Reliability Analysis of Wind Turbine Blades Considering Lightning Strike

W. Hu*, W. Zhao*, Y. Wang**, Z. Liu*, J. Tan*
*School of Mechanical Engineering, Zhejiang University, Hangzhou, P.R. China
**Department of Aerospace Engineering, Mississippi State University, Mississippi State, MS, USA
Corresponding author: W. Hu (weifeihu@zju.edu.cn)

Abstract. Lightning strike damage accounts for a significant amount of wind turbines failure. An accurate evaluation of wind turbines’ reliability considering lightning strike is thus of critical importance. This research develops two novel lightning stepped leader models considering the stochastic properties and the branching geometry of lightning. In the framework of the reliability analysis of wind turbine blades, the finite element analyses including the two new leader models are conducted and then the electric field in the wind turbine blades are studied. The results show that the branched model adds extra increment of the electric field in the wind turbine blades which is more practical for the wind turbine lightning protection, wind farm siting, and operations and maintenance of wind farms.

1. Introduction
As the wide applications of composite materials in large outdoor structures, e.g., megawatt-scale wind turbine blades, manned and unmanned aerospace structures, lightning strike damage has been drawing increased attention for safety and reliability of composite structures. For instance, the lightning strike damage accounts for 23.4% of wind turbine failure, especially for the blades, reported by the 2012 US wind energy insurance claim [1]. The lightning strike could cause serious hazards to outdoor composite structures, including rapid temperature rise, dielectric breakdown, melting or burning on the lightning attachment points, and mechanical damage due to magnetic force and acoustic shock wave [2-4]. Such severe damage occurs to blades, generators, controllers, and other components exposed to the threat of lightning strikes. Among those, the blade tends to suffer from the heaviest negative influence which includes the highest frequency of breaking down (approximately 75%), the highest maintain cost, and the longest downtime (approximately ten days per lightning incident) [5]. Therefore, careful analysis of the lightning-induced electric field in blades is excessively critical to testify the reliability of damage tolerant design. The goal of this paper is to introduce two more lightning stepped leader models based on the stochastic properties of lightning into the wind turbine lightning analysis based on former research. [2]

Developing a complete and totally accepted lightning stepped leader model is a complex task since it deals with microscale processes such as air breakdown, and macroscale processes such as leader propagation mechanisms. [6] In spite of a substantial number of studies related to [2, 4, 6-8] lightning strike damage on wind turbines, the lightning stepped leader model they used lack several significant characteristics of the natural lightning strikes. In [2] and [4], electrostatic model consists of the straight lightning stepped leader model is used to determine the electric field in the wind turbine blades. [7]
and [8] consider a notable feature of wind turbine lightning analysis that wind turbine blades are generally in a rotating state during lightning strikes, whereas, the lightning channel is still simplified as a straight-line model. Hence, to achieve a better approaching to the natural lightning strikes, more properties of lightning strikes like the random of the downward stepped leader channel should be introduced. The development of the natural lightning strike studies forms the basis of the switch from the straight-line model to the tortuous model or the branched model. On the one hand, the probability distribution of the peak current has been shown from measured data to approximately log-normal. [9, 10] As a result, the value of the peak current which obeys to the approximate distribution used in the electrostatic model can be generated randomly. On the other hand, the branching behavior of downward stepped leader in negative natural lightning has been proven through high-speed video observations in [11] and [12]. It is advisable to introduce the tortuous leader model, the branched leader model, and their stochastic features of the stepped leader propagation into wind turbine lightning analysis. Furthermore, [6] extensively presents electrostatic models of the lightning stepped leader channel for negative cloud-to-ground discharges, assuming the tortuosity or branches of the channels, which enables the calculation of electric field in the wind turbine blades. Ultimately, this paper focuses on the comparison of three aforementioned lightning stepped leader models and analyzes the change of electric field owing to these models. Moreover, a reliability analysis of wind turbine based on the uncertainty of peak current is conducted in this paper.

The rest of the paper is organized as follows. In section two, the detailed definition and generation processes of the straight lightning stepped leader model, the tortuous lightning stepped leader model, and the branched lightning stepped leader model are discussed. In section three, the electric field in wind turbine blades modeled as tapered beam-shape at different lightning protection levels (LPL) are studied. In section four, the reliability analysis of wind turbine blades considering the uncertainty of peak current is conducted. Finally, section five is the conclusion.

2. Parametric stepped leader models
A substantial number of positive charges accumulated on the ground as a result of the negative charge at the bottom of a typical thunderstorm. The electric potential between them causes a strong atmospheric electric field. As the negative charge at the bottom of the thunderstorm develops, a lightning stepped leader is formed after the appearance of the streamer charge. [13] The lightning stepped leader is a weakly luminous leader that originates from the cloud and travels through the air toward the ground prior to the formation of the first lightning return stroke [14, 15]. When the lightning stepped leader reaches within a certain distance to the wind turbines, answering leaders will be emitted from the wind turbines attempting to arrest the lightning stepped leader. Once one of the answering leaders connects with the lightning stepped leader, then the first lightning return stroke forms, producing a luminous lightning arc channel in the air.

2.1. The electrostatic approach
The charge of the downward leader induces a strong electric field on the wind turbine blades. The electric charge distributed along the lightning stepped leader is highly dependent on the peak current of the lightning return stroke. It is non-uniform and can be expressed as [13]:

\[
\rho_v(\eta) = a_0 \cdot (1 - \frac{\eta}{H-z_0}) \cdot G(z_0) \cdot I_{\text{peak}} + \frac{I_{\text{peak}}(a+b\eta)}{1+c\eta+d\eta^2} \cdot F(z_0), 0 \leq \eta \leq L, z_0 \geq 10,
\]

Where \( \rho_v(\eta) \) is the charge density (in C/m); \( \eta \) is the distance from the tip of the lightning stepped leader (in m) to the ground and \( \eta = z - z_0 \); \( H \) is the height of the cloud (typically \( H = 4,000 \) m); \( z_0 \) is the distance from the ground to the tip of the leader (in m); \( I_{\text{peak}} \) is the peak current of the return stroke (in kA); \( G(z_0) = 1 - (z_0/H) \), \( F(z_0) = 0.3a + 0.7\beta \), \( a = \exp(-((z_0-10)/75)) \), \( \beta = 1 - (z_0/H) \), \( a_0 = 1.476 \times 10^{-5} \), \( a = 4.857 \times 10^{-5} \), \( b = 3.9097 \times 10^{-6} \), \( c = 0.522 \) and \( d = 3.73 \times 10^{-3} \). The charge density modeled by Eq. (1) has found good agreement with the physical lightning strike measurements [13]. Thus, three different lightning stepped leader models with the above parameter values are used in this paper.
2.2. The generation of the downward stepped leader channel

An example of an artificial lightning arc channel produced at the High Voltage Lab at Mississippi State University is shown in Fig. 1, from which the tortuosity of the lightning arc channel can be visually observed. To account for the tortuosity of the lightning arc, geometric domains of the tortuous channel will be randomly generated following the suggestions regarding the stochastic parameters of the tortuous channel proposed by Refs. [6, 16]. The charge density in Eq. (1) will be assigned as a boundary condition to the tortuous channel domain. To generate the tortuous channel geometric domain, a spherical coordinate is used (as shown in Fig. 2). The tortuous channel is represented by multiple line segments that are connected to each other with different angle parameters. The first segment of the tortuous channel originates from the cloud and vertically propagates along the negative z-direction, where the z-direction is the reversed direction of the lightning propagation (see Fig. 2). The direction of the rest of the line segments of the tortuous channel (i.e., segments other than the first channel) is governed by two angle parameters, θ and ϕ, where θ is the azimuthal angle in the spherical coordinate and ϕ is the angle between two adjacent line segments, as shown in Fig. 2. Here, θ is uniformly distributed between 0° and 360°, allowing the channel to extend in all direction of the horizontal plane while ϕ follows a Gaussian distribution whose mean was 180° and the standard deviation is fitted in order to obtain a mean absolute value around 17° as suggested by Refs. [6, 16]. The length of each segment (hereinafter referred to as step length) is defined by ρc, which follows a uniform distribution. According to real lightning strike observations, the step length lies between 50 m and 100 m at the beginning of the stroke and gradually reduces to between 10 m and 30 m [6]. However, creating geometries with step lengths within such ranges can cause inverted cells which can easily lead to unsuccessful meshing when FEA is performed. Therefore, we amplify the step length to be between 80 m and 100 m, which partly sacrifices the fidelity but improves the success rate of the meshing. The random generation procedure of the tortuous lightning channel is terminated when the distance between the tip (i.e., the tail end) of the tortuous channel and the ground structure becomes smaller than the striking distance. More details regarding the striking distance can be found in Refs. [12, 13, 17, 18] and are omitted here for brevity.

According to the photographs and observations of natural branched channel carried by Eriksson [19], 50% of the discharges exist two or three branches, and only 12% do not show any branching. Hence, it is reasonable to add the branching property into the lightning stepped leader model construction. The branched lightning stepped leader model is developed based on the former description of the tortuous lightning stepped leader model. First, a tortuous channel generated as aforementioned is regarded as the main direction of propagation. Then branches form a bifurcation between the main tortuous channel at certain heights. According to [19], the deviation angle of the branches with respect to the main direction of propagation shows a typical branching angle of 45 degrees. After that, the generation of branches follows the same procedure as the generation of the tortuous lightning stepped leader model. In this paper, the number of branches is fixed as two. The upper bifurcation happens at the height near 2500m while the lower bifurcation occurs at the height approaching 1500m. The exact heights depend on how the main tortuous is generated which is an uncertain process. Moreover, the overall length of branches is also uncertain. We assume that the number of segments of the upper branch follows a geometric distribution whose mean is 18, while the number of segments of the lower branch obeys to a geometric distribution whose mean is 8. Noted that the assumption of the overall length of branches lacks the support of measurement or experiment. One of our future projects aims at solving this problem.

3. Modeling of the electric field in a conductive wind turbine blade due to parametric lightning stepped leader models

3.1. Problem formulation
The lightning strike electrostatic analysis models described in Section 2 are implemented using FEA with COMSOL Multiphysics. The computational domain is a square-cube with a side of 4000 m. The domain is chosen such that the full length of the lightning stepped leader and wind turbine are both included and the four vertical sides of the square-cube are far enough that their boundary condition effects are negligible.

Three different lightning stepped leader models are developed as the generation process mentioned in section two. The wind turbine is modeled as a cutout with geometries of a square-shaped tower and three tapered beam-shaped blades in the square-cube air domain (see Fig. 3-5). The dimensions of the wind turbine geometry are the same as those used in the authors’ previous work [2]. It is worth mentioning that the wind turbine is not modeled as an actual physical object in the domain, but rather a hollow part of a wind turbine geometric shape subtracted from the square-cube air domain.

The problem setup in COMSOL is shown in Fig. 3-5. Both the square-cube air domain with the wind turbine geometric cutout and the lightning stepped leader domain are assigned with the “air” material property from the COMSOL material library. The non-uniform charge density (see Eq. (1)) is assigned to the lightning stepped leader domain. Moreover, a ground boundary condition is assigned to the wind turbine cutout assembly including the tower and the three wind turbine blades to account for the electrically-conductive tower (i.e., often made of steel) and multiple conductive receptors that are embedded on the surfaces of the wind turbine blades.

The distance between the tip of the lightning stepped leader and the ground structure prior to the connection with the answering leader is called the lightning striking distance. According to the IEC 61400-24 standard [14], in the wind turbine blades longer than 20m, the lightning striking distance can be defined using the rolling sphere method. As a result, the radius of the rolling sphere attached to the ground structure is considered to be equal to the lightning distance. In the next section, the striking distance is used to define the relative position between the lightning stepped leader and the wind turbine blade. The lightning striking distance $L_s$ is a function of the peak current of the lightning return stroke and it is expressed as below [10, 13, 15]:

$$L_s = 0.6 \cdot I_{\text{peak}}^{1.46}.$$  \hspace{1cm} (2)

3.2. Estimation of electric field

After the lightning stepped leader is created and the electric charge density boundary condition is assigned, the electric and magnetic fields induced by a tortuous lightning stepped leader are solved using Maxwell’s equations:

$$\nabla \cdot \mathbf{E} = \rho_v / \varepsilon_0,$$  \hspace{1cm} (3)

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$  \hspace{1cm} (4)

$$\nabla \cdot \mathbf{B} = 0,$$  \hspace{1cm} (5)

$$\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right).$$  \hspace{1cm} (6)

where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic field tensors, $\rho_v$ is the electric charge density, $\varepsilon_0$ and $\mu_0$ are the permittivity and permeability of vacuum, respectively, and $\mathbf{J}$ is the electric current density tensor (equals zero prior to the formation of the lightning return stroke).

In the current study, we focus on the static electric field induced by a still lightning stepped leader with a non-uniform charge density at the moment when the tail end of the leader reaches within the striking distance of the composite structure. With such a simplification, the problem becomes electrostatic and only Eq. (3) will be solved. At the same time, the electric potential $V$ will be solved using the relation

$$\mathbf{E} = -\nabla V.$$  \hspace{1cm} (7)

3.3. Estimation of the dielectric breakdown strength

The dielectric breakdown strength of composite material is generally a function of the thickness, the surface tracking resistance, and other environmental factors (e.g., temperature and moisture). Under elevated temperatures, for example, the resin component in the glass fiber reinforced plastic (GFRP)
composite will decompose which can lead to mass loss, charring, and property variations of the composites. Unfortunately, the explicit dependences of the dielectric breakdown strength of the GFRP composite on the temperature and other environmental factors have not been reported to the authors’ knowledge. Hereafter the dielectric breakdown strength of the GFRP composite is considered only a function of laminate thickness $t$. For the GFRP composite material used in the composite wind turbine blade in Section 5, the dielectric breakdown strength (in V/m) is written as [20]

$$E_b = 5.3 \cdot 10^4 / t + 8.0 \cdot 10^6.$$  \hspace{1cm} (8)

where $t$ is the thickness of the laminate. Similar relationships between the dielectric breakdown strength and thickness of solid materials are suggested by the ASTM standard [21].

3.4. FEA results and discussion

In this section, the FEA of the electric field in a wind turbine blade due to three different lightning stepped leader models is conducted. Three different lightning protection level, LPL I, LPL II, and LPL III are analyzed. The LPLs represent three different lightning severity levels as identified by the IEC 61400-24 [14]. Peak current $I_{\text{peak}} = 200\text{kA}$ of the first short-duration stroke is defined as LPL I, $I_{\text{peak}} = 150\text{kA}$ and $I_{\text{peak}} = 100\text{kA}$ is classified as LPL II and LPL III, respectively. As shown in Fig. 3-5, the starting point of the lightning stepped leader models is exactly above the tip of the vertical blade OA. According to the generation steps mentioned in Section two, it is assumed that the tip of the vertical blade OA is the attachment point on the blade which will trigger an upward leader connecting with the downward leader. Therefore, the electric field on the vertical blade OA tends to be larger than the electric field on other blades, which is consistent with our former research [2]. Besides, [7] has proven that the vertical blade whose rotating angle is $0^\circ$ suffers from the highest electric field. Therefore, for the sake of safety, only electric fields on the vertical blade OA is performed by FEA.

Primarily, the influence brought from diverse lightning stepped leader models are studied at the same LPL. Fig. 6 shows the magnitude of the electric field on the vertical blade OA owing to three different lightning stepped leader models at LPL I. It shows that the magnitude of the electric field owing to the branched lightning stepped leader model is obviously larger than other models, while the magnitude of the tortuous lightning leader model and the straight lightning stepped leader is relatively similar. Such results are reasonable because both the tortuous lightning stepped leader model and the straight lightning stepped leader model ignore the branching property of lightning stepped leader and only retain its main channel. The increment of the electric field caused by branches is ignored as a result of this simplification. Even if at LPL II or LPL III, this conclusion still holds as shown in Fig. 7-8. Therefore, to guarantee the safety of the wind turbine, the branched lightning stepped leader model rather than other lightning stepped leader models should be considered when the lightning strike protection is designed.

Furthermore, the relationships between the peak current and the electric field on the vertical blade OA owing to the same lightning leader model is studied. Both the striking distance and the relative position between the wind turbine and the lightning stepped leader model influence their relationships. In this paper, the distance between the tip of the vertical blade OA and the tip of the lightning stepped leader model is defined as the striking distance. Meanwhile, the lightning stepped leader model is placed exactly above the wind turbine. Under such circumstances, Fig. 9-11 shows how the magnitude of the electric field changes when at different LPLs. It can be seen that the electric field on the vertical blade OA corresponding to the higher LPL is smaller than that corresponding to the lower LPL. This phenomenon can be explained by checking the equation (2). When the magnitude of the peak current increases, the electric field should be larger as the energy associated with the lightning stepped leader model increases. On the contrary, when the peak current increases, the striking distance correspondingly increases, which makes it more difficult to establish the connecting leader. Since the reduction of the electric field caused by the striking distance’s increment dominates the change of the overall electric field, the magnitude of the electric field decreases. Moreover, such results may differ when the equation of the striking distance is changed. As in the former research [2], only at the tip of blade OA, the magnitude of the electric field corresponding to LPL I is considerably lower than that
corresponding to LPL II. Because at the same LPL, the striking distance equation used in this paper leads to the larger striking distance.

4. Reliability analysis considering the uncertainty of peak current

In this section, the reliability analysis of the wind turbine blade OA considering the uncertainty of the peak current is conducted. All three lightning stepped leader models are applied. Due to the stochastic nature of the lightning strike discharge, the energy associated with the lightning stepped leader is stochastic. The lightning strike current is the dominant factor accounting for the total energy associated with the lightning stepped leader, which is characterized by a rapid rise to the peak, $I_{\text{peak}}$, within a few microseconds and then slowly decays, reaching half of the peak value in tens of microseconds. Accounting for the uncertainty of the peak current, and hence the uncertainty of energy associated with the lightning stepped leader is crucial for determining the safety margins for reliability analysis of the outdoor composite structures. Although the lightning and the value of its peak current is random in nature, the probability function of some lightning parameters, including the peak current, have been shown from the measured data of real lightning discharges as to follow the log-normal distribution \[9, 10\] The median value and the standard deviation of the peak current of the first negative return stroke suggested by Chowdhuri et al. are 31 kA and 0.48, respectively \[10\]

Some of these cases may fail because of two main reasons. For the tortuous lightning leader model and the branched lightning stepped model, some cases may fail the terminating requirement aforementioned in Section 2.2. These cases should be regarded as invalid because the connecting leader is not formed successfully. Besides, models solved through FEA sometimes exist mesh problems. The probability of infeasible mesh becomes larger when the complexity of the lightning stepped leader model increases. Ultimately, the magnitude of the electric field on the vertical blade is obtained by performing the lightning strike electrostatic analysis described in Section 3. To account for the uncertain peak current, a total of 1000 simulation cases for each lightning stepped leader model are performed using different values of the $I_{\text{peak}}$ generated from the log-normal distribution. During the simulation, the tortuous lightning channel and the branched lightning channel is automatically generated in the computational domain using COMSOL (see Fig. 3-5). Among 1000 cases, the total number of valid cases for the straight model, the tortuous model, and the branched model is 1000, 387, and 41 respectively. Then, the mean of the electric field in all valid cases is obtained, as shown in Fig. 12. The results illustrate that the average electric field induced by the branched lightning stepped leader model is the largest, which is consistent with the conclusion in Section 3.4. Moreover, the safety ratio which is equal to the ratio between dielectric breakdown strength and the average electric field is obtained as shown in Fig. 13. The safety ratio has a sharp decline as the distance from the root to the tip increases. Fig. 13 shows that for the wind turbine blade, the most vulnerable are to lightning strikes is within the 3 m region from the tip. Hence, it is recommended that extra lightning protection should be placed within this range.

5. Conclusion

In this paper, the detailed generation processes of three lightning stepped leader models considering their stochastic nature are introduced. Then, the calculation of the electric field on the wind turbine blade owing to diverse lightning stepped leader models is conducted. The relationships between the electric field on the vertical blade and the types of the lightning stepped leader model are studied. The result shows that the electric field on the vertical blade induced by the branched lightning stepped leader model is the largest since it considers the increment of the electric field caused by branches. Additionally, the change of the electric field on the vertical blade at three different LPLs owing to the same lightning stepped leader model is investigated. Under certain conditions that the lightning stepped leader model is placed above the wind turbine and the striking distance is calculated through equation (2), it is concluded that the magnitude of the electric field decreases as the peak current increases associated with the increment of the striking distance. Lastly, the reliability analysis using three different lighting stepped leader models is conducted. To reflect the true naturalness of lightning...
phenomena, the parametric lightning stepped leader model is controlled by three random parameters, the azimuthal angle, the angle between two adjacent line segments, and the segment length, which follows a uniform distribution, a Gaussian distribution, and another uniform distribution, respectively. In addition, the peak current of the lightning discharge follows a log-normal distribution. As a result, the uncertain and stochastic nature of the lightning is comprehensively represented. After that, the electric field strength, which is obtained by solving Maxwell’s equations for electrostatics, is compared with the dielectric breakdown strength of the composite structure to estimate the occurrence of dielectric breakdown damage and determine the lightning safety ratio. The results show that the safety factor calculated through the branched lightning stepped leader model is the smallest and the tip of the wind turbine’s blade tends to have the lowest safety factor. Therefore, when the damage tolerant design of the wind turbine blade is designed, the branched lightning stepped leader model should be applied and the tip of the vertical blade should be paid extra attention.

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Fig. 1. A photo of a tortuous artificial lightning strike electric arc channel. Courtesy of the High Voltage Laboratory at Mississippi State University.
Fig. 2. Generation of the tortuous lightning stepped leader in spherical coordinates.
Fig. 3. Problem setup in COMSOL Multiphysics for calculating the electric field induced by the straight lightning stepped leader.
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Fig. 12 The average magnitude of electric field on the blade OA induced by three different lightning stepped leader model considering the uncertainty of the peak current.
Fig. 13 The average safety factor on the blade OA induced by three different lightning stepped leader model considering the uncertainty of the peak current.