Probability and frequency of damage of electrical and electronic systems due to indirect lightning flashes

A. Kern, G. Dikta, Z. Flisowski, M. Marzinotto, *Member, IEEE*, C. Mazzetti, *Member, IEEE*

***Abstract*—In the present paper data collected from the field related to the damage statistics of electrical and electronic systems due to lightning overvoltages are reported. These damages were registered by German insurance companies in 2005 and 2006 in different 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 probability of damage distributions obtained by using the analytical method, which is the basis for the IEC Standard rules.

***Index Terms*—Probability of damage, lightning induced overvoltages, stochastic models.**

I. INTRODUCTION

LIGHTNING flashes to ground near a structure or near 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 lightning electromagnetic pulse (LEMP) with possible loops formed by the internal circuits; in the case of flash near a line the overvoltage results by the electromagnetic 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 equipment to be protected and on protection measures installed to reduce the electromagnetic field coupling with the loop circuit.

In the present paper data collected from the field related to the damage statistics of electrical and electronic systems are reported. These damages were registered by German insurance companies in 2005 and 2006 in different 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 probability of damage distributions obtained by using the analytical method proposed in [1,2] which is the basis for the IEC Standard rules [3].

II. DATA FROM THE FIELD – INVESTIGATION USING DATA FROM GERMAN INSURANCES

A. *Data available for the investigation*

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

The data from the field contains:

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

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Alexander Kern is with the Aachen University of Applied Sciences, Juelich Campus, Section Electrical Engineering, Ginsterweg 1, 52428 Juelich, GERMANY (e-mail: a.kern@fh-aachen.de).

Gerhard Dikta is with Aachen University of Applied Sciences, Juelich Campus, Section Technomathematics, Ginsterweg 1, 52428 Juelich, GERMANY (e-mail: dikta@fh-aachen.de).

Zdobyslaw Flisowski is with Warsaw University of Technology, Plac Politechniki 1, PL 00-661 Warszawa, POLAND (e-mail: zdobyslaw.flisowski@acn.waw.pl)

Massimo Marzinotto is with the Electrical Engineering Department at the Sapienza University of Roma, via Eudossiana 18, 00184 Roma, ITALY (corresponding author, phone: +39 06 44585544; fax: +39 06 4883235; e-mail: maxmarzinotto@ieee.org).

Carlo Mazzetti is with the Electrical Engineering Department at the Sapienza University of Roma, via Eudossiana 18, 00184 Roma, ITALY (e-mail: carlo.mazzetti@uniroma1.it).

A critical point using data from the field is, that it is not absolutely clear whether a reported damage is really a damaged equipment. These cases should be excluded with a high reliability (see Section 2-B).

The damaged equipment 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 equipments in the investigated area (then the relationship would reflect the probability of damage), and it is even unknown, whether all damaged equipments are documented (e.g. further damaged equipment 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,

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

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

$$\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1}\exp(-t)dt \tag{2}$$

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

$$f(x;\alpha,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(x-\alpha)^2}{2\sigma^2}\right) \tag{3}$$

The total dataset was modelled according to the mixture

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

where the portions of the categories are denoted by

$$\Psi = (\psi_1,\psi_2,\psi_3,\psi_4) \tag{5}$$

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

$$f_g(x) = \frac{\Psi_1}{\Psi_1+\Psi_2} f_1(x,\Theta_1) + \frac{\Psi_2}{\Psi_1+\Psi_2} f_2(x,\Theta_2) \tag{6}$$

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. [4] 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 I shows the mixing portions of the 4 densities given for the total dataset and the three areas, that is rural, suburban, and urban.

TABLE I
ESTIMATED PORTIONS OF THE DENSITIES FOR THE TOTAL DATASET AND THE SUBCLASSES BASED ON THE 2005 DATA

	Portion of the categories			
Dataset	y_1	y_2	y_3	y_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

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 II the estimated parameters for the individual densities are listed for the total dataset and for the three areas.

TABLE II
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

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

Fig. 1 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.

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 III for some distances.

TABLE III
PERCENTAGES OF SOME MARKED POINTS OF THE DISTRIBUTION FUNCTIONS DUE TO 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.

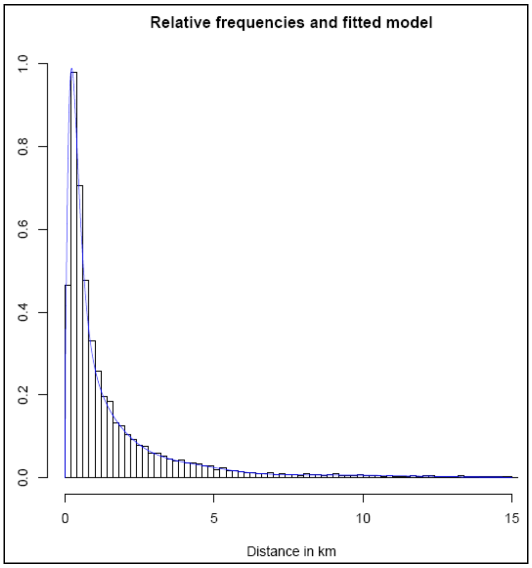

Fig. 1. Relative frequencies of the total dataset and the fitted model.

A comparison of the distribution function defined by the global model based on the 2005 data with the corresponding distribution function based on the total dataset of the 2006 data shows hardly any difference. This confirms the applied approach.

D. Consideration of the inaccuracy of the lightning detection system used

For the registration of the nearest cloud-to-ground lightning the German lightning location network (LLN) BLIDS was used, which is a part of the European EUCLID network. 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, respectively indicates the probability of a single stroke or flash, 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. [5, 6]). 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 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.

III. DISCUSSION OF THE RESULTS

Based on the statistical investigations described above, the following conclusions are possible:

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:
    - distribution 1 describing closer distances between point-of-strike and point-of-damage;
    - distribution 2 describing wider distances between point-of-strike and point-of-damage.
2) The two gamma distributions can be sufficiently interpreted electromagnetically:
    - distribution 1 represents the damages caused by induction effects due to nearby, indirect lightning strokes;
    - distribution 2 represents the damages caused by incoupling on the external service lines entering the structure.
3) Damages caused by induction effects are probable up to a distance to the point-of-strike of approx. 500 – 700 m, if the geometrical detection error of 1000 m is excluded. Following that, the value of 250 m distance of lightning strokes to the structure given in IEC 62305-2 [3] is not a worst-case consideration. For induction effects the influence of the population density (environment) is negligible, however there is a tendency to smaller distances in an urban area ("shielding" effect by structures between the point-of-strike and the point-of-damage).
4) Damages caused by incoupling effects on the external service lines entering the structure are probable up to a distance of more than 2000 m, if the geometrical detection error of 1000 m is excluded again. For this distribution there is a clear influence of the population density (environment). However, a distinction into urban and suburban environment in agreement to IEC 62305-2:2006 [3] is not possible, due to the superimposed geometrical detection error of 1000 m. The maximum distances given in table y.1 could be found.

TABLE IV

DISTANCES BETWEEN THE POINT-OF-STRIKE AND THE POINT-OF-DAMAGE WITH A SIGNIFICANT PROBABILITY OF AN INCOUPLING EFFECT ON THE EXTERNAL SERVICE LINES ENTERING THE STRUCTURE.

Urban/suburban	Rural	„Special case“ 1)
500 m	1000 m	2000 m

Special case represents structures without any surrounding property within a distance of few km. This is valid especially for agricultural properties in sparsely populated regions. However, the insurance date 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. Following that, 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, again is not a worst-case consideration. (Remark: Probable or significant probability here means that the number of cases still part of the gamma distribution is less than 10% of all cases).

5) If the damage cases are separated into the two main categories of electrical equipment, it was found, that the equipment connected to one service only is damaged via the incoupling effects on the external service line, whereas equipment connected to at least two services is damaged via the incoupling effects on the external service line and via induction effects. This result again can be sufficiently interpreted electromagnetically: in case of only one service the possible induction loop is negligible.
6) Taking all damage cases, induction effects are responsible for 1/3 of all cases, incoupling effects on the external

service lines for 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.

Finally it should be noted, that the results and conclusions are purely valid only for the investigated apparatus: household contents. However, also for other equipment most of the conclusions are at least qualitatively correct and can be transferred.

IV. PROBABILITY OF DAMAGE FOLLOWING THE IEC STANDARD RULES

It is demonstrated in [1,2] that the probability of damage due to overvoltages induced on a loop circuit within a structure by nearby flashes at a distance *r* to the centre of the loop can be evaluated as follow

$$P(r) = \int_{I(r)}^{I_{\max}} g(I)dI \qquad (7)$$

where:

- *g(I)* is the probability distribution function of the lightning current peak values of the subsequent strokes;
- 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 *I(r)* evaluation the following simple relation may be used:

$$I(r) = \frac{2\pi}{\mu_o} \cdot \frac{V_w T_1}{S} \cdot r \qquad (8)$$

with:

- μ_o is the vacuum permeability;
- V_w is the impulse withstand voltage of the apparatus;
- T_1 is the time to peak value of lightning current, which has been assumed equal to 0.25 μs considering subsequent strokes according to values suggested by International Standard [3].

For the estimation of I_{max} the electro-geometrical model has been used, which according to Ericksson formula [7] gives:

$$I_{\max} = \left(\frac{r}{0.67 \cdot H^{0.6}} \right)^{1.43} \qquad (9)$$

where *H* is the height of the structure.

In Fig. 2, 3 and 4, the cumulative probability of damage vs. striking point distance from the structure in a rural, suburban and urban area are reported (dashed line) and compared with the estimated distribution (Group 1) from field data (solid line). The comparison shows that the best fitting is obtained by considering an average height of structures of 10 m and a withstand voltage of the apparatuses of 1.5 kV and

- for rural area with an average loop area of 120 m^2,
- for suburban area with an average loop area of 90 m^2,
- for urban area with an average loop area of 80 m^2,

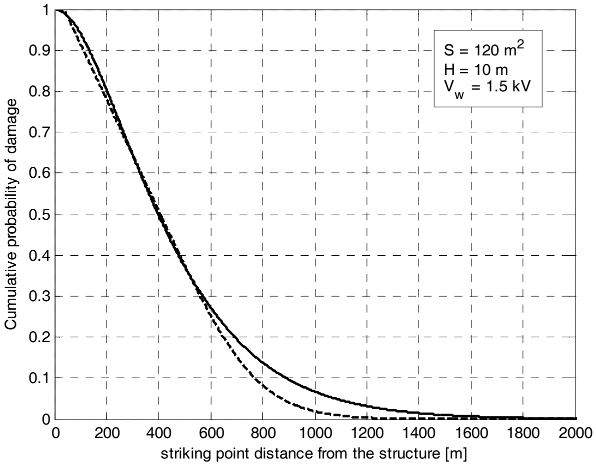

Fig. 2. Cumulative probability of damage vs. striking point distance from the structure in a rural area: estimated distribution (Group 1) from field data (solid line) and evaluated through the numerical program (dashed line) considering an average loop area of 120 m^2, an average height of structures of 10 m and a withstand voltage of the apparatuses of 1.5 kV.

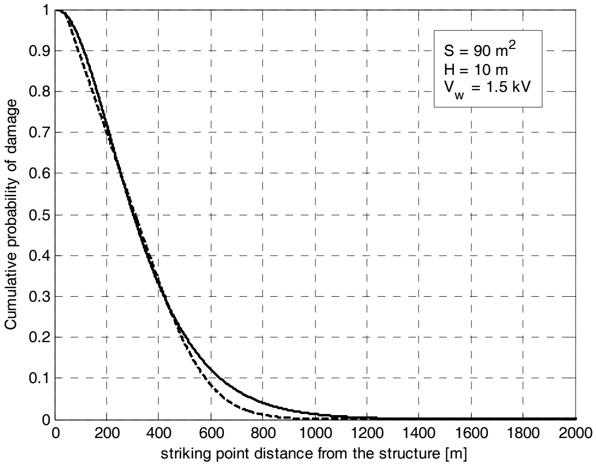

Fig. 3. Same as Fig. 2, but for suburban area – loop area 90 m^2.

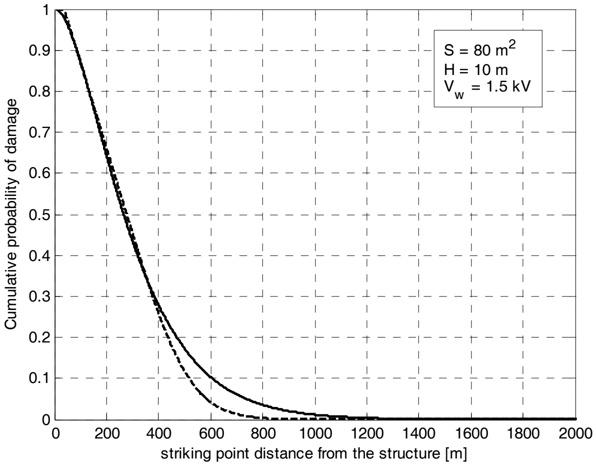

Fig. 4. Same as Fig. 2, but for urban area – loop area 80 m^2.

It is important to note that the best fitting is obtained for a quite large loop area that could be the case of apparatuses connected to at least two services, i.e. power and telecommunication lines.

V. 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 or coupling to lines.

The statistical data allow to verify the correspondence of the Standards rules with the field data and to establish, eventually, correction factors. The results could lead to a model which could allow information about the probability whether a reported damage is really caused by indirect lightning.

It is important to outline that the data from the field still contain the uncertainty from the lightning location system. In any case this is a first approach to the problem that needs to be further investigated in order to distinguish for different environments (urban, suburban and rural) the damages due to nearby lightning to structures and to power lines.

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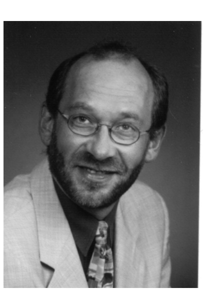

Alexander Kern was born in Weiden, Germany, on May 27, 1962. He received the Diploma degree in Electrical Engineering and the Ph.D. degree at the University of the Federal Armed Forces in Munich in 1985 and 1990, respectively. Since 1996 he is Full Professor for "High Voltage Engineering and Fundamentals of Electrical Engineering" at Aachen University of Applied Sciences.

He is the German representative in IEC-TC81 (Lightning Protection) and member of WG8 and WG9. His main interests are lightning protection research and lightning risk assessments. He is author of about 50 papers on lightning protection and HV simulations.

Massimo Marzinotto (S'97, M'01) was born in Latina, Italy, on March 24, 1975. He received the 5 years degree and the Ph.D. degree in Electrical Engineering at the Sapienza University of Roma in 2000 and 2006 respectively. He has currently a research contract with the Electrical Engineering Department of the Sapienza University of Roma. His main interests are high polymeric electrical insulating materials, statistical techniques for high voltage engineering, power cables, power systems transients analysis. He is member of IEEE-DEIS, IEEE-PES and TC 20 "Power Cables" of CEI (Italian Electrotechnical Committee) on WG "HV/LV electric cables", on WG "Burning characteristics of electric cables" and on WG "Ampacity". He is author and co-author of international publications on applied statistics, power cables, power system insulation and transients.

Carlo Mazzetti (M '89) was born in Roma, Italy on May 5, 1943. He received the Dr. Eng. degree in Electrical Engineering from the Sapienza University of Roma in 1967 where he is now Full Professor of "High Voltage Engineering" and "Power Systems". From 1986 until 1989 he has been of Director of the Electrical Engineering Department of the same University. Since 1996 he is President of the International Conference on Lightning Protection (ICLP). He is Convener WG8 and WG9 of the IEC-TC81 (Lightning Protection). His main interests are HV transient analysis and measurements with particular reference to lightning effect and diagnostic tests on electrical insulation. He has author of about 150 papers and two books on HV impulse generators and HV measurement techniques.

Gerhard Dikta was born in Bielefeld, Germany, on November 19, 1955. He received the Diploma degree in Mathematics from Ludwig–Maximilians–University of Munich in 1983 and the Dr. rer. nat. degree from Justus–Liebig–University of Giessen in 1987. Since 1993 he is Full Professor for "Applied Mathematics" at Aachen University of Applied Sciences. His research interests are in Mathematical Statistics and Operations Research.

Since 2004 he is Adjunct Professor at the Mathematical Institute of the University of Wisconsin-Milwaukee and, since 2007, also at the Division of Biostatistics at the Medical College of Wisconsin.

Zdobyslaw Flisowski was born in 1931 in Brzesc, Poland. He received the Doctoral degree in electrical engineering from the University of Technology,Warsaw, Poland in 1952. He joined the faculty of the Electrical Engineering Department, University of Technology, in 1952. In 1971 he became an Associate Professor and in 1987 a Full Professor. In 1991 he became Head of the High-Voltage Technique Division and from 1988 to 1992 he was Prorector of the University. He is the author of four books and more than 110 scientific papers.His main interests are high-voltage technique and lightning protection. Prof. Flisowski is a member of the Polish Committee on Lighning Protection of which he was President in 1972. He is also a member of the Scientific Committee on the International Conference on Lighning Protection and is a Fellow of the Institute of Electrical Engineers.