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10/350 LIGHTNING TEST WAVEFORM IN FOCUS

Bruce Glushakow

Member IEEE, MCG Electronics, USA – bglushakow@ieee.org

Abstract - Dr. Karl Berger was a Swiss researcher whose work on Mt. St. Salvatore rates him the title of "father of direct lightning research." He documented his findings in an article published in *ELECTRA* magazine in 1975. Some 40 years later the IEC immortalized that work by characterizing it as the closest representation of the actual lightning flash and using it as the basis for the parameters of the 10/350 Class 1 test waveform adopted in IEC 62305-1 "Protection against lightning". This paper examines the content of Berger's *ELECTRA* article and the process by which info extracted from that article led to the formulation of the 10/350 test waveform. Five widely held assumptions about lightning parameters which have been inferred from Berger's article are examined. When the data that underlie them are scrutinized, four of those five assumptions are found to be unsupported by fact. Finally the paper offers some expanded proposals for testing surge protective devices that rely on more than the exclusive use of a single testing wave form.

1 INTRODUCTION

Since 1995, most international lightning standards have referenced the lightning model first advanced by IEC Technical Committee 81 in IEC 61312-1 [1]. This includes IEC 61643-1 [2] and the most recent IEC 62305-1 [3].

These standards all stipulate the same basic parameters of peak impulse current (I_{imp}) , charge transfer (*Q*), and specific energy (*W/R*, also expressed as I^2dt) to be used in the Class I testing of surge protective devices [3, Sec. C2].

The sole source of this lightning model has been cited as: "the results of CIGRE given in ELECTRA Magazine Issue 41 (1975) and Issue 69 (1980) [*1,* Annex A, Para. A.1] and *[3,* Annex A, A2]."

These are the two referenced articles:

- K. Berger, R.B. Anderson, H. Kröninger, *Parameters of lightning flashes.* ELECTRA No 41 (1975) [4].
- R.B. Anderson, A.J. Eriksson, *Lightning parameters for engineering application*, ELECTRA No 69 (1980) [5].

K. Berger, a pioneer in lightning research, did the major part of his work between 1963 and 1971. It was his data on positive lightning, taken from studies at 2 small stations in the mountains above Lake Lugano in Switzerland, to which has been attributed the parameters which subsequently led to the 10/350 Class 1 test waveform requirement in standards.

Although it is commonly believed that there is an acceptable alternative Class 1 test based on an 8/20 waveform, findings of a task force of the IEEE SPD Committee (Work Group 3.6.4) challenge that notion. The only impulse that can actually satisfy the parameters of the Class I Test is the 10/350 test waveform [6].

Many parameters of lightning discharges registered 40 years ago are very similar to those registered today. However our perception and understanding of the lightning process have improved enormously with the introduction and application of new technologies. For example, today's 11,800+ frames-per-second video gives a far better look at such features as lightning branching, continuing currents, and M-components than the 50 frames-per-second video upon which Berger had to rely.

What was Berger actually looking at when he reported his data all those years ago? What type of lightning was it? What were the current distributions? And what is the significance of those findings on today's lightning protection and the testing of SPDs? That's what we are looking at in this paper.

2 10/350 WAVEFORM:
WHAT WE THOUGHT WE KNEW

IEC 61312-1 adopted Berger's data on positively charged cloud to ground (CG) lightning as its "sole source" [1, Annex A, Sect. A1] for the values of its Class 1 test. TC 81 explained its reasons:

> *"As a first approach it is assumed that 10% of all flashes are positive and 90% are negative. Despite this low ratio of positive to negative flashes, the positive ones… determine the maximum values of the parameters I, Q and W/R to be considered* [1, Sec. 2.2 & 3.1]."

This "Berger lightning model" was subsequently imported unchanged into IEC 62305-1 as the Class I Test using the same parameters as in IEC 61623-1: Peak Current (I) =

200kA, Short Stroke Charge (Q_{short}) = 100 C Specific Energy (W/R) = 10 MJ/Ω, and Time Parameters = 10/350 [3, Table 5]. The five basic justifications which have been advanced for adopting these parameters are as follows:

- "The lightning current parameters in IEC 62305-1 standard are based on the results of the International Council on Large Electrical Systems (CIGRE) data [3, Annex A, Tables A1, A2]."
- "A polarity ratio of 10 % positive and 90 % negative flashes is assumed [3, Annex A, A2]."
- Berger's data shows that positive CG lightning flashes are characterized by much higher peak currents and far longer continuing currents than negative cloud-to ground lightning flashes. In order to protect against 99% of potential lightning flashes it is necessary to consider the parameters of … positive… lightning [4], [3, Annex A, A.3.1]."
- The high values of the positive lightning parameters are correlated: TC 81 explains: "The threat of the first return strokes mainly originates from the positive lightning having higher current peaks I_{max}, higher impulse charge (Q) and higher specific energy (W/R) compared to the negative lightning. According to the measurements of Berger, a relatively strong correlation exists between these three current parameters [7]."
- Only the spark gap type SPDs which can withstand high amplitude 10/350 waveform impulses, and pass the Class 1 Test, should be installed at the building or structure entrance [3, Sec. E.4].

3 10/350 WAVEFORM:
THE UNDERLYING FACTS

Reasonable as the above assertions appear, the facts upon which they are based do not bear up too well under scrutiny.

A) Does the data on "positive lightning" extracted from ELECTRA 41 represent the 10% of CG lightning that is positively charged?

Berger's 1975 *ELECTRA 41* article reported on the results of his research between 1963 to 1971. During that period he measured 24 lightning flashes which he was then calling positive CG lightning. Because only 4 of those 24 had any similarities to each other Berger qualified his findings concerning these 24 positive lightning flashes as follows: "Positive strokes…do not have enough common features to produce an acceptable mean current shape. This may also be due to partly to the small number of positive strokes which were recorded in the period [4, p.35]."

By 1980, Berger's continuing research had persuaded him that those 24 flashes were in fact not positive lightning at all, but rather UPWARD lighting. In *ELECTRA 69*, Anderson explained: "Berger has recently pointed out that all positive records from this station should, in fact, be classified as upward discharges [5, p.81]." He went on: "Note: the parameters of positive flashes were originally analyzed by Berger et al in 1975 (*ELECTRA 41)* – but on the assumption that these were downward flashes. In his new analysis, he has …classified all these records as upward. **In consequence, there is apparently no comprehensive source of data available on the impulse characteristics of positive downward flashes** [5, p.84]."

Rakov & Uman corroborate Anderson's data at the beginning of Chapter 5 of *Lightning: Physics and Effects*: *"*Finally, Berger and Garbagnati (1984) assigned all 67 positive flashes observed on Monte San Salvatore to the upward discharge category [8]."

So of those 24 "positive flashes" in *ELECTRA 41*, (of which only 4 had any commonalities) the number that turned out to be actual positively charged CG lightning is: ZERO.

Berger's conclusion that he was viewing mostly upward flashes is consistent with the findings of many subsequent studies at tall towers. The higher the tower, including the factor of site elevation, the greater the proportion of upward lightning flashes that will be seen there. By 500m height, there will ONLY be upward lightning. Diendorfer, in 2010, catalogued direct measurements of lightning on instrumented towers made by researchers in the United States, Italy, Russia, South Africa, Canada, Germany, Japan, Switzerland, Austria and Brazil. He concluded: "In most studies, the towers experienced predominantly upward discharges [9, p.5]."

It is correct that positive CG lightning may account for approximately 10% of all lightning [8, p. 222] and [10]. But, we must remember, Berger was registering "upward lightning" not positive CG flashes.

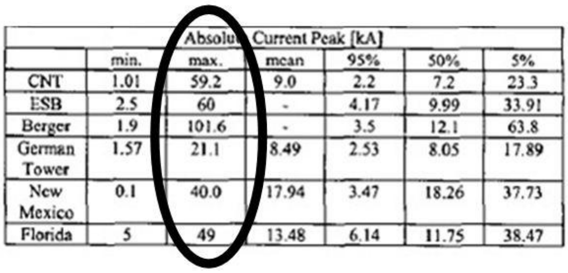
Upward lightning is actual lightning but it is rare. It is only known to exist at towers taller than 100m which can initiate upward moving leaders. The upward discharge would not occur if the tower were not there [9, p.1]. As such, it is not natural lightning. The upward lightning recorded by Berger does not represent the 10% of positive lightning that IEC 62305-1 would lead us to believe. Of the 3 billion natural lighting flashes hitting the earth each year, upward lightning accounts for less than 1/1,000th of one percent.

B) Is Berger's peak current and charge transfer data consistent with more recent studies of positive lightning?

Even though, as we have seen, Berger was not registering positive CG lightning, it is illuminating to compare his *ELECTRA 41* data with more recent studies of actual positive CG lightning.

i. Table 2 below comes from an analysis of Hussein et al 2003 [11] which compares Berger's findings on the distribution of peak currents with those of 5 more recent studies employing broad band high-resolution current measurement systems.

Table 2. Hussein et al comparisons of Berger's findings



	Absolu Current Peak [kA]					
	min.	max.	mean	95%	50%	5%
CNT	1.01	59.2	9.0	2.2	7.2	23.3
ESB	2.5	60	-	4.17	9.99	33.91
Berger	1.9	101.6	-	3.5	12.1	63.8
German Tower	1.57	21.1	8.49	2.53	8.05	17.89
New Mexico	0.1	40.0	17.94	3.47	18.26	37.73
Florida	5	49	13.48	6.14	11.75	38.47

The chart reveals the anomaly that Berger's peak current (I_{max}) data was 160% to 480% higher than any of the more recent studies with which it was compared.

ii. Berger believed and reported that positive CGs were characterized by higher peak currents than negatively charged CGs [4, Table 1].

However, when the National Lightning Detection Network (NLDN) completed its census of 60 million measured flashes, it found "for all values of Imax >75 kA, the large negative CGs outnumbered the large positive CG events by considerable margins**.** In terms of absolute numbers for all ranges of peak current>75 kA, negative CGs are clearly dominant… the largest -CG peak current found was 957 kA compared to the largest +CG Imax of 580 kA [12] and [13]."

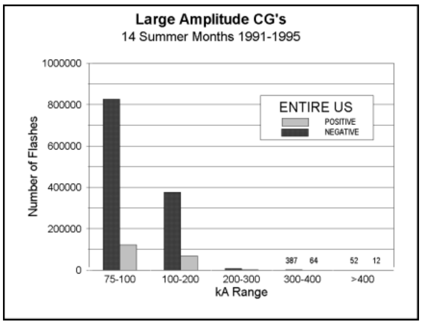


Fig. 1 – NLDN large amplitude +ve and –ve CGs

Percentage-wise, Lyons reports that 2.4% of negative CG lightning flashes have currents greater than 75kA compared with 7.4% of positive CG lightning[14]. Given existing margins of error, this may not be such a significant difference.

iii. Continuing Currents: Berger was aware of the existence of continuing currents but his equipment did not permit him to view them with much detail. He believed peak current amplitude was the most important parameter for engineering purposes[5, p.1]. More recently it has become generally accepted that it is the long duration continuing currents (associated with both positive and negative flashes) that cause lightning's large charge transfers and what is responsible for its thermal damage [8, Sec. 4.8], [15].

Interestingly, Campos et al 2008 [16] found these continuing currents to fall into 6 distinct types of current wave shapes. Type I approximates the shape implied by Berger's data—a gradually exponential decay.

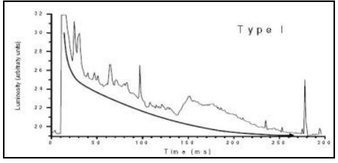


Fig. 2 Campos et al 2008 Type 1 wave shape.

Most negative flashes fall into the Type 1 category. However, 18 of the 26 **positive** cloud-to-ground lightning flashes measured clearly were of the Type II and VI varieties [16].

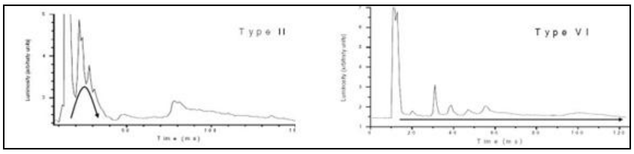


Fig. 3 Campos et al 2008 : Wave shapes Type 2 & 6.

It can be seen that the Type II and Type VI wave shapes in which over 70% of the positive flashes fell, would transfer considerably less energy than the Type 1 shape.

C) **What correlation exists between the high values of I_{max}, Q, and W/R that have been taken from *ELECTRA 41?* How likely is it for them to all appear in a single positively charged CG event?**

Since Berger was not registering positive lightning strokes, it is difficult to understand how one could make any conclusions about the correlation of positive lightning parameters from his work. Nevertheless it is interesting to take a brief look at the subject of the possible correlation between the three Test 1 parameters of I_{max} , Q, and W/R.

The view has been advanced that "According to the measurements of Berger, a relatively strong correlation exists between these three current parameters [7]."

There are published scatter plots which take Berger's peak current data, integrate it, and plot it against charge. See, for example, Figure 2 from Cooray et al [17].

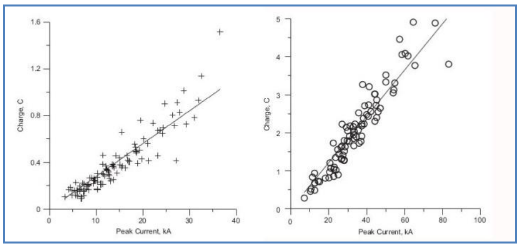


Fig 2. Scatter plots from Cooray et al [17].

The data does show a correlation, but only negative first strokes were considered by Cooray and the correlation only extends to **peak currents of 30-60kA.**

In over 8 years of recording lightning, Berger recorded only 4 or 5 lightning flashes with peak currents over 100kA. Although he originally deemed them "positive CG" lightning [4], when he later reclassified them as upward lightning [5], he effectively eliminated any legal or scientific authority for the *ELECTRA 41* "positive lightning" parameters.

In fact, there has never been a correlation between positively charged currents of 100-200 kA and charge (Q) of 100C. TC 81 understood this when they first introduced the Class I test parameters in IEC 61312-1: "In Fig. A.1 the probabilities of several lightning stroke parameters are shown**. Probabilities are substantially independent of each other** [1, Annex A]."

D) What are contemporary researchers finding?

Let's have a look at the results of contemporary researchers. How many 200kA 10/350 positive lightning flashes have been documented in the past 10 years?

- Dr. M.M.F. Saba's group has measured 3,000 lightning flashes in Brazil. Out of that set, 100 were positive and of those only 2 or three had currents as high as 100kA [18].

- Dr. A. Hussein has for over 10 years been measuring lightning at the CN Tower in Toronto using high-speed cameras. In this period he has recorded 200 lightning flashes. Of these only 2 were positive and both had peak currents under 20kA [19].

- According to its Director, the Conghua Triggered Lighting Laboratory in Guangdong, China, has never succeeded in triggering a positive CG flash [20].

- In the southeast of Brazil, the MCS Tower was built in 1985 to measure CG lightning. Pinto reports: "For positive CG flashes, the average peak current is not statistically significant due to the low number of events." [21]

- Finally, in 17 years of vigorous efforts at the International Center for Lightning Research and Testing at Camp Blanding, Florida, only 3 of the 300 flashes measured were positive flashes. All three had peak currents of only several tens of kilo amperes [22].

One might well ask: Do those 200kA 10/350 positive polarity CG lightning flashes exist anywhere else besides in lightning standards and testing laboratories?

E) Did CIGRE originate the parameters for positive lightning now known as the 10/350 waveform?

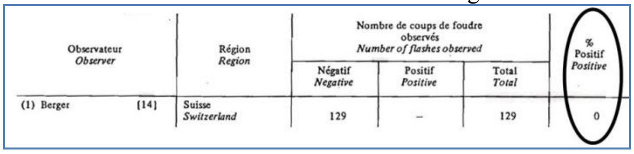
Every reference to the 10/350 waveform states "it comes from CIGRE." But does it? The CIGRE website identifies the following classes of CIGRE documents:

i. CIGRE publications (the result of the collective work of CIGRE through its Study Committees and their Working Groups and Task Forces.)
ii. Study Committee and Technical Committee papers
iii. *ELECTRA* articles whose purpose is to inform members of new publications. These are reserved for CIGRE members only… *ELECTRA* also includes "invited papers" which are not the results of CIGRE Working Groups or Study Groups [23].

The Berger paper that appeared in *ELECTRA 41* was an "invited paper" under category (iii) above. It was not the result of a CIGRE Working Group, was never issued as an official CIGRE technical report, and is not on the list of Study Group Publications published on the CIGRE website [24].

On the other hand, Anderson's article in *ELECTRA 69* was reporting the results of an authorized CIGRE Study Committee (Committee #23, Overvoltages and Insulation Coordination.) As such the *ELECTRA* 69 article **does** have the official weight of CIGRE behind it. CIGRE's views on Berger's "positive CG lightning" are quoted in full in Section 3A above, but to leave no room for misinterpretation they included the following Table 1 in their report showing the # positive CG flashes they considered to be encompassed by Berger's data: **zero** [5, p. 70].

Table 1: *ELECTRA 69* conclusion re: Berger's data



Observateur *Observer*	Région *Region*	Nombre de coups de foudre observés *Number of flashes observed*			% Positif *Positive*
		Négatif *Negative*	Positif *Positive*	Total *Total*	
(1) Berger [14]	Suisse *Switzerland*	129	–	129	0

As a consequence, the CIGRE work group was unable to tender any correlation between positive CG lightning peak current and charge (Q) in *ELECTRA 69* [5, p. 69-

71]. This tends to nullify any claims that correlated parameters of positive CG lightning “came from CIGRE.”

Please do not construe this to mean that CIGRE is ignoring this issue. The author has just attended (as an observer) the 6th meeting of CIGRE Work Group WG C4.407 “Lightning Parameters for engineering applications” held in Sapporo Japan. This work group, chaired by V. Rakov and with an international membership of 21 of the brightest stars of lightning science, was charged in 2008 with updating the lightning parameters that appeared in the earlier *ELECTRA* articles. The work group hopes to have its findings ready for release by September 2012. In its final report, new lightning parameters will be standardized, methodology clarified, and the results of recent studies compiled.

4 CONCLUSIONS

At first, it must be confronted that the Berger data, on which the 10/350 waveform is based, was not a record of positive CG lightning. As such it does not represent the 10% of natual lightning that has been alleged.

Does the 10/350 waveform exist in nature at all? And, if so, how often can it be seen? Unfortunately, there are no definitive answers to those questions.

Will the forthcoming CIGRE report to be published at the end of 2012 be able to either confirm or deny the existence of 200kA/100C positive CG lightning flashes conforming to a 10/350 waveform? Unfortunately, the answer is again negative. As shown in Section 3-D above, there is simply insufficient contemporary data of any such lightning impulses for any conclusions to be drawn. If the data doesn’t exist, it doesn’t exist.

There is some anecdotal data that might help give some perspective to this matter: The successful lightning protection experience in North America (world’s densest concentration of electrical and electronic installations) using SPDs tested with the 8/20 test waveform according to such standards as IEEE C.62.41.2-2002 [25] and FAA 419D [26] tends to suggest that the 10/350 waveform does not represent any significant percentage in the environment of actual lightning flashes.

This is not to say that the 8/20 waveform is more representative of lightning than the 10/350. Waveforms are in fact models that are not strictly reproduced in nature. These forms are used to characterize and compare products. They exist only because generators exist. The 8/20 waveform is not a more efficacious waveform for testing SPDs than a 10/350 waveform. But neither is it less efficacious.

Uman and Rakov have said it the most eloquently: “Unfortunately, lightning does not always produce waveforms similar to those specified in the standards. In fact, it may seldom do so [8, p.602].”

An effective and relevant SPD testing protocol is best not based solely on finding the “perfect” testing waveform. No single wave shape can characterize all lightning because of the myriad factors in the lightning environment that must be considered.

The stresses of multiple strikes (which can be fatal to an SPD) can now be the subject of testing. Additionally, since SPDs are designed to sacrifice themselves, standards could mandate built-in redundancy to guarantee continuity of protection of downstream equipment even after an SPD element goes into failure mode.

5 PROPOSALS

A) The IEC62305-1 lightning parameters for Type 1 Test should be limited to peak impulse current and charge transfer, but with additional specific guidance on how these two parameters are related, including selection of one or more appropriate and practical non-mandatory test waveforms.

B) The W/R parameter in the Type 1 Test should be re-examined. Although significant for the design of the conductors of a lightning protection system, when it comes to the SPDs – typically nonlinear devices – the concept of specific energy (based on a constant value of the circuit resistance) becomes less relevant.

C) The 10/350 waveform may continue to be used for testing purposes, as may the 8/20 waveform, but standards ought to clearly state that neither waveform has exclusivity, seniority, or special significance.

D) Another set of lightning parameters which may be useful are those specified in the lightning protection guides of power systems in Japan. For transmission lines: 2/70μs and 5/70μs; for substations: 1/70μs; and for transmission lines: 3.5/45 μs [27].

E) A new approach to SPD testing that would employ multiple discrete 8/20 impulses has been proposed by Yang et al [28]. Wave generators now exist which are capable of delivering up to 10 impulses with adjustable durations and intervals. These might better replicate the stresses to SPDs caused by actual lighting flashes.

F) In a surge protection system, redundancy is an obvious and effective engineering principle to guard against the consequences of SPD failures. The diagram in Fig 5 was extracted from IEC 60364-5-53 [29]. Such a design shares the current between the SPDs, permits larger peak currents to be diverted away from the equipment under test, and greatly extends the life of the individual SPDs.

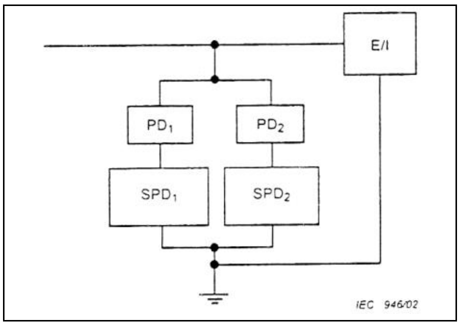


Fig. 5 taken from IEC 60364-5-53

Most importantly, if one SPD fails, there is a backup to keep the downstream electronics protected.

The proposal here is to take this concept one step further. Standards might require this design to be incorporated into individual SPDs which are to be tasked with diverting high amplitude transients away from critical loads.

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