LIGHTNING PROTECTION OF WIND TURBINES – A COMPARISON OF LIGHTNING DATA & IEC 61400-24
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Abstract—IEC 61400 – 24 dealing with lightning protection of wind turbines was first introduced in 2002. This was initially developed as a technical report. Since then, wind power has been rapidly developing with wind turbine manufacturers developing larger wind turbines which are at an increased risk of lightning strikes. With the move of large wind farms offshore, maintenance of wind turbines also becomes harder owing to the harsh and unpredictable environment. Limiting lightning strike damage on wind turbines becomes even more important. The IEC technical report has recently been developed into a full standard by the committee. The test levels (at which components should be tested) stated in the standard are based on those presented in IEC 62035 – Protection against Lightning. The present paper discusses the relevancy of the test levels in comparison to actual lightning strike data gathered from different wind farms of the world.

Index Terms—Lightning, wind turbine, data Analysis, high voltage and high current.

I. INTRODUCTION

Wind turbines were first introduced to generate electricity in the early 1900’s. Since then wind power has increased and is now one of the major options for renewable energy. According to the GWEC [1], there has been an increase of 27% in the total global installation capacity since 2006. The European Union continues to be the world’s strongest market for wind energy development [1]. Wind turbines continue to increase in size and are simultaneously being moved offshore as suitable onshore sites and planning constraints reduce the number of onshore projects.

Wind turbines are large structures, placed in locations where wind is abundant. They are also exposed to lightning. The high peak currents carried by lightning strikes are a source of significant energy. If a lightning protection system does not divert this lightning current safely to ground through a low impedance path, significant damage can result. Lightning can also damage equipment through the production of large induced voltages/currents as a result of the high levels of electromagnetic field produced during a lightning strike. Tall structures are more prone to lightning strikes than others, wind turbines are therefore particularly likely to be struck. Examples of surveys of wind turbine damage can be found in [2]-[4]. The importance of lightning protection to wind turbines brought forth the original IEC 61400-24 technical report in July 2002.

The trend of wind turbines increasing in size does not look likely to abate in near future thus increasing the importance of proper lightning protection measures. This and the increased knowledge gained over the last 5-6 years is one major reason for the conversion of the IEC 61400-24, from a technical report to a full standard. The original technical report introduced lightning protection methods and statistics of lightning related damage on wind turbines. The new standard, which still includes the features of the technical report introduces a new regime of testing for the wind turbine lightning protection systems. The test levels in the standard are based on those presented in the IEC 62035. The test methods have been developed with the help of existing methods used for testing of lightning protection systems in the aircraft industry.

When lightning does strike the wind turbine, the likely levels of lightning current are currently described using data captured from tall towers. This data details the lightning current levels expected in one specific environment only. The present paper is a discussion of the new standard in comparison to actual lightning strike data that has been gathered over different wind farms over the world.

II. LIGHTNING

Lightning is an atmospheric discharge of current. The highest recorded value of lightning current is around 250kA [5], [6]. However this value is very rarely seen, the median (for a downward negative stroke) being about 30kA with the median values of charge transfer and specific energy being 5.2C and 55kJ/Ω respectively [5], [6]. The visible part of the lightning strike process, whether lightning strikes the ground or not, is termed as a “lightning flash”. The individual components of this lightning flash are defined as strokes. Lightning can be classified into two main types, upward and downward initiated. These are also known by the names, cloud-to-ground and ground-to-cloud lightning. These two forms of lightning...
can be further subdivided into positive and negative polarity, the polarity being that of the charge transferred from the cloud to the ground.

A. Downward Initiated Lightning

A downward initiated lightning starts from the cloud with a stepped leader moving towards the earth. The end of the leader, the leader tip, is in excess of 10MV with respect to the earth [4]. As the tip descends, it raises the electric field strength at the surface of the earth. Where this field is elevated significantly, typically around sharp and/or tall objects, local ionization of the air takes place and answering leaders are emitted and travel towards the downward propagating leader. When an answering leader and stepped leader meet, this completes the channel or path from the cloud to earth, thus allowing the charge in the cloud to travel through the ionised channel. The location from which these answering leaders form is critical in determining which point of the wind turbine will be hit by lightning. The first transfer of significant current is the first return stroke, which has a peak value of upto a few hundred kiloamps and a typical duration of a few hundred microseconds. After a certain time interval, further strokes may follow the already ionised path, these are known as subsequent return strokes (Fig 1). On average, a negative downward lightning flash may contain 2 to 3 subsequent return strokes. Positive downward flashes (only 10% of those observed worldwide) are higher in magnitude but typically contain no subsequent strokes.

Fig. 1. Profile Downward Initiated Lightning

B. Upward Initiated Lightning

The presence of tall structures and objects brings rise to another form of lightning, which is upward initiated. Tall structures enhance the electric field produced by a thundercloud and this can give rise to upward propagating leaders that move towards the cloud and which can then develop into a lightning flash. The attachment process is therefore somewhat different to downward propagating lightning and this issue will be dealt with in a later section. This phenomenon is particularly common where the cloud height is quite low (often during winter months in coastal areas or in mountainous regions). The profile of an upward discharge is different as compared to that of a downward initiated discharge (Fig 2). An upward initiated discharge often starts with a continuing current on which may be superimposed short duration high magnitude current pulses.

Although the current values are quite low at around 10kA [4] as compared to downward lightning, the charge transfer associated with the continuing current phase can be quite high. The initial continuing current may be followed by a number of return strokes that are similar to those observed in a negative downward lightning flash.

C. Lightning Currents and Magnitudes

Lightning strikes to small towers and buildings are mostly downward initiated while those from larger structures tend to be upward initiated. According to [9] there have been a large number of instrumented towers on which lightning studies have been conducted. Research that stands out from these is the one performed by Berger at Mont San Salvatore [5] on which most of the lightning standard parameters are based. Most of the observations made on top of Mont San Salvatore are of downward initiated lightning. From Berger’s observations, the median value of the negative polarity strikes was found to be 30kA. 5% of these strikes were above 80kA. The positive strikes had a median value of 35kA and 5% of these strikes were above 250kA. Similarly, results found from Italian research stations [33] [34] gave a median of 28.4kA from 27 first strokes. Berger’s observations from Mont San Salvatore also included 135 subsequent strokes which had a median of 12kA.

In the above analysis, all the strikes were downward initiated. With increase in structure heights, the risk of upward initiated lightning increases. The effect of the structure height was investigated in [35] where 208 flashes on chimneys in Czechoslovakia where evaluated. The heights of the chimneys were divided into different groups of height. It was observed that for the negative flashes the median value of current decreased with the increase in the height.

The earliest investigation of upward initiated lightning was performed on the Empire State Building in New York. Out of the 135 strikes recorded (which include both downward and upward leaders), the median current exceeded 10kA.

Similar recordings were made on the Gaisberg Tower in Austria and Peissenberg Tower in Germany. These two towers are 100m and 160m tall respectively [9] [30] [31], thus falling in the range of modern day wind farms. For the Peissenberg
III. AN INTRODUCTION TO IEC 61400 – 24

The new IEC 61400 – 24 consists of the main informative section and new testing sections. The informative section includes information relating to the lightning phenomena and the types of lightning. The test regimes described in the standard are divided into high voltage and high current tests. The tests can be used to determine [4]:

- The location of possible leader attachment points and flashover or puncture paths on blades and non-conducting structures.
- The optimal positioning of the location of protection devices (air terminals, receptors etc)
- The likelihood of flashover or puncture paths being formed along or through dielectric surfaces.
- The performance of lightning protection devices.

The new tests in the standard have been formulated with the help of aircraft industry lightning standards [12 - 13]. The standard also introduces measures for earthing of wind turbines, information regarding personal safety and lightning exposure assessment.

The high voltage tests that have been proposed are not discussed in detail in this paper since they are used to assess the likelihood of successfully capturing the lightning strike to a preferred attachment point. What will be discussed are the current levels stipulated in the high current tests. High current tests are used to determine that a component can withstand the temperature rise, charge transfer and mechanical forces imposed on it in the event of a lightning strike. The exact test and the manner by which current is applied to a component depends on the location of that component within the wind turbine. For example, a tip receptor will be subject to arc attachment damage while the blade down-conductor would not. The current level at which a component needs to be tested is decided according to the protection level of the component. Protection levels of different components of a lightning protection system are selected according to [7]. For wind turbines, category I lightning protection is recommended in [4]. Components categorized in under lightning protection level I are tested at 200kA. This value of lightning current is based on historic data (discussed in more detail later). Too low a value set by the standard will result in an increased level of lightning damage. Too high a level will result in a design of a wind turbine that is not economic. In the next section actual levels of peak currents that do attach to wind turbine components are analyzed. The relevancy of test current levels in the IEC 61400 – 24, in accordance to actual lightning data that has been gathered over different wind farms, will be discussed in the later sections.
IV. LIGHTNING DATA SOURCES

The data set that has been analysed comes from windfarms all over the world. The database contains records of over 450 wind turbines recorded over a span of 7 years. Peak current registrations are made by the use of PCS cards. Peak current sensor (PCS) cards manufactured by OBO Bettermann are placed on the down-conductor of each of the blades and of the air terminals protecting the wind-vane. These cards have a magnetic strip imprinted with a pre-defined signal. When placed near a down conductor, the magnetic field resulting from the flow of lightning current erases a portion of this magnetic strip and by the use of a card reader, the current that the card has observed can be found [17]. The limitations and difficulties in sorting the data are

- The error margin on the PCS cards means that they fail to record small peak currents (lower than around 5kA according to the manufacturer’s specification) [17].
- The PCS cards are capable of only recording one peak current (the highest observed) and if multiple attachments are experienced by a component, it is not possible to determine the number of strikes or which strike had the higher peak current.
- The system cannot determine if one component of the wind turbine was hit before another. For example, did the initial stroke go to a blade tip and then a subsequent stroke to another component?
- This means that between the installation and replacement date of the cards (typically between 5 to 6 months) they could have been exposed to more than one lightning strike. They would only be able to record the highest peak current.

V. DATA ANALYSIS AND DISCUSSION

The data is used to examine the current levels given in the new IEC 61400-24 lightning protection standard and the magnitude of currents expected versus those observed.

A. Lighting Current Parameters and Probability Distribution

In order to compare the lightning current parameters detailed in the standard with peak currents of actual lightning strikes on wind turbines, a probability distribution of the peak currents of lightning strikes on different components is plotted in figure 3. This has been done with the help of the peak currents that have been registered on the PCS cards of each component. Examining the probabilistic distribution of lightning current values yields some interesting findings. The blades are shown to capture lightning strokes with lower peak currents in comparison to the windvane. This is something contradictory to the typical downward lightning attachment models such as the electro geometric model [23]. However, in both the cases, the median value of the peak currents lies between 6-10 kA, much less than the median values of the first return and the subsequent strokes defined in the literature for downward strokes (30kA and 12kA respectively) [9].

The large number of low peak current strikes can be explained by two factors. Firstly, there is a likelihood of increased upward lightning strikes due to large wind turbine heights. Secondly, it is possible that upward leaders forming from the wind turbine in the presence of a downward leader result in the passage of currents through the wind turbine down-conductor systems. A typical leader would contain some 45μC of charge per metre [21]. With a typical propagation speed of 1.5cm/μs, this would correlate to an average current requirement of 0.68A for propagation. A sudden collapse in the leader due to a nearby lightning strike / change in electric field could cause higher currents to flow. To produce a current of 5kA, a 100m upward leader would need to collapse in around 1μs (equivalent to 1/3rd the speed of light). A third option is also possible, namely that the standard distribution of lightning strike currents as used by the IEC standards is conservative.

Figure 3: Cumulative Probability of Peak Currents on Different Components

According to [10], the probability of the stroke current ‘$P_l$’ exceeding the stroke current $I$ (kA) is given by:

$$
P_l = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}} P, \mu
$$

(1)

where $P_l$ is the probability of exceeding a certain value of stroke current $I$ (kA).

Equation 1 can be used to verify the percentage of strokes that theoretically would exceed a certain value of peak current. This can then be compared to the real data to see if the values do coincide. Using (1) the theoretical number of strokes that would exceed a certain peak current value for the 2127 strikes observed at the worldwide windfarm data compared with those actually seen.

<table>
<thead>
<tr>
<th>Stroke Current I (kA)</th>
<th>Number of strikes exceeding I according to (1)</th>
<th>Number of strikes exceeding I according to the real lightning</th>
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<tbody>
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</table>

TABLE 1 - COMPARISON OF THEORETICAL AND OBSERVED CURRENT MAGNITUDES
From the above table a large number of the strikes from the real data set lie between 5 and 20 kA. This proportion is higher than the theoretical assessment. This coincides with the previous assumptions that a large percentage of the lightning strike data consists of low peak current strikes and that these may be upward initiated lightning.

The relevancy of the real lightning data with that of the current parameters can be done by comparing values present in the standard with those from the real lightning data. Table 2 is a comparison between the values based in the standard [4], [7] for the first stroke (positive and negative) and the subsequent stroke of a lightning flash with those found from figure 3.

**TABLE 2 - COMPARISON BETWEEN IEC LIGHTNING PARAMETERS AND REAL DATA**

<table>
<thead>
<tr>
<th>From standards</th>
<th>First Short Stroke +ve kA (50%)</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First Short Stroke –ve kA (50%)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Subsequent Negative –ve kA (50%)</td>
<td>11.8</td>
</tr>
<tr>
<td>From measurements</td>
<td>Blades kA (50%)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Windvane kA (50%)</td>
<td>7</td>
</tr>
</tbody>
</table>

The question that therefore arises here is how relevant it is to base the general lightning parameters used for design of lightning protection systems on (particularly in the case of downward lightning) a small data-set that has been gathered from a mountain which evidently is prone to a large number of strikes the nature of which appear to be strongly influenced by the mountain site itself.

**B. Comparison of Data from Lightning Cards with Models Based from Standards**

The data that has been produced from the measurements of lightning current on actual wind turbines shows lower than expected peak values of lightning current. This section examines different scenarios and computes theoretical cumulative probability distributions of lightning current based on the known capabilities of the PCS card readers and various combinations of upward / downward lightning. The simulation considered lightning striking 10,000 objects all fitted with a PCS card. For downward lightning, the probability distributions were assumed to follow those contained within the IEC guidelines [7]. For upward lightning, data detailing the cumulative distribution of lightning current observed for upward lightning strikes was considered [26]. In this analysis, the probabilistic distributions are used in combination with knowledge from the PCS card tests. The rules applied are:

- A strike of less than 5kA will be ignored on the basis it is unlikely to be detected by the PCS card system
- Strikes of over 120kA will be limited to a reading of 120kA owing to the limitation of the PCS card system
- Where multiple strikes are assumed to hit one wind turbine, the highest peak current will be stored on the PCS card

The scenarios applied were:

- Scenario 1: One first downward negative return stroke followed by two subsequent negative strokes
- Scenario 2: As for Scenario 1 but with 60% of the cards struck by an additional first downward return stroke and two subsequent strokes
- Scenario 3: A first downward negative stroke followed by two subsequent strokes, each attaching to a different location
- Scenario 4: 80 % upward initiated and 20% downward initiated strikes (subsequent strokes attaching to different locations).
- Scenario 5: 80% upward initiated and 20% downward initiated strikes all attaching to the same location

From figure 4, Scenario 4 and 5 are close matches to the real scenarios. It is accepted that an 80% probability of upward strikes is high based on the accepted equations for estimating upward lightning strike frequency probability. According to [37][9], for 80% of all strikes to be upward initiated the

<table>
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The distribution used in the IEC standards is based on measurements carried out by Berger Mont San Salvatore (Switzerland), and further analysed by Kroninger H, Anderson R.B and Eriksson A.J [5],[6],[25] The measurements were performed using two towers each 70m high and separated 400m apart. The peak of Mont San Salvatore is 915m above sea level [5]. This site was prone to upward and downward lightning as over an 8 year period [5]. 129 of these strikes have been identified as downward propagating (these being used to formulate the IEC lightning current distributions).
structure needs to be 300m. This does not compare with today’s wind turbines which stand between 100 – 150m tall. According to [37][9], for a structure of 150m tall, only 23% of all strikes are upward initiated.

Figure 4 Cumulative Probability of Assumed Scenarios

A poor match between Scenarios 1-3 and the real data could also be explained if the lightning current probability distributions recommended by IEC 62305 and largely based on the data by Berger probably being conservative. As discussed before, there are certain extreme cases where lightning strikes of very high peak currents have been noticed, for example, winter lightning in Japan. The findings of researchers investigating winter lightning data in Japan contradicts the above findings as they claim the testing parameters are too conservative although in the papers [27],[28], no evidence of these large lightning strikes to wind turbines has been given.

VI. CONCLUSION

1. By simulating different scenarios, it was observed that the lightning parameters found in probability distributions of the new IEC standard are not a perfect fit for large wind turbines.

2. Larger data sets of lightning strikes over offshore and onshore windfarms will provide a insight to defining better lightning parameters in upcoming lightning protection standards for wind turbines.

VII. REFERENCE


32. J. Montanya, Overview of Lightning in Tall Instrumented Towers.


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