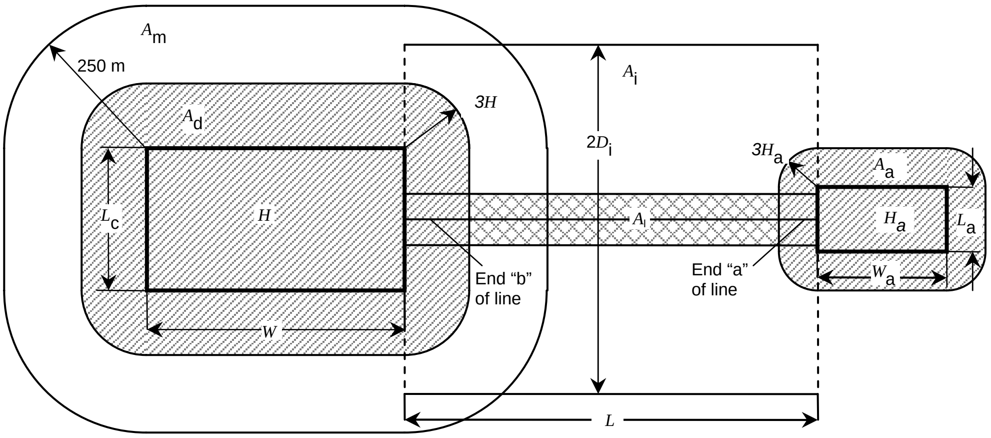

Fig. 1 - Collection areas A_d, A_m, A_l, A_i for direct and indirect lightning flashes to the structure [3].

IEC 62305-2 defines the following number of dangerous events (due to the number of dangerous lightning flashes) dependent on the point-of-strike, which are relevant for a damage in the structure under consideration (Figure 1):

N_D number of dangerous events due to direct flashes to the structure;
N_M number of dangerous events due to flashes near the structure (to the ground or neighbored structures);
N_L number of dangerous events due to direct flashes to a service connected to the structure;
N_I number of dangerous events due to flashes near a service connected to the structure.

The calculation of these individual numbers of dangerous events is given in detail in IEC 62305-2, Annex A. The parameter N_D (based on the collection area A_d) is not of interest for this investigation, because direct flashes were excluded. For the remaining parameters it is defined:

- The number of dangerous events due to flashes near the structure is given as:

$$N_M = N_g \cdot A_m \tag{3}$$

N_g is the lightning ground flash density at the location of the structure. A_m is the area of influence for flashes near the structure, which extents to a line located at a distance of 250 m from the perimeter of the structure.

- The number of dangerous events due to direct flashes to a service connected to the structure is given as:

$$N_L = N_g \cdot A_l \cdot C_d \cdot C_t \tag{4}$$

C_t and C_d are correction factors for the presence of a transformer and for the location of the service. The collection area A_l of flashes striking the service directly is dependent on:
- the type of service (aerial, buried);
- the length L_c of the service;
- in case of buried cables the resistivity of the soil ρ;
- in case of aerial lines the height H_c of the service conductors above ground.

The worst-case for the length of the service is fixed to L_c = 1000 m. This value should be also assumed, if the length is unknown.

- The number of dangerous events due to flashes near a service connected to the structure is given as:

$$N_I = N_g \cdot A_i \cdot C_e \cdot C_t \tag{5}$$

C_e is a correction factor for the environment of the service. The collection area A_i of flashes to ground near the the service is dependent on:
- the type of service (aerial, buried);
- the length L_c of the service;
- in case of buried cables the resistivity of the soil ρ.

The worst-case for the length of the service is again fixed to L_c = 1000 m.

3 STATISTICAL INVESTIGATION OF DAMAGE CASES 2005 – 2006 COLLECTED BY GERMAN INSURANCES

A Data available for the investigation

The computed results have to be compared with data of possible damages obtained from the field relevant to different types of apparatus, location, and kind of electric and electronic cabling. These data were delivered by up to five German insurance companies representing approx. 74100 damage cases of household contents insurances registered in 2005 and 2006. The data from 2005 (approx. 35700 cases) were used to conduct the investigations, to develop a stochastic model and to formulate results. The data from 2006 (approx. 38400 cases) were used to control the stochastic model and the results.

The data from the field contains:

- exact location of the damaged apparatus (residence of the policy holder, reporting the damage);
- type of the damaged apparatus;
- date of the damage;
- distance of the nearest cloud-to-ground stroke (point-of-strike) registered by the German lightning location network BLIDS at the date of the damage to the location of the damage (point-of-damage).

A critical point using data from the field is, that it is not absolutely clear whether a reported damage is really a damaged apparatus. These cases should be excluded with a high reliability (see Section 3-B). Furthermore it must be stated, that for the investigated damages there was no information available, whether there were any lightning protection systems or measures installed in or at the structure. Consequently, in this paper lightning protection measures and their effect on the damages are not investigated.

The damaged apparatus was distributed into two main categories:

- electrical apparatus connected only to one service (usually the power supply), e.g. refrigerators, cooking stoves, washing machines, etc.
- electrical apparatus connected to at least two services (power supply and information cable), e.g. TV sets, radios, telecommunication devices, PC, etc.

Finally a commercial data base was used to divide the locations of the damage cases from 2005 into three environmental categories, described by their population densities (PD):

- PD > 1000/km^2, representing urban areas (cities);
- PD > 100/km^2, but PD < 1000/km^2, representing suburban areas;
- PD < 100/km^2, representing rural areas.

For the investigation of the data from the field it is impossible, to get results of damage probabilities, and it is even doubtful, whether frequencies of damages can be evaluated. For the numbers of reported damages on the one side it is unknown, which is the overall number of electrical apparatuses in the investigated area (then the relationship would reflect the probability of damage), and it is even unknown, whether all damaged apparatuses are documented (e.g. further damaged apparatuses may be insured by other insurance companies or even not insured). For that, the investigation was focused only on the relative relationship of the reported damages as a function of their distance to the nearest registered lightning stroke.

B Statistical method of investigation

Due to the nature of the data, the reported cases are a mixture of several types or categories of cases. For the statistical model, that is a distribution or density function assumed to describe the data, the overall assumptions was made, that the reported cases belong to one of the following 4 groups:

- Group 1: The damage is caused by induction based on a lightning strike.
- Group 2: The damage is caused by a lightning strike into the power supply or the information cable.
- Group 3: The damage might not be caused by a lightning but is within a reasonable distance to the reported lightning.
- Group 4: The damage might not be caused by a lightning and is not within a reasonable distance to the reported lightning.

To model the real damages, that is the data belonging to the first two groups, a gamma-distribution was taken for each group, that is,

$$f(x,\alpha,\sigma) = \frac{x^{\alpha-1}\exp\left(-\frac{x}{\sigma}\right)}{\sigma^{\alpha}\Gamma(\alpha)} I_{x>0} \qquad (6)$$

Here x denotes the distance between the location of the damage and the reported lightning, and

$$\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1}\exp(-t)dt \qquad (7)$$

The data belonging to group 3 and 4 were modelled group-wise by a normal–distribution, where the density of the normal – distribution is given by

$$f(x,\alpha,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(x-\alpha)^2}{2\sigma^2}\right) \qquad (8)$$

The total dataset was modelled according to the mixture

$$f(x;\Psi,\Theta)=\sum_{k=1}^{4}\psi_k f_k(x;\Theta_k) \tag{9}$$

where the portions of the categories are denoted by

$$\Psi=(\psi_1,\psi_2,\psi_3,\psi_4) \tag{10}$$

the densities of each group by Ψ_1, …. , Ψ_4, and the two parameters of each density by $\Theta_i=(\alpha_i,\sigma_i)$, for i=1, . . , 4, respectively.

This model was fitted to the total dataset. Based on this fit, a global model was defined by separating the two gamma - distributions from the normal – distributions and taking the two gamma–distributions for the global model. Thus the global model has the form

$$f_g(x)=\frac{\Psi_1}{\Psi_1+\Psi_2}f_1(x,\Theta_1)+\frac{\Psi_2}{\Psi_1+\Psi_2}f_2(x,\Theta_2) \tag{11}$$

where the parameters and mixing portions are the estimated ones based on the fit.

The fit itself was based on a maximum–likelihood–approach. Since the data neither provide individual information about the categories of the reported cases nor any information about the mixing portions of the groups in the overall dataset, the corresponding likelihood – function is incomplete. To maximize an incomplete likelihood–function, the expectation – maximization – algorithm of Dempster et al. [5] is the first choice and was used here to estimate the parameters of the densities and the mixing portions.

The global model was fitted to the total set of the reported cases. Moreover, the same approach was used to fit corresponding models to the three subclasses, that is to the reported cases from urban, suburban, and rural areas.

To verify the obtained model, the same approach was applied to fit a global model to the data of the year 2006, which was then compared to the global model based on the data of the year 2005.

C Results

The following two tables summarize the obtained results.

Table 1 shows the mixing portions of the four densities given for the total dataset and the three areas, that is rural, suburban, and urban.

Table 1: Estimated portions of the densities for the total dataset and the subclasses based on the 2005 data

	Portion of the categories			
Dataset	ψ_1	ψ_2	ψ_3	ψ_4
rural	0.3871	0.5862	0.0210	0.0059
suburban	0.3478	0.5648	0.0473	0.0401
urban	0.4963	0.4051	0.0274	0.0712
total	0.3127	0.5985	0.0442	0.0446

Table 2: Estimated parameters of the individual densities based on the total dataset and on every subclasses for the 2005 data.

	Parameter of the densities							
Dataset	α_1	$1/\sigma_1$	α_2	$1/\sigma_2$	α_3	σ_3	α_4	σ_4
rural	2.17	4.64	1.17	0.62	10.17	2.58	4.32	0.26
suburban	2.54	7.32	1.13	0.93	9.17	2.74	4.30	1.22
urban	2.07	6.57	1.23	1.02	9.25	1.94	4.08	1.33
total	2.44	6.56	1.17	0.86	9.08	2.83	4.34	1.24

Overall, the first two portions, i.e. the portions corresponding to the two gamma–distributions, cover roughly 90% in every model. Furthermore, the portion of the first gamma–distribution is higher in the urban areas compared to the other areas.

In Table 2 the estimated parameters for the individual densities are listed for the total dataset and for the three areas.

It is important to note here, that the first gamma–distribution is always more concentrated on short distances than the second one, indicated by $1/\sigma_1 > 1/\sigma_2$.

Figure 2 shows the relative frequencies of the reported cases in 2005 together with the fitted density function. Obviously, the model fits very well to the data.

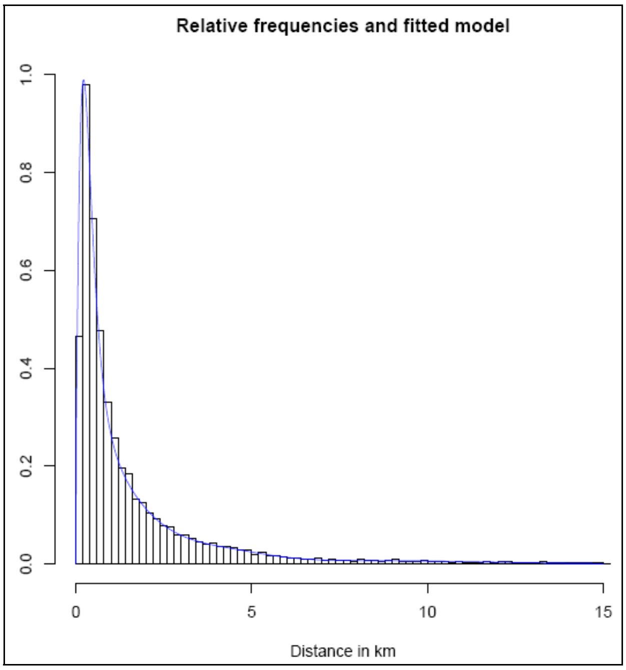

Fig. 2 - Relative frequencies of the total dataset and the fitted model.

Based on the above portions and estimated parameters, global models can be specified for each dataset. The corresponding distribution functions are listed in the Table 3 for some distances.

Table 3: Some points of he distribution functions of the estimated global models based on the 2005 data.

	Percentages with distance larger than					
Dataset	**0.5km**	**1.0km**	**1.5km**	**2.0km**	**2.5km**	**3.0km**
rural	63.04	39.84	28.65	21.39	16.04	12.01
suburban	50.37	28.45	18.16	11.69	7.50	4.79
urban	50.06	28.77	18.04	11.32	7.06	4.38
total	56.00	33.50	22.27	14.93	9.98	6.64

It is remarkable here, that there are hardly any differences between the distribution functions corresponding to the urban and suburban areas. Furthermore, the distribution function modelling the cases belonging to the rural area shows substantial higher percentages for greater distances between location of the damage and the lightning than the other two distributions. Finally, and this result could be expected, the distribution function based on the total dataset lies between the others.

To check the stability of the obtained results, the same type of model was fitted to the 2006 dataset. This fit was then compared with the one based on the 2005 data. The following Table 4 shows the portions of the four categories based on these two fits.

Table 4: Estimated proportions of the densities for the total datasets of 2005 and of 2006.

Dataset	Portion of the categories			
	ψ_1	ψ_2	ψ_3	ψ_4
2005	0.3127	0.5985	0.0442	0.0446
2006	0.3488	0.6159	0.0062	0.0291

The estimated parameters of the densities are listed in Table 5. Minor changes between the two fits can be observed both in the portions of the categories and the parameters of the estimated densities. But these changes are quite small.

Table 5: Estimated parameters of the individual densities based on the total datasets of 2005 and of 2006.

Dataset	Parameter of the densities							
	α_1	$1/\sigma_1$	α_2	$1/\sigma_2$	α_3	σ_3	α_4	σ_4
2005	2.44	6.56	1.17	0.86	9.08	2.83	4.34	1.24
2006	2.27	6.06	1.02	0.71	13.22	1.10	7.39	2.47

The two global models based on these fits, that is, the mixture based only on the two gamma distributions, are given in the following Table 6 for some significant points. Comparing the corresponding percentages, hardly any differences can be detected. Thus, both fits result in roughly the same distribution function.

Table 6: Some points of the distribution functions of the global models based on 2005 and 2006 datasets.

Dataset	Percentages with distance larger than					
	0.5km	1.0km	1.5km	2.0km	2.5km	3.0km
2005	56.00	33.50	22.27	14.93	9.98	6.64
2006	55.11	32.62	21.65	14.51	9.70	6.45

This is also emphasized by the visualization of the two densities, given in Figure 3. Hardly any differences between the two densities of the global models can be detected. Overall, this stability also validates the approach to a certain extent.

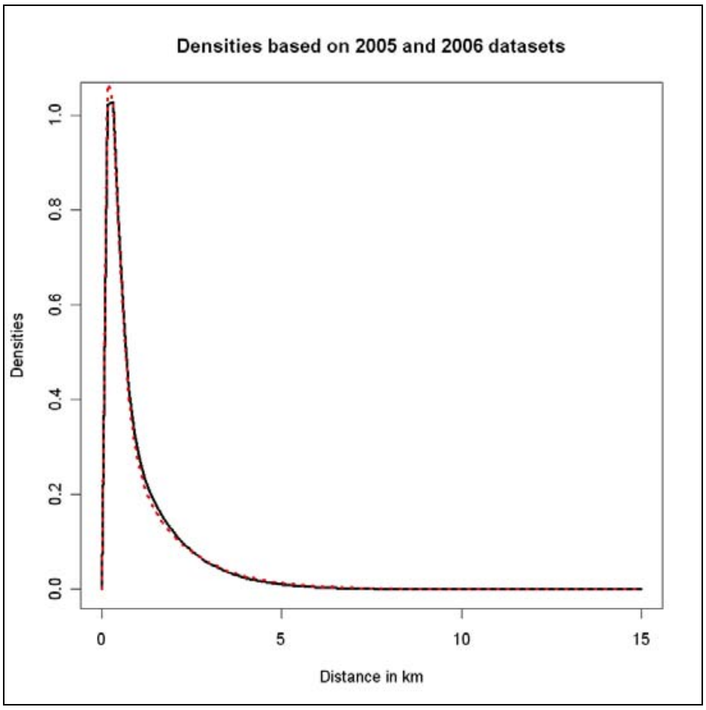

Fig. 3 - Densities of the global models fitted to the 2005 data (solid black) and to the 2006 data (dotted red).

4 CONSIDERATION OF THE ACCURACY OF THE LIGHTNING DETECTION SYSTEM USED

For the registration of the nearest cloud-to-ground stroke the German lightning location network (LLN) BLIDS was used, which is a part of the European EUCLID network [6, 7]. LLN necessarily have inaccuracies, which influence the data and which, therefore, have to be taken into account.

For a LLN, generally the following criteria are important:

- Detection efficiency (DE) for flashes;
- Detection efficiency (DE) for strokes;
- Geometrical detection error;
- Selectivity between cloud-to-ground strokes and other incidents (cloud-to cloud strokes, intracloud strokes, etc.).

DE for flashes and strokes, resp. indicate the probability of a single stroke or flash, resp. to be detected by the network. The DE for strokes usually is less important than the DE for flashes, because for indicating a lightning flash as a possible source of damage it is sufficient to detect only one stroke out of the flash.

Due to the used technologies and algorithms and also due to the physics of lightning, a geometrical detection error of some 100 m is usual. The error in case of a single lightning stroke depends on a number of influencing factors, e.g. the number of sensors detecting the lightning stroke, the distance to the sensors, the statistical error of the time measurement, the maximum value of the electrical field pulse, etc. Besides that, also systematic errors may be important, e.g. differences in the wave propagation above ground based on topological conditions (mountainous area - flat area, rock – sand – water, seasonal influences).

Selectivity between cloud-to-ground strokes and other incidents means the unambiguous distinction in the categories cloud-to-ground lightning and others. For lightning protection purposes on the ground it must be highly probable, that a detected cloud-to-ground flash is really one and vice versa. Finally, it must be stated, that the individual criteria are not independent. Thus, usually a compromise must be found for a well designed LLN.

The geometrical detection error of the LLN BLIDS is intensively discussed and investigated (e.g. [8, 9]). The mean detection error is approx. 200 m, if existing systematic errors at some locations are excluded. However, if an inaccuracy of a LLN should be given not only for the average, but also for low probabilities, this has to be combined with the DE for flashes.

The DE for flashes is investigated in detail for the Austrian LLN ALDIS. It is 93%, if the maximum lightning current is > 4 kA, and 98%, if the maximum lightning current is > 10 kA. Comparisons between ALDIS and the German LLN BLIDS show slightly worse values for BLIDS for the smaller maximum currents. For maximum currents > 10 kA, the differences are a few percent only.

Based on these information, it can be stated for BLIDS, if a geometrical detection error of 1000 m is used, that approx. 90% of all cloud-to-ground lightning flashes with maximum currents > 4 kA are detected correctly, 95% with maximum currents > 10 kA.

Under the assumption, that the geometrical detection error of 1000 m is simply superimposed to the real distances between the point-of-strike and the point-of-damage, the results based on the data from the field described in the previous chapters have to be modified for the further analysis. If small probabilities of damage are of interest, in a rough approximation the value of 1000 m can be simply subtracted, to get the real possible distance for the investigated cases.

5 NUMERICAL SIMULATION OF PROBABILITIES AND FREQUENCIES OF DAMAGE IN CASE OF NEARBY FLASHES

A Background

Following [1,2] the probability of damage due to overvoltages induced in a loop circuit within a structure by nearby flashes at a distance r to the centre of the loop can be evaluated as:

$$P(r) = \int_{I(r)}^{I_{\max}} g(I)dI \tag{12}$$

where:

- g(I) is the probability distribution function of the lightning current peak values of the subsequent strokes (derived from the statistics given in IEC 62305-1:2006-01, Annex A [10]);
- I_{max} is the maximum value of the lightning current for an indirect flash at a distance r from the structure;
- I(r) is the minimum value of the lightning current peak value of flashes striking the ground at distance r from the loop able to originate an overvoltage high enough to cause the damage.

For the evaluation of the parameter I(r) the following simple relation may be used:

$$I(r) = \frac{2\pi}{\mu_o} \cdot \frac{V_w \cdot T_1}{S} \cdot r \tag{13}$$

where:

- μ_o is the magnetic field constant (permeability in vacuum);
- V_w is the impulse withstand voltage of the apparatus;
- T_1 is the time to peak value of lightning current;
- S is the induction loop area.

Finally, for the estimation of I_{max} the electro-geometrical model has been used, which according to the formula given by Ericksson [11] leads to the relationship:

$$I_{\max} = \left(\frac{r}{0.67 \cdot H^{0.6}} \right)^{1.43} \tag{14}$$

where H is the height of the structure.

Remark: Numerical simulations in these detailed manner were only possible for the magnetically induced voltages in loops (S2). The probabilities or frequencies of damage caused by voltages occuring in service lines, either as a result of a direct flash (S3) or as an induced voltage due to a nearby flash (S4), depend mainly on the length of the service conductors. However, unfortunately for the parameter service length probability distribution functions were not available.

B Sensitivity of the loop area

In IEC 62305-2 [3] the induction loop area was assumed to $S = 10\ m^2$. For this investigation also two other loop areas were considered:

- $S = 1\ m^2$ for an apparatus, which is connected to only one electrical service (usually the power supply);
- $S = 50\ m^2$ for an apparatus, which is connected to at least two electrical services (e.g. power supply and telecommunication, power supply and antenna, etc.).

Numerical simulations using MATLAB [12] were conducted with all three loop areas ($S = 1\ m^2$, $10\ m^2$ and $50\ m^2$). Figure 4 shows the probabilities of damage P of overvoltages for the three loop areas. For the simulations the following determinations are valid:

- The simulations were conducted only for the subsequent strokes, because this lightning current component leads to the highest magnetically induced voltages in loops. The probability distribution function for the lightning current peak values of the subsequent strokes g(I) is given in [10].
- According to [10] the time to peak value of lightning current was fixed to $T_1 = 0.25\ \mu s$.
- As a typical height of the structure a value of H = 10 m was taken.
- The impulse withstand voltage of the apparatus was fixed to $V_w = 1.5$ kV.
- The orientation of the induction loop was perfectly perpendicular to the penetrating magnetic field, so that the highest induction could occur (worst-case).

Using eq. (2) and eq. (3) and the probability of damage P, as the next step the frequency of damage F was calculated (see Figure 5). The lightning ground flash density was fixed to $N_g = 4$ flashes per km^2 and per annum; this is a comparatively high, but still typical value in Germany.

The frequency of damage (in damages per annum) is valid for a concentrical ring in a distance d to the point-of-strike. The ring has a width $\Delta d = 1$ m; therefore the area A, to which the frequency of damage is belonging, is:

$$A = 2 \cdot \pi \cdot d \cdot \Delta d \tag{15}$$

Remark: The frequency of damage goes to 0 for small distances d. This is due to the decreasing area A for smaller d; see eq. (15). The frequency of damage F is determined by the product of probability of damage P and area A. For small distances d we get indeed P ≈ 1, but also small values for A.

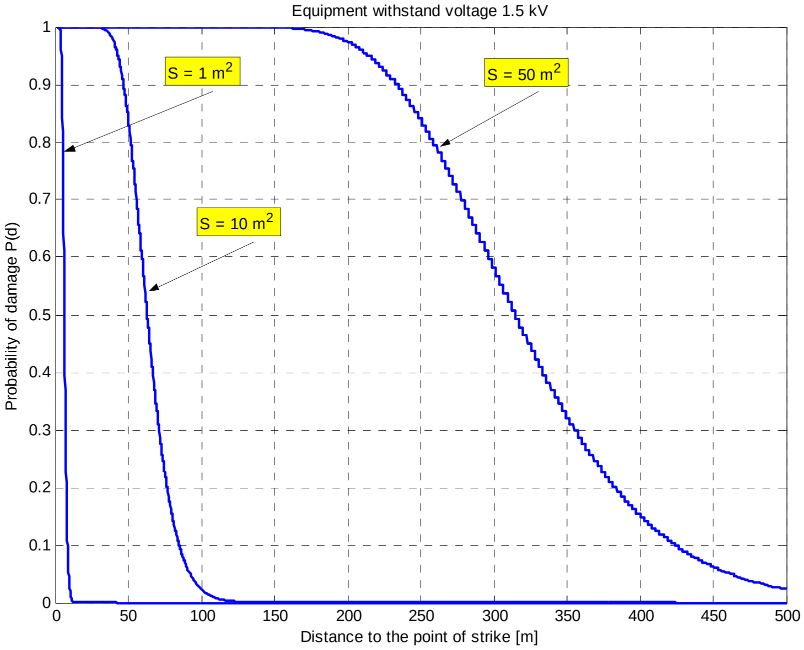

Fig. 4 – Probability of damage P for nearby flashes vs. distance d from the damage location to the lightning striking point for three loop areas (V_w = 1,5 kV).

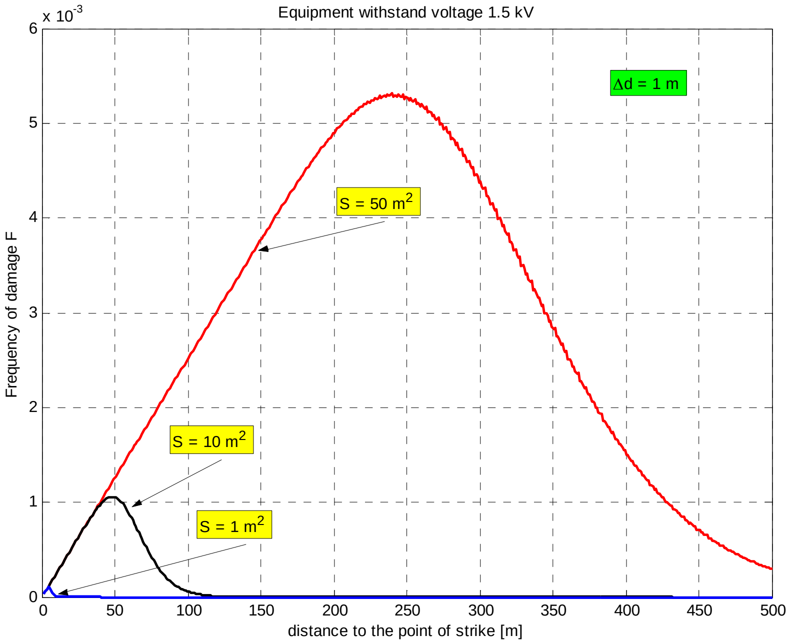

Fig. 5 – Frequency of damage F (per annum) for nearby flashes vs. distance d from the damage location to the lightning striking point for three loop areas (V_w = 1,5 kV).

From the Figures 4 and 5 the following results can be derived:

1. For small values of the distance d the frequency of damage F increases nearly proportionally together with d, because the probability of damage is still approximately constant in this range ($P \approx 1$) and the area A depends linearly on d. With further increasing d the probability of damage P decreases disproportionately high, so that then the frequency of damage decreases.
2. If nearby flashes have distances of at least some 10 m to the structure (otherwise they would be direct flashes), remarkably high induced overvoltages in loop areas of $S = 1$ m^2 can be excluded. For electrical and electronic apparatuses connected only to one service induced overvoltages due to nearby flashes are hardly relevant.
3. For “typical” loop areas (10 m^2 according to [3]) relevant overvoltages are possible up to a distance d of somewhat more than 100 m.
4. For larger loop areas (50 m^2) created by the wiring to the apparatuses relevant overvoltages occur up to a distance d of somewhat more than 500 m.

C Sensitivity of the withstand voltage

In the following only the two larger loop areas (10 m^2 and 50 m^2) were considered. The impulse withstand voltage was varied as V_w = 0.5 kV / 1.0 kV / 1.5 kV / 2.5 kV. The other determinations described in the previous subsection were vaild again. Figure 6 and 7 show the frequency of damage for the two loop areas.

Here, the following results can be derived:

1. For “typical” loop areas (10 m^2) relevant overvoltages are possible up to a distance d of some 100 m, if the impulse withstand voltages decrease down to 0.5 kV.
2. For larger loop areas (50 m^2) and the lowest impulse withstand voltage level of 0.5 kV relevant overvoltages occur up to a distance d of more than 1500 m.
3. It is assumed, that the impulse withstand voltage level of 0.5 kV is not realistic for apparatuses connected to services entering the structure. However, values of V_w = 1.0 ... 1.5 kV are typical. Hence, the distances d for relevant overvoltages are 100 ... 200 m for the loop area of 10 m^2, and 500 ... 700 m for the loop area of 50 m^2. So the distance of 250 m fixed in [3] can serve as a worst-case for the smaller loop area, but not for the larger loop area.

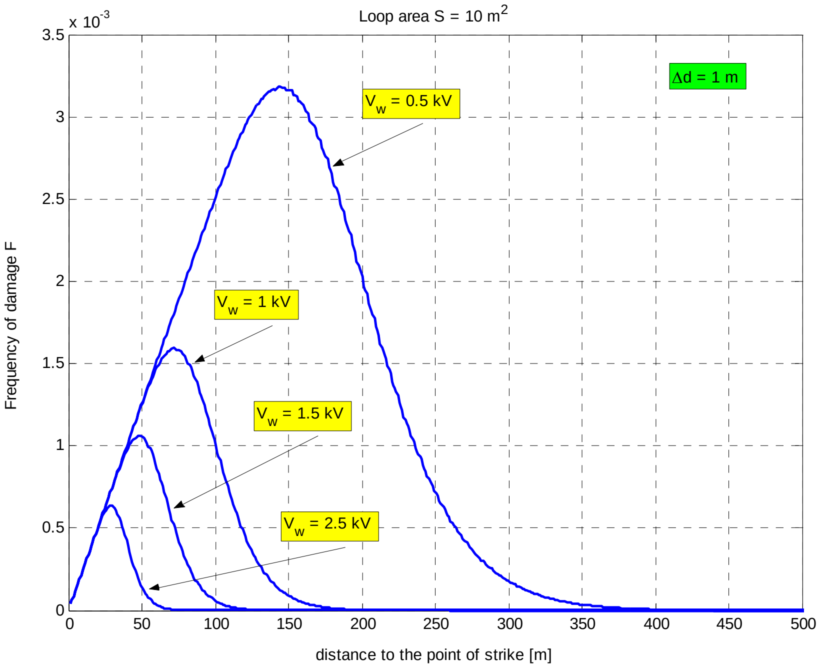

Fig. 6 – Frequency of damage F (per annum) for nearby flashes vs. distance d from the damage location to the lightning striking point for different withstand voltages (loop area 10 m^2).

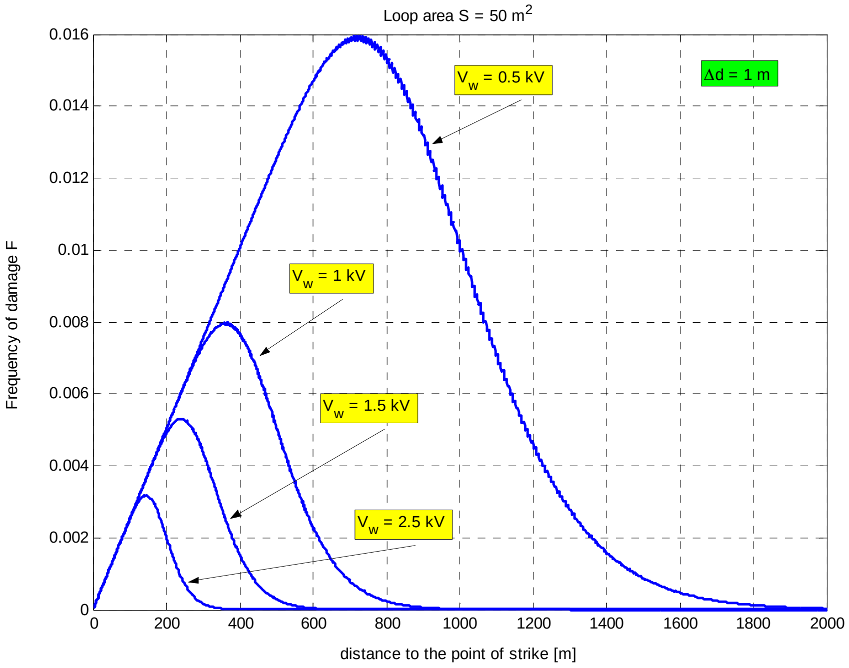

Fig. 7 – Frequency of damage F (per annum) for nearby flashes vs. distance d from the damage location to the lightning striking point for different withstand voltages (loop area 50 m^2).

6 DISCUSSION OF THE RESULTS - EVALUATION OF A STOCHASTICAL MODEL

Based on the statistical investigations and the complementary numerical simulations described above, firstly the following conclusions are possible, leading secondly to a stochastical model for the probability of overvoltages at apparatuses caused by indirect lightning flashes:

1. If the damage cases are excluded, which were with high probability not caused by lightning (log-normal distributions), two gamma-distributions can be distinguished:
   - Group 1 describing closer distances between point-of-strike and point-of-damage;
   - Group 2 describing wider distances between point-of-strike and point-of-damage.
2. The two gamma-distributions can be sufficiently interpreted electromagnetically:
   - Group 1 represents the damages caused by induction effects due to nearby, indirect lightning flashes;
   - Group 2 represents the damages caused by flashes to or nearby service lines entering the structure.
3. The damaged apparatuses can be divided into two categories:
   - Category A with galvanic connections to only one electrical service (usually the power supply), e.g. household appliances;
   - Category B with galvanic connections to at least two electrical services (usually the power supply and telecommunication, broadband, antenna, etc,), e.g. IT equipment, TV sets, DVD recorder, hi-fi systems and control systems.
4. Damages caused by induction effects due to nearby flashes are probable up to a distance to the point-of-strike of approx. 500 – 700 m, if the geometrical detection error of the LLN BLIDS (1000 m) is excluded. The influence of the population density (environment) is negligible; however, there is a tendency to smaller distances in an urban area (a “shielding” effect by other structures between the point-of-strike and the point-of-damage).
5. Following item 4, the value of 250 m distance to the structure as given in IEC 62305-2 [3], describing the area for nearby lightning flashes creating the source of damage S2, is not a worst-case consideration. This value should at least be doubled. This is already the state-of-discussion in the Standardization team IEC TC81 MT9 and it will be

published in the 2nd edition of IEC 62305-2 [13].

6. Damages caused by external service lines entering the structure are probable up to a distance of approx. 2000 m, if the geometrical detection error of the LLN BLIDS (1000 m) is excluded again. For this distribution there is a clear influence of the population density (environment). A distinction into urban and suburban environment is difficult if only based on the statistical data, due to the superimposed geometrical detection error of 1000 m. However, in combination with IEC 62305-2:2006 [3] it is possible. Therefore, the maximum distances given in Table 7 could be found.

Table 7: Maximum distances between the point-of-strike and the point-of-damage with a significant probability1) for a coupling effect on the external service lines entering the structure.

Urban	Suburban	Rural	„Special case“ 2) (stand-alone)
200 m	500 m	1000 m	2000 m

1) Probable or significant probability here means that the number of cases still part of the gamma-distribution is less than 10% of all cases.

2) Special case represents structures without any surrounding property within a distance of a few km (stand-alone structures). This is valid especially for agricultural properties in sparsely populated regions. The insurance data indicate, that there is a certain number of damage cases with distances of much more than 1 km, with still approx. 10% of all the cases exceeding a distance of 2 km.

7. Following item 6, the value of 1000 m given in IEC 62305-2 [3] as the maximum length of an external service line, which has to be considered, is not a worst-case consideration. It is sufficient for rural environment, but not for stand-alone structures. This item should be also discussed in the near future by the Standardization team IEC TC81 MT9, possibly leading to another change in the 2nd edition of IEC 62305-2 [13].

8. If the damage cases are separated into the two main categories of electrical and electronic apparatuses, it was found, that the apparatuses connected to one service only (Category A) is damaged via the effects on the external service line (S3 & S4), whereas apparatuses connected to at least two services (Category B) is damaged via the effects on the external service line (S3 & S4) and via induction effects (S2). This result again can be sufficiently interpreted electromagnetically: In case of only one service the possible induction loop is negligible.

9. Taking all damage cases, induction effects are responsible for approx. 1/3 of all cases, effects on the external service lines for approx. 2/3. In case of a higher population density (urban/suburban area) the portion of the induction effects increases (due to the decreasing effect of the external service lines because of their decreasing length), but it never exceeds 50% of all cases.

Table 8: Maximum distances (without consideration of the LLN's accuracy) between the point-of-strike and the point-of-damage with a significant probability that an apparatus' damage is caused by a lightning flash.

Category of apparatus	Coupling mode	Urban	Suburban	Rural	„Special case“ (stand-alone)
Category A	via induction	-	-	-	-
	via external service	200 m	500 m	1000 m	2000 m
Category B	via induction	500 m	500 m	700 m	700 m
	via external service	200 m	500 m	1000 m	2000 m

All results are combined to a stochastical model (Table 8). If the distance between the point-of-strike and the point-of-damage exceeds the given values (plus a factor for the geometrical detection error considering the accuracy of the used LLN), a correlation of the damage with the lightning flash is very improbable.

Finally it should be noted, that the results and conclusions are purely valid only for the investigated apparatus: household appliances. However, also for other apparatuses and for other fields (administration, business, craft, industry) most of the conclusions are at least qualitatively correct and can be transferred, if the impulse withstand voltage levels of the electrical and electronic apparatuses, the relevant areas of the induction loops and the lengths of the external service lines do not diverge too much.

7 CONCLUSIONS

The reassessed data relevant to the possible damage of electrical and electronic systems within structure clearly show two distributions: one caused by induction effects due to nearby strikes, the other caused by lightning direct strikes to lines or coupling to lines.

The results lead to a stochastic model which could give the information about the probability whether a reported damage is really caused by indirect lightning, or not.

The statistical data allow to verify the rules and determinations given in Standards and to define correction needs or correction factors.

It is important to outline that the data from the field still contain the geometrical detection error from the lightning location system. As a continuing step it is further planned to investigate this influencing parameter more in detail. If it is possible, to describe the geometrical detection error with a stochastical model, the analysis of the statistical data could be even more exact.

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