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# Extremely high lightning peak currents

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**Abstract— Lightning flashes are still a major cause of injury, fire, mechanical destruction and, above all, surges. Time and again there are reports of extremely high lightning currents which, of course, can cause considerable damage and destruction. In some cases, peak values of over 300 kA are mentioned. This throws up questions because the "classical" lightning statistics (e.g., CIGRE and IEC [9, 11]) do not recognize such values. These extreme lightning currents are, as a rule, identified using the data provided by lightning detection systems.**

**This article will examine such extreme lightning currents. The necessary fundamentals of lightning detection will be explored as well as the limits when verifying extreme values. "Classical" lightning statistics and further studies of extreme lightning currents will be discussed.**

***Keywords— Lightning peak current, lightning protection, testing***

## I. INTRODUCTION

In 2016, the local press in Essen (Germany) reported a "Mega-Blitz" (mega-lightning) [1]. The lightning location system (LLS) BLIDS (**BL**itz **I**nformations**D**ienst **S**iemens) estimated a peak current value of 405 kA (Fig. 1).


Fig. 1. Report of a "Mega-Blitz" in local media in Essen [1]

Near the small city Berching in Bavaria, a lightning flash caused a huge oak to literally burst (Fig. 2). On June 8th , 2016 BLIDS registered two almost simultaneous (time interval 2 µs!) cloud to ground lightning at exactly this point, one with a peak current of 335.1 kA and the other with a peak current of 347.3 kA [2]. The lightning discharge was a so called "cold lightning". The term "cold" is commonly used when lightning did not ignite the tree and burn it down. In cases like this, the energy of the flash and the resulting generation of heat causes that any liquid in the tree turns to vapor within just fractions of a second. One liter of water turns into 1673 liters of vapor and consequently the tree explodes.

Although two strokes have been located by BLIDS in case of the oak tree (Fig. 3), it appears that there has been a single high peak current discharge. Due to the extremely high field amplitudes, such discharges are registered by 40 or more LLS sensors (see section 2), located several hundreds of kilometers around the point of strike. Sometimes, as is seems to be the case in this particular event, the location algorithm results in two almost simultaneous discharges from the abundance of available sensor messages, although in reality there has only been one lightning event. Detailed examination of lightning strikes to trees can be found in [3].

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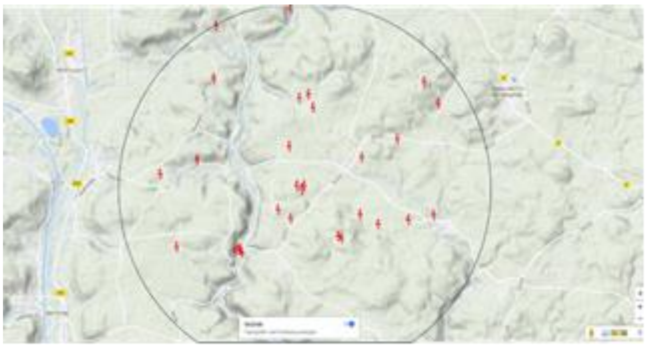
Fig. 2. Lightning strike to an oak tree near Berching [2]



| Date / time | Coordinate | Type | Current | Distance |
|---|---|---|---|---|
| 08.06.2016 08:22:55 | 11.545° / 49.140° | Earth | 335,1 kA | 0,0 km |
| 08.06.2016 08:22:55 | 11.545° / 49.141° | Cloud | -11,8 kA | 0,1 km |
| 08.06.2016 08:22:55 | 11.543° / 49.140° | Earth | 347,3 kA | 0,2 km |
| 02.07.2016 08:08:56 | 11.540° / 49.133° | Cloud | -6,1 kA | 0,9 km |
| 15.06.2016 14:06:00 | 11.536° / 49.135° | Cloud | -11,7 kA | 0,9 km |
| 15.06.2016 14:06:00 | 11.540° / 49.150° | Cloud | -6,8 kA | 1,2 km |
| 02.07.2016 08:08:57 | 11.558° / 49.128° | Cloud | -17,6 kA | 1,6 km |
| 15.06.2016 14:06:00 | 11.566° / 49.134° | Earth | 19,1 kA | 1,7 km |
| 02.07.2016 08:08:56 | 11.558° / 49.127° | Cloud | -8,7 kA | 1,7 km |
| 04.06.2016 23:28:06 | 11.567° / 49.147° | Cloud | 6,3 kA | 1,8 km |
| 08.06.2016 08:22:55 | 11.549° / 49.159° | Cloud | 15,9 kA | 2,2 km |
| 04.06.2016 23:28:06 | 11.573° / 49.131° | Cloud | 7,7 kA | 2,2 km |

Fig. 3. BLIDS lightning location system evaluation of the lightning strike to the oak tree

The above described two cases pose the question as to the extent to which such high peak current lightning bolts really exist. LLS estimated peak currents are derived based on model calculations originating from measured peak values of the electromagnetic fields. Yet the peak current values estimated in this way are used directly in scientific publications and information for the general public without mentioning the fact that they are merely the result of a model calculation and therefore subject to some degree of uncertainty:

## II. Localisation of Lightning Events with Very High Peak Current Values

### A. Fundamentals of lightning detection

LLS estimate the maximum current Imax of a discharge from the peak values $E_{max}$ or $H_{max}$ of the electromagnetic field registered by the LLS sensors. This is based on (1) resulting from the so called Transmission Line Model (TLM) [5].

$$I_{max}=(2\pi*\varepsilon_0*c^2*D)\,/v_{RS}\,*E_{max} = K * E_{max} \qquad (1)$$

The constant K can either be determined experimentally via measurements [4] or derived from the TLM assuming infinite ground conductivity. Equation (1) depends solely on the return stroke velocity $v_{RS}$ in the lightning channel which varies between 1/3 and 2/3 of the speed of light $c$. The EUCLID lightning detection system [6] (covering almost the whole of Europe up to the Russian border) assumes $v_{RS} = 1{,}2.10^8$ m/s resulting in a constant $K$=5.12 for a reference distance $D$ = 100 km when the current is given in kA, and the field strength in V/m.

Assuming infinite ground conductivity the field strength $E_{max}$ shows a 1/D distance dependency. Thus, the LLS sensors at varying distances from the point of strike register and report different peak field strengths. However, as soon as the point of strike has been identified by the detection system, the distance $D_i$ to the individual sensors involved becomes a known factor and the field strengths $E_i$ reported by the i-th sensor are normalised to the reference distance of 100 km using a simple relation

$$E_{i,100} = E_i * D_i\,/100 \qquad (2)$$

Ideally, the resulting reference field strengths $E_{i,100}$ should be the same for all sensors. In reality, there are deviations, e.g., due to field propagation over finite ground conductivity or measuring errors. In order to minimise these errors, the average value of all available $E_{i,100}$ values is applied for $E_{max}$ in (1) to estimate $I_{max}$.

The coherence between the lightning current amplitudes $I_{GB}$ measured at the Gaisberg Tower (GBT) near Salzburg and the corresponding lightning current amplitudes $I_{EUCLID}$, recorded by the EUCLID detection system is shown is Fig. 4.

The varying return stroke velocities $v_{RS}$ of the individual strokes lead to the observed dispersion of the LLS estimated amplitude values, because the LLS assumes a constant velocity of $v_{RS}$ = 1.2 108 m/s. When we draw a regression line for the full data set it almost perfectly coincides with the diagonal black line in Fig. 4. This confirms that on average the amplitudes given by the detection system are a very good method of determination. Similar results were found when comparing the amplitudes of rocket triggered lightning flashes and the NLDN (US National Lightning Detection Network) peak current data in the USA [7].

It is important to note here that, until now, the method for estimating the lightning peak currents by LLS has only been validated for negative lightning peak currents up to -40 kA. It is generally assumed that the linear relationship in (1) also applies to positive discharges and the entire amplitude range up to several 100 kA.

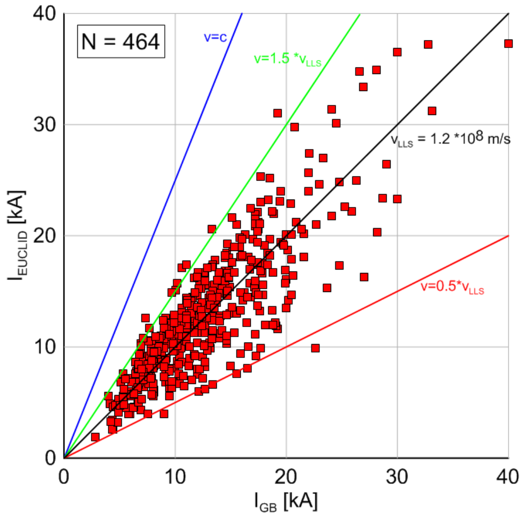



Fig. 4. Comparison of directly measured ($I_{GB}$) and LLS estimated ($I_{EUCLID}$) current amplitudes at the Gaisberg Tower (2005 – 2014). The lines represent the theoretical relationship according to the transmission line model for different return stroke velocities [6]

## B. *EUCLID detected lightning strokes with peak currents greater than 300kA*

Fig. 5 shows the frequency distribution of detected lightning strokes with estimated peak currents of >300 kA which were obtained when evaluating a time period 2014-2016 and a geographical area from 0°- 20° east and 40°- 60° north (comprising the whole of central Europe plus surrounding areas). In order to be as sure as possible that LLS estimated high peak current discharges are not the result of any detection errors when false positions result in false peak currents, this evaluation includes only lightning discharges detected by 10 or more sensors.

With a total of 1,973,704 positive and 16,110,975 negative lightning strokes in the evaluated geographical area and time period, the 1,204 positive and 1,439 negative discharges with amplitudes >300 kA constitute only a very small percentage of 0.061 % (positive) and 0.009 % (negative), respectively. It is interesting to note that the absolute numbers of detected discharges with these extreme amplitudes are in the same range for both polarities, although negative lightning is, typically much more common than positive. A detailed evaluation of high peak current (> 200 kA) lightning in Europe has been published recently [8] showing some regional and seasonal dependency of the occurrence of this high peak current events.

Fig. 6 shows the statistics for lightning currents >300kA for Germany in the year 2014. It is important to note that when estimating the peak currents from electromagnetic peak field data in individual cases (not on average) there is a degree of uncertainty which should not be ignored

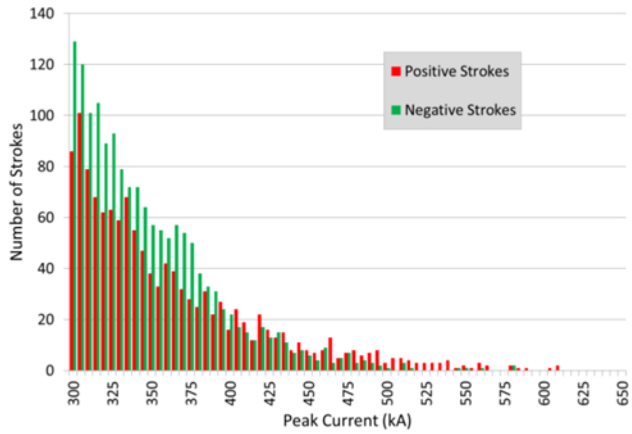



Fig. 5. Histogram of lightning detected by EUCLID with amplitudes >300 kA in the area 0°- 20° east and 40° - 60° north in the years 2014 – 2016

This also becomes clear when we take a closer look at Fig. 4: EUCLID reported amplitudes between 10 kA and 30 kA for a directly measured lightning peak current of 20 kA, depending on the actual velocity $v_{RS}$. If one assumes e.g., a conservative uncertainty of a factor of 2 for individual strokes, EUCLID estimated extreme lightning peak current with a real peak value of 300 kA would be estimated with peak current values somewhere between 150 kA and 600 kA. In a detailed analysis as performed in this paper, the lower value would then be classified as unremarkable and no longer be considered. The upper value of 600 kA, on the other hand, would massively change the case statistics, e.g. if we are looking for an upper limit for natural lightning peak currents. This is despite the fact that 600 kA is not a true measured current but the result of a significant deviation from the assumed average of the return stroke velocity $v_{RS}$ in the given case.

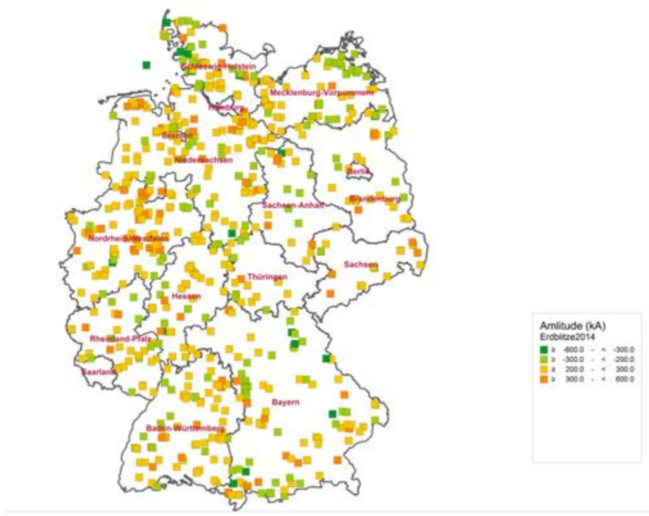


Fig. 6. Geographic distribution of lightning with peak current >300 kA in Germany in 2014

## III. Lightning Current Parameters from Measurements

### *A. Specifications according to IEC and CIGRE*

When lightning strikes a building, lightning current is injected and a lightning discharge can be regarded as an almost ideal current source. Lightning current is the cause of damage to building structures and other objects in case of a lightning strike [9]. As a result, lightning current is a primary threat and as such forms the basis for all protective measures in the lightning protection standard IEC 62305 Ed.2:2010 [10]. Current of a lightning flash can be split into individual lightning current components:

- First positive short stroke
- First negative short stroke
- Subsequent short stroke
- Long stroke.

To achieve effective lightning protection, one must consider the thermal and mechanical effects of the lightning current and the thermal and electric sparking resulting from the impulse current of a lightning discharge. The following effect parameters of lightning current are important for lightning protection technology:

- Peak current value I
- Charge $Q = \int i \, dt$
- Specific energy $W/R = \int i^2 \, dt$
- Maximum current steepness $(di/dt)_{max}$.

Depending on the discharge mechanism, one can differentiate between two basic types of ground flashes:

- Downward lightning (cloud to ground lightning): The lightning discharge is initiated by a downward propagating leader.
- Upward lightning (ground to cloud lightning): Lightning channels develop upward initiated on top of very exposed objects (towers, high-rise buildings, wind turbines, etc.).

When determining the lightning current parameters, it is important to note that the lightning occurring on flat terrain and around low building structures is almost always cloud to ground lightning.

Fig. 7 shows the statistical distribution of all relevant lightning current parameters as given in the international lightning protection standard by the IEC (International Electrotechnical Commission) and represented in IEC 62305-1 Ed.2:2010 [9, 10]. The distributions of the peak values for positive and negative first strokes have been highlighted with kilo-ampere [kA] as unit on the x axis.

These statistical distributions are based on the so-called CIGRE parameters. In a recent study, CIGRE (French: Conseil International des Grands Réseaux Électriques = International forum for large electrical networks) recommends maintaining these parameters for determining lightning as a source of interference [11].

The highest peak current values occur with positive first strokes. According to the data provided by CIGRE, the probability that impulse currents of $I_{max} > 200$ kA will occur in positive first strokes is approximately 7% [11]. In the absence of tall buildings, a positively charged downward leader is usually initiating a positive lightning flash.

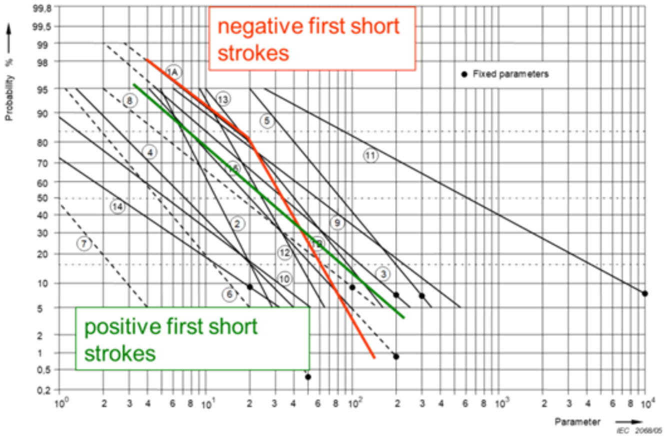



Fig. 7. Frequency distribution of lightning current parameters according to [9]

The statistical distribution of the individual lightning current parameters can be used to define different protection levels (LPL = Lightning Protection Level). The LPL is used to describe lightning effects as a source of damage. For every level, a set of maximum parameter values (sizing criteria) and minimum parameter values (interception criteria) has been specified. The maximum values of the lightning current parameters influence the dimensioning and the rating of the protective measures. The minimum values of the lightning current parameter influence the arrangement of the air-termination system used to intercept direct lightning strikes to building structures. Four different lightning protection levels (I, II, III, IV) are specified in the international and national lightning protection standards.

A lightning protection system can fail in two ways:

- The sizing efficiency documents the effective parameters for lightning current which the components of the lightning protection system can no longer withstand when exceeded and therefore they are destroyed. This occurs with very high lightning current parameters.
- The interception efficiency conveys that there is a certain percentage of natural lightning discharge which cannot be intercepted by the lightning protection system. This is defined in [9] in a simplified way as falling below certain "smallest possible" lightning current peak values. The interception efficiency of course only applies to the air-termination system of the lightning protection system.

Table I shows the maximum values of the lightning current parameters for the first positive impulse currents. They are used to size lightning protection components (e.g., conductor cross sections, current carrying capacity of surge protective devices) and to define the testing parameters for simulating lightning effects on such components. If the agreed parameter values are exceeded, it is no longer guaranteed that the lightning protection components can withstand the load undamaged.

For lightning protection level I, there is an estimated probability of 99% that the predefined maximum values (see Fig. 7) will not be exceeded. This is based on the assumption that 10 % of cloud to ground lightning flashes has positive and 90% negative polarity. This polarity ratio is assumed to be independent of the geographical location. This ratio should be used in the absence of more detailed information. Thus, the values taken from positive lightning must have a probability of less than 10 % and those from negative lightning of less than 1%. The resulting values (e.g., the above-mentioned 7% for positive impulse current) are "rounded up" conservatively.

The maximum values are reduced to 75 % for LPL II and to 50% for LPL III and IV (linear for *I*, *Q* and $(di/dt)_{max}$, but quadratic for *W/R*).

TABLE I. TEST PARAMETERS FOR FIRST POSITIVE IMPULSE CURRENTS FOR LPL I ACCORDING TO [9] WITH ACCEPTABLE TOLERANCES FOR TESTING LIGHTNING PROTECTION COMPONENTS

| Test Parameters | Unit | LPL I | Tolerance |
|---|---|---|---|
| Peak Current *I* | kA | 200 | ± 10 % |
| Charge $Q_{short}$ | C | 100 | ± 20 % |
| Specific energy *W/R* | MJ/□ | 10 | ± 35 % |

### *B. Lightning flashes with parameters exceeding the standard lightning current parameters*

In the following section we will explore and deliberate extreme lightning flashes which go beyond the specifications in [4]. Over the last few decades, it was nuclear power plants (NPP) which have invariably demonstrated the most conservative view on lightning as interference. For these critical installations the risk of a failure of their safety systems must be eliminated, even in case of a lightning flash with outstanding lightning current parameters.

The current specification of lightning parameters for German NPPs is given in the document KTA 2206:2009, Table 3.1 and Table 3.2 [12]. The lightning parameters correspond with the current parameters given in the international lightning protection standard for LPL I in IEC 62305-1 Ed.2:2010 [9], and therefore with the values in Table 1.

A previous version KTA 2206:1992 [13], in contrast, included a lightning current peak value of 500 kA. This was apparently based on a Polish publication about the measurement of a lightning current with a peak value exceeding 400 kA. This measured value was subsequently seriously doubted and could never be verified in any way. On the other hand, there were contributions to the discussion by Prof. Lundquist from Sweden and Mr Neuhaus from Germany on a existence of a "natural upper limit" being in the range of this value of 500 kA.

In contrast, the Swiss regulations for NPPs have specified a lightning peak current value of 300 kA for one of three layout lightning current waveforms [14]. This value can be traced back to a contribution by Prof. Berger from Switzerland to the discussion regarding a "natural upper limit" for lightning peak current values. Prof. Berger, a major contributor to the CIGRE specifications of lightning parameters, assessed this "natural upper limit" to be lower, presumably under consideration of the geographic conditions in Switzerland. The authors do not have any further details on this historical attempt to determine a "natural upper limit".

Up to now the highest directly measured current worldwide was registered for positive lightning during a winter storm in Japan with a charge transfer of several 100 C. Fig. 8 shows this positive lightning current of approx. 320 kA measured in a tower [15].

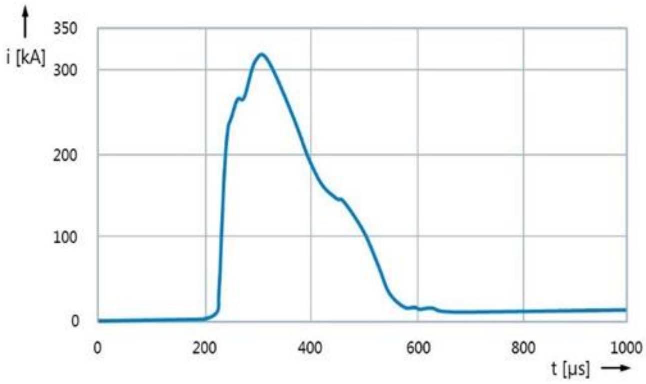



Fig. 8. Example of lightning current with peak value >300 kA according to Goto et.al. [15]

Among other things, a recent CIGRE report [11] reviewed all lightning current measurements conducted worldwide, revealing that a peak value of >300 kA[1)] for positive lightning has never been verifiably documented or confirmed by direct lightning measurements. The maximum value for negative lightning amounts to < 200 kA. In general, the study confirms that 90% of all lightning is negative and 10% positive.

The discrepancy between this value and the measurement shown in Fig. 8 with a peak value of approx. ca. 320 kA can be put down to the doubts held by the CIGRE work group with regard to the reliability of the measurement by Goto et.al. CIGRE continues to publish <300 kA as the maximum value measured. The difference is, however, not especially significant.

The values recorded for positive lightning discharges with peaks of up to approx. 300 kA were recorded, in particular, during winter storms in Japan. This appears to be the result of specific regional meteorological conditions which have now led to plans to increase in a national Japanese lightning protection standard the lightning current load for wind power plants to a higher value (apparently 282 kA). There are no intentions to increase the peak current values in other countries or in the relevant parts of the IEC standards.

The CIGRE statistics regarding the peak values of positive lightning [9] are based on just 26 lightning discharges measured by Prof. Berger [11]. An extrapolation of this parameter, which is basically presumed to be log-normal distributed, beyond the range of measured values is therefore not permissible for reasons of statistical uncertainty. Attempts to ascertain a probability of 1% or less for positive lightning discharge based on the available data soon lead to absurd physical lightning current values of >500 kA … 1000 kA.

A theoretical study [16] on the upper and lower limit for lightning peak currents gives maximum peak values for negative lightning of 450 -500 kA in the tropics and approx. 300 kA at more temperate latitudes. This involves applying the most favourable and unfavourable conditions and values to the basic physical attributes of lightning (charge density, electrical strength of the air, etc.) in order to theoretically estimate the peak values. Despite the fact that this study only deals with negative lightning discharges, it is possible to determine a plausible theoretical peak value.

Between 2013 and 2016 the German Reactor Safety Commission (RSK) also reviewed the values of extreme lightning. Taking all existing measurements, examinations and deliberations into consideration they reached the following conclusions for calculations:

- Approximately 1% of natural lightning discharges has a peak value of 200 kA or higher;
- A peak value of 300 kA is set as a realistic natural upper limit at temperate latitudes, higher values can be ruled out.

### *C. Outlook – Implementation of commercial lightning measuring systems*

Until now the validation of the peak current estimates provided by LLS has been limited to a few, academically accompanied, direct lightning measurements, e.g., on high towers or rocket-triggered lightning measuring stations. The implementation of commercial lightning current measuring systems is becoming more frequent, particularly in wind power plants [19]. Such lightning current measuring systems are capable of recording lightning currents with a maximum amplitude of at least 200 kA [20]. In near future, the increased number of measuring facilities and the resulting increased data pool should allow to verify the accuracy of LLS when recording lightning currents with very high amplitudes.

In order to keep track of confirmed measurements of extreme values of lighting current parameters an online database (http://tiny.cc/extremelightning) collecting those values worldwide was introduced in [21].

## IV. Lightning Protection with Maximum Values above Lightning Protection Level (LPL)

The 2nd version of the lightning protection standard [9] published in 2010 included additional notes on how to design lightning protection measures in case when the maximum and minimum values of the lightning current parameters are exceeding those of lightning protection level I (LPL I). The valid lightning protection regulations now specify that "more effective measures" are required to protect against lightning when the maximum and minimum values of the lightning current parameters exceed the parameters for the lightning protection level I described in the standard. These "more effective measures" should be selected and implemented on an individual basis. For example, lightning protection systems for buildings in the nuclear power sector are designed for lightning currents up to 300 kA 10/350µs [14, 17]. Such protection principles should, however, be looked at individually. Lightning current tests with impulse currents exceeding lightning protection level I, i.e. 200 kA, 10/350µs for the first positive impulse current, open up the possibility of taking an individual approach to special applications. Such analyses require an appropriately high performance test facility to simulate extremely high lightning currents [18]. Fig. 9 and 10 show the assembly and the lightning current wave forms of a lightning impulse current generator up to 400 kA, 10/350µs.

Fig. 9. Tandem pulse generator for lightning current up to 400 kA, 10/350 µs

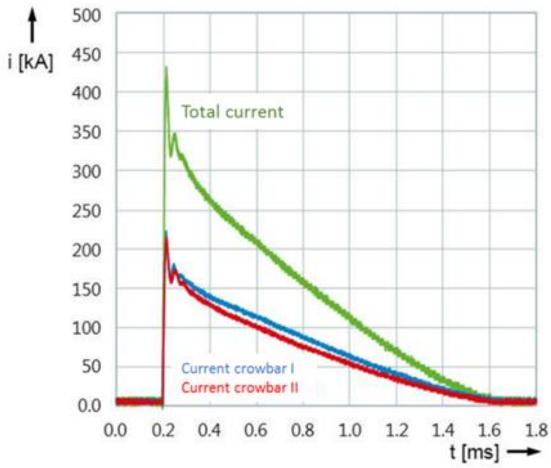



Fig. 10. Impulse current wave forms of a tandem pulse generator for a lightning current up to 400 kA, 10/350 µs

## V. Conclusions

- Lightning currents >200 kA have been measured directly and can occur.
- Lightning currents >300 kA are sometimes cited but have not yet measured directly and are therefore the result of calculations based on the data from LLS.
- The estimation of lightning currents >200 kA by LLS includes a degree of uncertainty because the model upon which it is based or the correlations between the field maxima recorded and the maximum current derived from that is not necessarily correct with these extreme values. Such correlations can, at present, only be validated up to approx. 40 kA and then only on average, never for an individual event.
- The increased implementation of lightning current measuring equipment, particularly in wind power plants, and the larger database to be expected as a result should, in future, make it possible to verify the accuracy of LLS when registering lightning currents with very high amplitudes. This observation is a topic of further studies.
- Having said that, one must assume that very high peak field values which are simultaneously reported by a multitude of sensors throughout Europe can only result from a lightning discharge with accordingly high peak current amplitude.
- Whilst lightning currents >300 kA can therefore not be completely ruled out, it is highly probable that individual cases can be explained by the tolerances involved when deriving the peak currents from the peak electromagnetic field data. The most important influencing parameter here is the return stroke velocity $v_{RS}$, which is assumed to be a constant in the calculation model, despite the fact that variable velocities with a ratio of 2:1 have been observed for real lightning discharges.
- More than 99% of all lightning discharges fall under the category of lightning currents with a peak value of less than 200 kA [9, 11].
- Lightning protection systems for a lightning peak current > 200 kA can be designed according to the standard IEC 62305 but require individual consideration, for instance, appropriate lightning current tests.

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