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A call to standardize the waveforms used to test SPDs

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Abstract: This paper reviews the history of test waveforms used in SPD testing. The source of each of the major waveforms was identified as well as the technical data which supported its use. Various lightning-measurement efforts that have been undertaken around the world were surveyed to see if any parameters could be imputed to a typical lightning strike. The results show the 10/350 waveform to be an inappropriate waveform for simulating actual lightning in the laboratory.

Keywords: Class I test, SPD test waveforms, 8/20μs, 10/350μs, W/R

1. Introduction

Since the discovery of electricity, engineers and researchers have been obliged to keep themselves abreast of newly discovered knowledge impacting their disciplines. In the electronic world of 2004, this task has become more than daunting due to the sheer weight in gigabytes of newly released scientific papers.

Imagine our delight at the opportunity to present a paper that could result in the REDUCTION of this plethora of material.

For eight years a mass of articles has zipped back and forth across the Atlantic on the subject of waveforms best suited to simulate lightning in testing AC line surge-protective devices.

IEC 61643-1 established a Class I test intended to simulate partially conducted lightning current impulses. Although IEC 61643-1 nowhere mentions a 10/350 μs waveform, it uses IEC 61312-1 as its model for simulating lightning parameters and specifically references the 61312-1 test parameters as being representative of the “lightning threat.” [1] Subsequently 61643-12 (2002) reiterated those parameters mentioning the 10/350 μs wave shape by name. Because it uses the 61312-1 test parameters as a basis for its test methods, IEC 61643-1 has made the 10/350 μs the de facto waveform for its Class I tests.

The IEEE C62.45™ 2002 standard employs an 8/20 μs waveform for this purpose.

The two waveforms differ. The total amount of charge (in amperes.seconds) delivered by a laboratory-surge-generator 10/350 wave is 17 times the charge delivered by an 8/20 wave of the same peak.

All agree that lightning is one of nature’s mightiest forces. But what is the most faithful means of reproducing these forces in a laboratory? Proponents of the 10/350 waveform argue that the 10/350 waveform best simulates the parameters of a direct lightning stroke. Its detractors argue contrariwise: that 8/20 waveform testing is more than adequate as proven by the great success rate achieved by SPDs so tested.

For each of the eight years since the 10/350 waveform was introduced, acrimony has increased in a highly unscientific fashion. Our primary aim in writing this paper was to curb this controversy by adding some historical perspective to the up-to-now never-ending 10/350 debate.

2. History of waveform testing

2.1 Long duration waveforms

The 10/350 waveform was by no means the longest wave ever considered for SPD testing. There have been waveforms as long as 1,300 microseconds introduced for SPD testing.

2.1.1. 100/1300 μs waveform. In 1991 the IEC Technical Committee TC77 began considering a surge test requirement based on the scenario of current-limiting fuses clearing a fault at the end of a cable where the energy trapped in the system inductance causes a large transient at the time the fuse interrupts the current.[2] That scenario was first described and quantified by Meissen[3] and incorporated in the German standard VDE 0160.[4]

The high-energy surge test being proposed at that time was a 100/1300 µs waveform. The introduction of this new high-energy waveform was being considered solely over concerns of high-energy surges associated with current-limiting fuse operation as mentioned in the previous paragraph. There was no implication that the 1.2/50 µs and 8/20 µs impulses were in any way inadequate for simulating lightning waveforms in test methods.

Studies and experiments presented by the National Institute of Standards and Technology (NIST) at the 9th International Zurich Symposium on Electromagnetic Compatibility in 1991 [5, 6] proved the contradiction of across-the board application of a scenario limited to special cases of the German Standard and prompted the IEC TC77 to abandon this waveform in the revision of the 61000-4-1 overview.

2.1.2. 10/1000 µs waveform. A paper written in 1985 by Odenberg and Braskich reported that 90% of their 250,000 recordings showed the 50% point of surge durations to fall between 900 µs and 1000 µs.[7] That study generated talk of a "10/1000" test waveform in ac power circuits (it already was used for telecommunications components). IEEE C62.41.1TM-2002 refers to the Odenberg report as "unique among all surveys." The IEEE standard goes on to state: "Attempts to reconcile this singular finding with the observations reported by other surveys have not been successful."[8] For this reason, the 10/1000 µs waveform was not adopted as a mandatory AC line high I-peak testing waveform.

2.2 The 8/20 waveform

Traditional surge testing performed on electromechanical equipment was based on the unidirectional 1.2/50 µs impulse. This was deemed an appropriate, practical, and convenient method to generate (in the laboratory) a representation of the threat of lightning in power transmission networks. The purpose of those tests was to demonstrate the ability of high-impedance insulation to withstand a voltage stress. As a complement to these traditional tests, an 8/20 µs current waveform was defined to demonstrate the ability of low-impedance components such as surge arresters to carry the currents associated with simulated lightning discharges.[9] Application of systematic tests based on these two waveforms was a turning point in ensuring greater reliability of power systems and enjoyed broad acceptance in both IEC and ANSI/IEEE countries.

2.3 The 10/350 waveform

The 10/350 wave form gained notoriety with the introduction of the IEC 61643-1 Class I test in 1995. IEC 61343-1 Annex A p.143 gives IEC 61312-1 as the only reference for its lightning test parameters.

IEC 61312-1 asserted that the "time to half value" of a typical lightning stroke was 350 µs [10]

But upon what technical data was that 350 µs parameter based?

In IEC 61312-1, TC 81 gave as the sole basis for adopting it: "the results of CIGRE given in Electra Magazine Issue 41 (1975) and Issue 69 (1980)." [11]

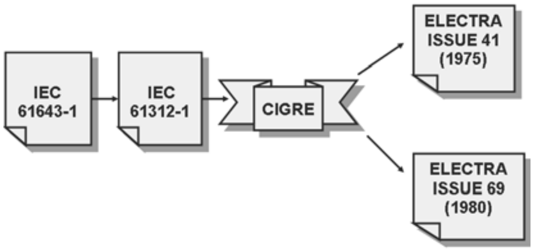

Figure 1 – Tracing back to the origin of Class I test "requirements"

What did those two Electra issues actually say? The answer to that question is both surprising and enlightening.

2.3.1 Electra Issue 69 (1980)

Electra Issue 69 published in 1980 contains an article entitled "Lightning Parameters for Engineering Application" written in by R.B. Anderson and A.J. Eriksson.[12] This article concerns itself with two important issues: (a) incidence of lightning and (b) front characteristics of lightning strokes.

Regarding impulse shape parameters, Eriksson believed he should concentrate *"mainly on the front characteristics, which are of particular importance in engineering system performance prediction studies."* [13] Regarding the shape of the tail, Eriksson notes: "*No new evaluation of the shape of the tail of lightning current impulses has been made nor of the consequent duration of strokes.*" [14]

In other words, Electra Issue 69 made no observation or contribution whatsoever concerning the duration of lightning strokes.

2.3.2 Electra Issue 41 (1975)

Electra Magazine Issue 41 included a paper entitled "Parameters of Lightning Flashes" that documented results of the lightning measurement station on Mount San Salvatore above Lake Lugano in Switzerland.[15] The Swiss author, Mr. K. Berger, had been involved with such studies for over 15 years and is a true pioneer in his field. His was the first comprehensive analysis of lightning current impulse shape characteristics. He categorized types of lightning flashes plus identified 10 parameters requiring measurement in order to better understand the phenomenon of lightning. He is responsible for many notable discoveries.

Particularly relevant to this paper is the parameter Berger termed the “Lightning stroke duration” and which he defined as: “the time interval between the 2 kA point on the front and the point on the tail where the current amplitude has fallen to 50% of its peak value.”[16]

IEC 61312-1 focused specifically on the parameters given by Berger for positive first strokes. TC81 explained their reasoning for this in Annex A of 61312-1: “*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, consisting only of a first stroke and a long duration stroke, determine the maximum values of the parameters I, Q and W/R to be considered. If according to protection level I, approximately 99% of all flashes are to be covered, the positive flashes with probabilities below 10% determine the maximum values of the peak current I, the charge of the flash Q_f, the charge of the short duration strokes Qs and the specific energy W/R. The values of the corresponding 1% of probabilities of negative flashes are much lower than the values of the 10% probabilities of the positive flashes and may be disregarded for that reason.”*.[17]

In other words, the authors of IEC 61312-1 determined that they would be “safe” if they used the parameters found by Berger to correspond to the much rarer but nominally longer positive first strokes.

In doing so IEC 61312-1 extracted what is arguably the weakest point in Berger’s study. Berger himself commented on this on p. 35 of Electra 41: “*Although positive strokes are characterized by greater charges and slower fronts than their negative counterparts, they do not have enough common features to produce an acceptable mean current shape. This may also be due partly to the small number of positive strokes which were recorded in the period. A selection of 4 of the most typical of 21 recorded curves is therefore shown in Figure 11.*” [18]

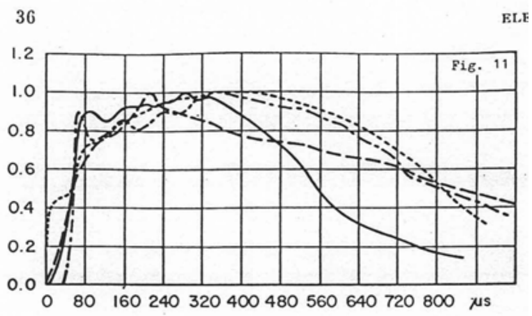

Figure 2 – Excerpt from Electra 41, Berger et al.

Thus it can be seen that IEC 61312-1 used Berger’s four recorded positive strokes as its sole source for adopting the 10/350 waveform as a representative current shape despite the fact that Berger himself had specifically argued against his research being used in that way.

Berger questioned the propriety of drawing any conclusions based on such limited data. Research since 1975 underscores Berger’s own doubts about the usefulness of his positive-first-stroke findings.

For one thing, all of the positive return strokes he documented originated from tall towers. It was subsequently discovered that return-stroke wave shapes measured on tall towers are contaminated by the reflections at both ends of the struck tower.[19]

Because all of Berger’s positive cloud-to-ground flashes originated from tall towers (and not even from any mountain peaks without tall structures) they fall under the category of “triggered” lightning, in contrast to those occurring naturally. All but one of the flashes he reported on had had an upward propagating leader followed by downward-moving return stroke. [20]

IEC 61312-1 stated that Berger’s data was representative of the 10% of naturally occurring positive first strokes, but it was not. Triggered lightning of this sort accounts for considerably less than 1% of all lightning.

3. New studies

Berger’s findings led the compilers of IEC 61312-1 to believe that the I-peak of positive (cloud to ground) return strokes was much higher than that of its negative counterparts. But 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*. “ [21] [22]

As more of the pitfalls inherent in lightning measurement were discovered, researchers became aware of the fact that waxing too enthusiastic about the results of any earlier studies of positive Cloud-to-Ground events was a mistake. "This is due to the paucity of + CG flash data, caused in part by the relative infrequency of + CG flashes and in part by the need for corroborative verification of the occurrence of each + CG flash until simpler detection techniques are proven."[23] As Orville has pointed out, "*No ground truth exists for negative flashes with peak current greater than 60 kA. In addition it should be noted that no ground truth exists for positive flashes of any current value*.".[24]

Thirty years after Berger published his results, his data were comprehensively re-analyzed and compared to three other sets of field test results.[25] Another anomaly was disclosed in results that seem to confirm long duration continuing currents obtained from single-station field-change measurements such as Berger's. "*The longer durations were obtained from single-station field-change measurements. The few streak-film and TV recordings of continuing current obtained thus far indicate that later portions of the slow field change may not always be from continuing current in the channel to ground but may be additional intra-cloud activity.*"[26]

4. Building consensus

At the beginning of this article we stated that we hoped this paper would quell the controversy surrounding this topic, not add to it.

The controversy began even before IEC 61312-1 was adopted. Attempts to forge a consensus for these parameters in the 1995 TC 81 committee resulted in only 78% of the 18 voting countries casting a positive vote for that document. (IEC documents are voted on by the participating national committees on the basis of one country, one vote.) When these lightning parameters were reissued in IEC 61312-3:(2000) the percentage dropped to 68% of 19 voting countries.[27]

IEEE C62.41.2™-2002 assessed the parameters of first stroke lightning, including the 350 µs "time to ½ peak" defined in IEC 61312 documents with the conclusion that: "*The case for "high-energy" surge requirements rests on a consensus based on limited data, a matter of some concern when comparing these "requirements" with the field performance of SPDs designed on the basis of the standards of the IEEE C62 family*."[28]

The French Lightning Protection Association points out that "*The other electrical devices in electrical installations (circuit-breakers, fuses, etc.) are not sized for the requirements corresponding to Class I tests at high amplitude. Yet destruction of these devices due to these phenomena is not observed. This tends to prove that these high 10/350 amplitudes do not exist or if so very rarely.*" The French Association concludes that it is "not reasonable" to use the 350 µs long-duration waves together with high I-peaks. They further state that "as part of the French Standard NFC 15100, Test Class I surge protectors with spark gap are not recommended."[29]

5. Lightning stroke duration

Even if the initial justification for adopting a 10/350 microsecond waveform for high I-peak AC line testing was flawed, we all know and appreciate the necessity for standards. There are recent studies which have measured the duration of direct lightning strikes and these studies have been surprisingly consistent in their findings, as summarized below:

5.1 A 5-year study by the Korea Electrical Power Corporation used an LPATS manufactured by Atmospheric Research Systems of USA. Their results found 95% of measured strokes to have a time-to-half-peak of less than 22 µs. The average time to half peak was 10.82 µs.[30]

5.2 A 3-year study in Japan found the mean value of the time to half peak of all lightning flashes recorded to be 50 µs and the longest duration 80-100 µs to occur in only 10% of all lightning flashes.[31]

5.3 The released observations of the FORTE SATELLITE (a low-earth orbit satellite carrying radio wave and optical instruments for the study of lightning) have corroborated the Japanese findings.[32]

5.4 The Western region offices of the US National Weather Service acquired lightning data through a cooperative agreement with the Bureau of Land Management in a 15-year study that ended in 1997. The results of that study showed that the nominal duration of a lightning stroke was 20 to 50 µs.[33]

5.5 A paper presented at the 10th International Symposium on High Voltage Engineering held in Montreal, Canada in 1997 reported on a seven-year study of lightning phenomena conducted by Japanese CRIEPI . Among the results was the fact that the measured pulse widths of lightning lay between 12 and 20 µs.[34]

5.6 The conclusion of the IEEE, based on a broad and exhaustive survey of testing waveforms and procedures, was issued in the IEEE Trilogy released this past year: "*The two standard waveforms recommended by IEEE Std C62.41.2-2002 are the 100kHz Ring Wave and the 1.2/50 µs-8/20 µs Combination Wave (the latter involving two waveforms, one for voltage and the other for current.)*"[35]

5. W/R parameter

Another 61643-1 lightning parameter that has questionable relevancy to SPD testing is the specific energy (W/R) parameter. Along with the 10/350 waveform, the W/R parameter was imported by IEC 61643-1 directly out of IEC 61312-1.[36] The formula is:

$$W/R = \int i^2 \, dt. \qquad (1)$$

This can be considered a significant parameter in the design of a linear (constant) resistor, such as the conductors of a lightning protection system. However, when it comes to SPDs -- typically nonlinear devices -- the concept of specific energy based on a constant value of the circuit resistance becomes irrelevant.

6. Conclusion

The results of our examination have led us to the conclusion that in this year of 2004, when IEC 61643-1 is up for review, the 10/350 µs waveform should be at the top of the list of items requiring revisiting. Moreover the irrelevant W/R parameter must be addressed at the same time. The confusion caused by its inclusion in the IEC 61643-1 table of SPD test parameters has acted as a sort of "red herring" which is one of the reasons the "10/350 controversy" has eluded resolution for so long.

The IEC 61643-1 table should be limited to the peak impulse current and charge transfer, and should be accompanied by additional specific guidance on how charge transfer is related to the peak impulse current and the particular test waveform selected among the possible representative waveforms.

Examples should be provided which show how any of the well accepted waveforms will "obtain" the stipulated charge transfer for a stipulated peak impulse. These include 4/10, 8/20, or even 10/350 so long as the latter is not construed as the default, de facto standard test waveform.

Lastly, any selected waveform should be supported by scientific evidence as well as be practical and appropriate for non-linear SPDs.

It has always been the task of technical associations such as the SEE to help circulate knowledge in the fields of electricity and electronics. We offer our results to the ICLP community in hopes that the outside world can be provided with a deeper understanding and background of how exactly these various lightning parameters were developed.

7. Acknowledgment

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