On the Risk of Upward Lightning Initiated from Wind Turbines

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***Abstract*—In recent years the number of wind turbines installed in Europe and other continents has increase dramatically. Appropriate lightning protection is required in order to avoid costly replacements of lightning damaged turbine blades, components of the electronic control system, and/or temporary loss of energy production. Depending on local site conditions elevated objects with heights of 100 m and more can frequently initiate upward lightning. From the 100 m high and instrumented radio tower on Gaisberg in Austria more than 50 flashes per year are initiated and measured. Also lightning location systems or video studies in Japan [1], [2] or in the US [3] show frequent occurrence of lightning initiated from wind turbines, especially during cold season. Up to now no reliable method exists to estimate the expected frequency of upward lightning for a given structure and location.**

About half of the flashes observed at the GBT are of $\mathrm{ICC_{Only}}$ type. Unfortunately this type of discharge is not detected by lightning location systems as its current waveform does not show any fast rising and high peak current pulses as typical for first or subsequent return strokes in downward lightning (cloud-to-ground). Nevertheless some of this $\mathrm{ICC_{Only}}$ type discharges transferred the highest amount of charge, exceeding the 300 C specified in IEC 62305 for lightning protection level LPL I.

Keywords*—*lightning, risk management, wind turbine, lightning current parameters, object initiated lightning, transferred charge

I. INTRODUCTION

Upward initiated lightning occurs relatively frequently when high objects such as radio towers or wind turbines are involved. The determining parameters for the initiation of upward lightning are still not completely clear and subject of ongoing research activities worldwide. Structures with heights in excess of 100 m above the surrounding terrain (like modern wind turbines) are particularly exposed to upward initiated lightning flashes.

As the initiation mechanism for upward lightning from high objects is still not understood completely, some recent studies [4], [5], [6], [7], and [8] were focused on the proportion of so called "self-initiated" and "other-triggered flashes". In case of a self-initiated upward flash, the upward propagating leader starts from the top of the object without any preceding lightning activity in the vicinity of the high object. Other-triggered flash are characterized by the initiation of the upward leader from the top of the object within a few milliseconds after the occurrence of a lightning discharge, either an intra-cloud (IC) or cloud-to-ground (CG) discharge, nearby the object. It has been observed in video studies that a single discharge to ground can simultaneously trigger upward leaders from multiple towers [3]. Often a positive discharge to ground with a high peak current value is the triggering event but there are also some indications for strong regional effects on the polarity of the triggering event [7].

IEC standard 61400-24 [9] specifies the requirements for the lightning protection of wind turbines. In this IEC standard Eq. (1) is used to estimate N_d, the average annual frequency of lightning flashes attaching to a wind turbine of given height H:

$$N_d = N_g . A_d . C_d . 10^{-6} \qquad (1)$$

where N_g is the local ground flash density in flashes/km^2 and year, A_d [m^2] is the collection area of lightning flashes to the structure, and C_d is the environmental factor.

IEC standard 61400-24 proposes $C_d = 1$ as an appropriate value for wind turbines installed on flat land and $C_d = 2$ for wind turbines on a hill or a mountain ridge. In paragraph 7.2 of IEC 61400-24 [9] it is suggested to assigned a higher environmental factor C_d when a wind turbines is placed at a location known to be very exposed to lightning in general or to winter lightning in particular, and to assign a value C_d of 3 to 5 when wind turbines are placed off-shore.

In the following section we will use the lightning observations to a 100 m high tower at the mountain Gaisberg (top is 1284 m ASL) to review the approach to obtain N_d given in this IEC standard. Although many wind turbines are installed in flat area, some are also located on mountain ridges at similar heights or even higher as the radio tower at Gaisberg. As an example at currently the highest wind park in Austria is located at

1 900 m ASL, and the highest wind park in Europe is in Switzerland at 2 350 m ALS [10]. Therefore we can assume the instrumented tower at Gaisberg to be a good representation for wind turbines of 100 m height and more and installed at exposed locations on mountain rides are mountain tops. For detailed information on the Gaisberg Tower (GBT) instrumentation and the measured lightning parameters see [11].

II. OCCURANCE FREQUENCY OF UPWARD LIGHTNING AND RISK EVALUATION

Eq.(1) is based on a probabilistic approach which assumes that downward propagating leaders occur more or less uniformly distributed over the area of interest and the striking point is defined by the so called final jump, when the connecting leader, initiated from an object, meets the downward leader. According to the so called electro-geometric model (EGM) connecting leader(s) are initiated from the grounded structures and this defines the collection area A_d. Actually the length of the connecting leader is a function of the peak current of the lightning discharge. As an approximation in lightning protection standards, the equivalent collection area A_d for isolated structures is estimated as the area enclosed with a border line obtained from the intersection between the ground surface and a straight line with a 1:3 slope which passes from the upper parts of the structure (touching it there) and rotating around it ($A_d = 9.\pi.H^2$) [9].

In the area of the Gaisberg Tower site we have determined an "background" ground flash density (GFD) of about 2 flashes per km^2 and year [12]. The background GFD is the flash density in the area excluding the upward lightning flashes initiated by the high object or in case of a wind turbine, the density in the area before one or more wind turbines were installed. Using $N_g = 2$ in Eq. (1) for a H = 100 m high tower on a mountain ($C_d = 2$) results in an estimated total number of $N_d = 1.1$ flashes per year to the object. According to Fig. 1 the annual number of flashes recorded at the GBT is ranging from 10 to 99 flashes per year with a total of 803 flashes during the 15 years period from 2000 - 2014. Therefore the mean number of recorded flashes to the GBT is about 54 flashes per year and this is about 50 times more than estimated above using Eq.(1). Although the local conditions at GBT might be not typical for wind turbine sites, but this example shows that N_d values obtained from Eq. (1) may dramatically underestimate the number of lightning flashes to elevated objects in case when upward initiated lightning is dominantly involved. More research is needed to determine the most critical parameters relevant for the initiation of upward lightning and to estimate the real risk of lightning occurrence for tall objects. Interesting approaches were done recently by several research groups (e.g. [13], [14], [15] and [16]).

This observed disagreement between Eq.(1) and the reality at the GBT is an indication that there is not a simple relationship between N_g, a value that is basically describing the average number of CG discharges, and the number of initiated upward discharges. For the number of expected upward lightning discharge from a planned and newly installed wind turbine parameters such as the height of the wind turbine, relative position (center or border area) of the turbine in case of a group of turbines in a wind park, the slope of the surrounding terrain, the cloud base height, the temperature profile in the atmosphere above the object, etc. may be of more relevance than the "background" N_g value observed before the wind turbine is built and not including any upward lightning discharges.

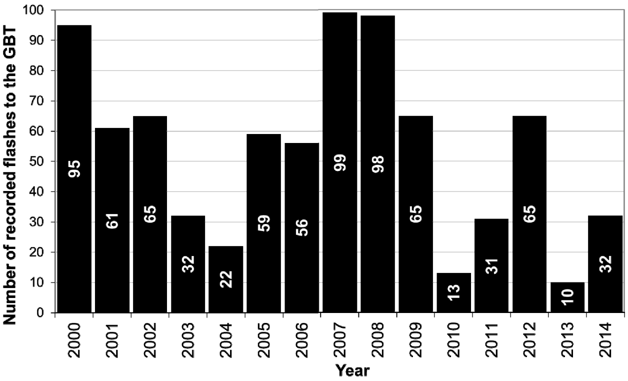


Fig. 1: Annual number of recorded flashes initiated from the Gaisberg Tower with a total of 803 flashes in 15 years

It is also worth noting that upward lightning from elevated objects often occurs at times, when there is almost no CG lightning activity in the region. At the GBT most of the upward flashes occurred during cold season in the months November and March (see Fig. 2) and distribution does not show any pronounced lightning season during the summer months.

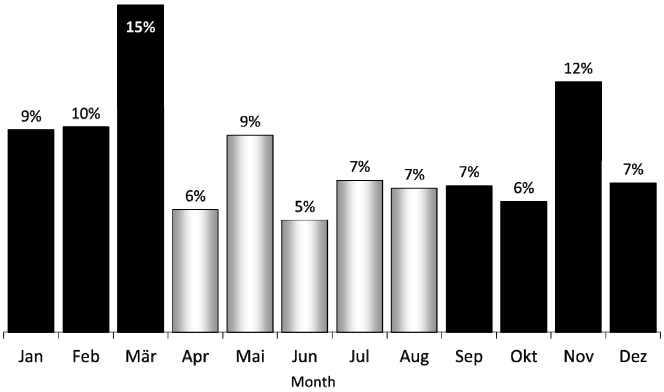


Fig. 2: Monthly occurrence of flashes initiated from the Gaisberg Tower (2000-2014). Grey shaded columns represent the convective (lightning) season in Austria

In terms of occurrence of upward lightning it is also worth noting that several flashes may be initiated from the same wind turbine or high tower within a period of hours when an electrically charged cloud is passing over the site. As mentioned before these upward initiated flashes may occur when there is no typical thunderstorm with a high number of CG lightning in the area. An example is shown in Fig. 3, when a total of 27 flashes were recorded at the GBT during a single day of March 1st, 2008. Very few discharges were detected in the surrounding area and the few ones detected are possibly initiated from other high objects too. The Austrian lightning location system ALDIS detected 70% (19/27) of the flashes to the GBT and 8 flashes were missed. The flashes not detected by ALDIS showed a pure initial continuing current that was not followed by any return strokes. The limited detectability of upward lightning by lightning location systems (LLS) is discussed in more detail in section IV of this paper. It is also worth noting that on this particular day of March 1st, 2008, the total charge transfer of three of the recorded flashes exceeded the value of 300 C, with a maximum charge transfer of 546 C obtained for a single flash. The value of Q_{Flash} = 300 C is specified in IEC 62305-1 (Table 5) for the maximum values of flash charge according to lightning protection level LPL I.

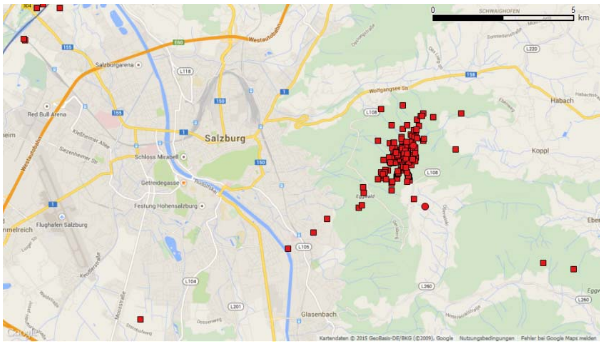


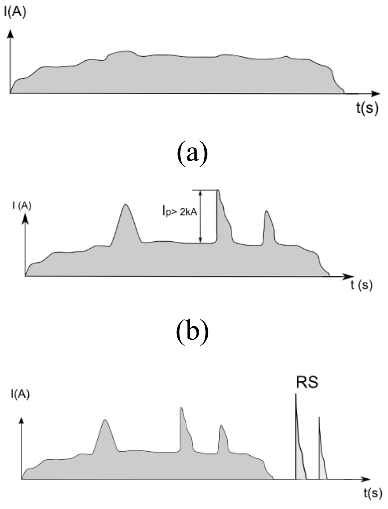
Fig. 3: Area of the city of Salzburg showing a cluster of lightning discharges at the GBT site on March, 1st 2008 and very few discharges in the surrounding area

Another day with 20 flashes recorded at the GBT within a period of about 5 hours is described in detail in [17] together with the specific meteorological conditions observed during that 5 hours period.

The flash with the highest value of transferred charge recorded at the GBT starting from the year 2000 up to now occurred on 15.10.2012 (Q_{Flash} = 783 A) and also on that particular day no other lightning activity was observed in a circular area of 20 km radius around the tower position.

III. LIGHTNING CURRENT PARAMETERS

Upward initiated lightning often shows relatively complex current waveforms. It is believed that the complexity is mainly a result of the branching of upward lightning. High speed video records reveal simultaneous or consecutive current flow in the different branches. At the attachment point, in case of wind turbines most of the times the tip of one of the rotor blades, the superposition of all these different current components is injected. Unlike in downward lightning there is always an initial continuing current, lasting for some tens to some hundreds of milliseconds with low current amplitudes in the range of some 100 A up to a few kA. Sometimes there is only this ICC current, in some cases current pulses >2 kA are superimposed on the ICC, and finally in some upward lightning the ICC, superimposed by pulses or not, is followed by one or more return strokes. The three categories of current waveforms just described are labeled in [11] as ICC_{Only}, ICC_{P}, and ICC_{RS}. Schematic drawings of these current waveforms and an example of an actually recorded ICC_{RS} type discharge at the GBT are shown in Fig. 4.



(a)

(b)

(c)

Fig. 4: Schematic current waveform of (a) ICC_{Only}, (b) ICC_{P}, and (c) ICC_{RS} type discharges observed in negative upward lightning (adapted from [11])

An example of a GBT measured current waveform of a lightning flash and one of the return strokes in that flash is shown in Fig. 5 and Fig. 6, respectively. This flash occurred in winter on Jan. 23rd, 2009 at 16:53:57. A total transferred charge of 28 As was obtained for the entire flash. The first current pulse exceeding 2 kA was classified as an ICC-pulse because it is superimposed on a low amplitude ICC current. After a period of no-current flow in the lightning channel the ICC was followed by 4 return strokes labeled RS1, RS2, RS3, and RS4 with peak currents of -13 kA, -10 kA, -12 kA, and -11 kA, respectively. In order to show the details of the ICC current waveform with amplitudes in the range of 100 A, the vertical axis in Fig. 5 is limited to current values up to -1 kA and hence all high amplitude current pules are clipped at -1 kA.

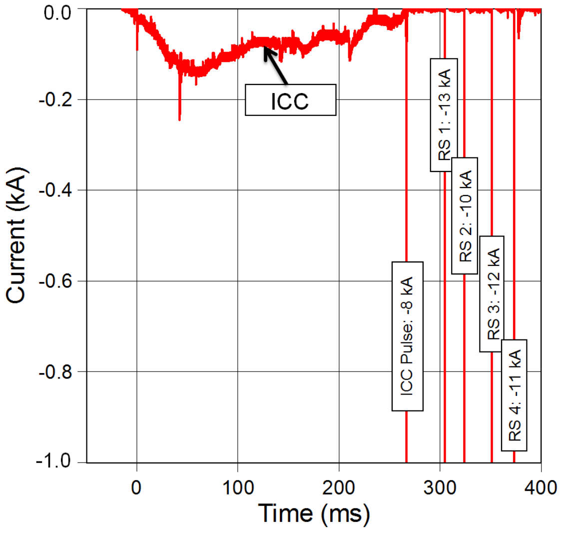


Fig. 5: Overall current waveform of an $\mathrm{ICC_{RS}}$ type upward flash with an ICC lasting for about 270 ms, one ICC pulse at the very end of the ICC, and 4 return strokes (RS1 to RS4) with peaks in the range of -10 kA to -13 kA

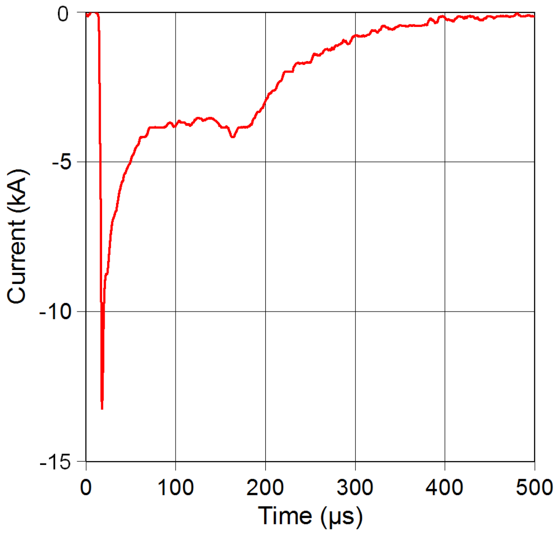


Fig. 6: Detailed current waveform of RS1 in Fig. 5 with a peak current of -13 kA

In the period from 2000-2013 a total of 713 negative upward flashes was recorded at the GBT. 32 % of them showed one or more return strokes following the ICC, 47% were of the $\mathrm{ICC_{Only}}$ type [18]. In high-speed video recordings of upward initiated lightning from towers in Brazil only 24% of the discharges showed one or more return strokes. All the flashes containing return strokes occurred during 5 out of the 23 thunderstorms that produced upward flashes [19].

IV. LLS DETECTION OF UPWARD LIGHTNING

Detectability of upward initiated lightning flashes by typical LLS differs very much from the typical performance of such systems in detecting cloud-to-ground lightning of ether positive or negative polarity. Performance characteristics of LLS to detect regular CG lightning has been validated based on ground truth data in different ways and detection efficiency is typically in the range of 87-98% for flashes, and 84-92% for individual strokes (e.g. [20],[21]).

In upward lightning the initial continuing current (ICC) is often not followed by any return strokes and it is only the return strokes, and some of the higher peak current ICC-pulses with short current risetimes, that radiate the electromagnetic field pulses typically detected by the sensors of an LLS and used to obtain a stroke location by either magnetic direction finding method, time or arrival method, or a combination of both. At the GBT only 43% of all upward initiated flashes were located by the LLS. None of the $\mathrm{ICC_{Only}}$ type discharges was detected [18].

This limitation in the detection efficiency needs to be considered whenever LLS data are requested to investigate damages of wind turbine blades that have been possibly caused by lightning. Different from CG lightning, where it is mostly the small peak current events that are not detected by a LLS the limited detection efficiency of upward lightning applies also to discharges with very high values of charge transfer. The amount of transferred charge is one of the most critical lightning current parameter determining the potential of a flash to cause severe damage to a wind turbine blade. For more details of the detectability of upward flashes see [18].

V. DISCUSSION

Wind turbines or any other elevated object of heights exceeding 100 m are potential structures to initiate upward lightning under certain meteorological conditions. Often these upward lightning is observed as relatively isolated single discharges and do not occur during typical thunderstorm conditions. With a number of lightning discharges that can be as high as several ten flashes per year, depending on the local site conditions (object height, height of the cloud base, temperature profile, etc.), proper lightning protection is a critical design requirement to these high objects. Unfortunately no reliable method is available up to now which allows an accurate estimate of the expected number of upward lightning when a new high object is erected at a given site for the first time. Further research is needed to develop such methods in order to allow cost effective lightning protection. Damages to a rotor blade may cause a downtime of a wind turbine for several weeks causing monetary losses due to the loss of energy production in addition to the maintenance or replacement costs of the turbine blade.

Some recent events of severe damage to wind turbine blades caused by lightning have shown that there is still room for improvements in the technical measures for the lightning protection of wind turbines.

Lightning parameters for protection level LPL I in IEC 62305 are assumed to be exceeded by only 2 % of the flashes. When objects like typical industrial buildings are exposed to a direct lightning strike every 10 or 20 years or even more, depending on the local ground flash density and the collection area of the building, there is a low probability that a flash exceeds the specified lightning current parameters of LPL I during the life time of the object. But when an object is hit, or better said, the object initiates lightning several ten times in a year, there is a good chance to see a flash whose lightning current parameters are outside the 98% probability range covered by the LPL I specifications.

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