Abstract: Lightning strikes that directly hit the wind turbine will probably attach to the blade could cause excess structural damage. The blade and hub usually represent around one fourth of the cost of a large modern machine and may be the most expensive components to replace. The blade is not only the link between wind energy and the mechanical energy going to the gearbox, but could be a lightning link to all the equipment associated with the wind turbine.

In this paper a model of lightning channel progression towards the earth is given based on physics of discharge of cloud. The physical assessment of the electric field is done with the charge simulation method which is adopted to describe into MATLAB software the parameters which are involved in the progression of the negative downward channels towards the earth and in the inception and propagation of upward positive channels from earthed structures. The method and results can be used for designing lightning protection system of wind turbine.

Keywords: Lightning, Wind turbine, Protection, Channel modeling.

1. Introduction
Placing a generator on top of tower will increase the chance of lightning damage to the generator and its control components. Generating equipment normally used by utilities is located close to ground level. Its location within a shelter gives it protection not available to generating equipment located up to 100 meters above the terrain [1]. Methods for lightning protection of tall structures are well documented in standards such as IEC-1024 and NFPA-780. The application of these standards to structure such as telecommunications tower is relatively straightforward [2].

The largest modern wind turbines have a rated power in the order of 1 MW to 2 MW. A typical windmill height is in the range of 50 m to 100 m and the length of one blade is approximately 30 m [3]. The large size and the placement of wind turbines in often isolated, mountainous conditions means that they are vulnerable to lightning flashes. Should lightning damage a wind turbine, production will be lost and expensive repairs may have to be carried out [3,4]. Standard lightning protection techniques such as shield wires can not be used to protect a wind turbine owing to the nature of the construction and the physical size [1,2,3,5,6]. The common methodology for protection proposed of wind turbine is based on IEC-61312 [3]. Up to now, the design of the lightning protection of wind turbines have been faced using the rolling sphere method.

In this paper a new approach to lightning protection of wind turbines is proposed based on the leader progression model, with aid of charge simulation method (CSM).

2. Charge Simulation Method
CSM is based on the principle that the surface charges on the electrodes or dielectric interface are replaced by a set of simulation charges located outside the field domain or on the boundary. The position and type of these simulation charges are predetermined, the magnitude is unknown. These magnitudes of the simulation charge have to be calculated so that their integrated effect satisfies the boundary conditions exactly at a selected number of collocation points [8,9]. If several dielectric charges of any type (point, line, or ring, for instance) are present in a region, the electrostatic potential at any point can be found by summation of the potentials resulting from the individual charges as long
as the point does not reside on any one of the charges. Let \( n \) be a number of \( n \) individual charges and \( \Phi \) be the potential at any point \( i \) with \( i \) in the space. According to super position principal:

\[
\Phi_i = \sum_{j=1}^{n} P_{ij}Q_j
\]  

(1)

Where \( P_{ij} \) are the potential coefficients which can be evaluated analytically for many types of charges by solving laplace or poisson’s equations. For example in figure 1 which displays three point charge \( Q_1, Q_2 \) and \( Q_3 \) in free space, the potential \( \Phi_i \) at point \( C_1 \) is given by [9]:

\[
\Phi_i = \frac{Q_1}{4\pi\epsilon_0 R_1} + \frac{Q_2}{4\pi\epsilon_0 R_2} + \frac{Q_3}{4\pi\epsilon_0 R_3} = P_{i1}Q_1 + P_{i2}Q_2 + P_{i3}Q_3
\]  

(2)

Thus, once the types of charges and their locations are defined, it is possible to relate \( \Phi_i \) and \( Q_j \) quantitatively at any boundary point. In the CSM, the simulation charges are placed outside the space where the field solution is desired (or inside any equipotential surface such as metal electrodes). If the boundary point \( C_1 \) is located on the surface of a conductor, then \( \Phi_i \) at this contour point is equal to the conductor potential \( \Phi_C \). When this procedure is applied to \( n \) contour points; it leads to the following system of \( n \) linear equation for \( n \) unknown charges.

\[
\begin{bmatrix}
P_{11} & \ldots & P_{1n} & Q_1 \\
\vdots & \ddots & \vdots & \vdots \\
P_{n1} & \ldots & P_{nn} & Q_n
\end{bmatrix}
\begin{bmatrix}
\Phi_1 \\
\Phi_2 \\
\vdots \\
\Phi_n
\end{bmatrix}
= 
\begin{bmatrix}
\Phi_i \\
\Phi_i \\
\vdots \\
\Phi_i
\end{bmatrix}
\]  

(3)

Equation (3) is the basic foundation of the CSM.

The elements of the \((n \times n)\) matrix \([P]\) depend on the type and the position of the charge. The vector \([\Phi]\) contains the potential of the collocation points on the boundaries. After the solution of the equation system for unknown magnitudes of the charges one must check whether the calculated simulation charges fit the boundary conditions. If this check is sufficient then the potential \( \Phi_i \) and the field strength \( E_i \) in any point \( C_i(x,y,z) \) in the field domain can be calculated by means of analytical expressions.

\[
\Phi_i(x,y,z) = \sum_{j=1}^{n} P_{ij}(x,y,z)Q_j
\]  

(4)

\[
E_i(x,y,z) = -\sum_{j=1}^{n} (\nabla P_{ij}(x,y,z))Q_j
\]  

(5)

### 2.1. Multi-Dielectric Systems

A multi dielectric arrangement should be divided into regions. Each region is homogeneous with regard to its material properties; i.e. it consists of only one dielectric. For the collocation points placed on the region boundaries (fig.2), the discrete charges are simulated as follow [8].

1- For each point on the electrode surface one charge is placed in front of the adjacent region.
2- For each point on the interface between regions two charges are placed in front of the interface, each on the opposite side.

The number of unknown charge values match the number of equations when taking into account that for the interface between two regions \( R_i \) and \( R_k \), the following two conditions must be fulfilled:

1. The continuity of the potential
   \[
   \Phi_i = \Phi_k
   \]  

(6)

2. The relation of the normal field strength components:
   \[
   \varepsilon_i E_{ni} = \varepsilon_k E_{nk}
   \]  

(7)

Fig. 1: Three points charges in free space

Fig. 2: Charge simulation in a model arrangement with multi dielectric [8]
2.2. Complex charge configurations

The use of complex charge configurations can be recommended for following cases:
1. To reduce the number of simulation charges and thus the system size of simultaneous equations [10,11].
3. To compute fields in multi dielectric systems [11,13].
5. To model electrodes with sharp points [13,14].

3. Leader progression Model

Up to now, the design of lightning protection of wind turbine have been faced using rolling sphere method [5,6]. In the following a new approach is proposed based on the knowledge of the physics of the discharge. The approach is based on the idea that a substantial similarity exists between lightning phenomena and discharges in large air gap [15,16,17]. The proposed model takes care of the involved phenomena mainly the propagation of downward leaders and the inception and propagation of upward leaders from earthed structures.

3.1. Model Explanation

The computer can be used to simulate the propagation of lightning and the striking process step by step. The simulation starts with the vertical straight section of the leader discharge developed up to a level which is high enough to nullify the influences of the earth objects. Because an object standing alone on the earth causes a distortion of the field only up to the level of double its height, the starting point of the simulation must be above this level.

Along the leader channel an equally distributed charge is considered. Some models take a concentrated charge at the bottom of the channel, or a downwardly increasing charge distribution is assumed. The charge in the channel produces an electric field which has its highest intensity near the bottom. The propagation is represented by equal steps with a length of 10 or 20 m [7]. Its direction is that in which the potential gradient is a maximum. Fig. 3(a) illustrates the start and the potential on a circle with a radius equal to the step. Here the potential is always negative, like that at the end of the channel. The difference is highest in the direction in which the potential on the circle reaches its smallest negative value. According to fig. 3(a), this point is in the middle and so the step goes vertically down, as shown in fig. 3(b). Fig. 3(c) illustrates such a case when an earth object modifies the field so that the highest potential difference comes into being to one side and the next step turns away from the vertical.

Fig.3: Phases of propagation of the leader

The computer simulation proceeds in the following way. The path leader is divided into sections with the length of a step (10 to 20m). The charge of each section produces potential expresses by [7]:

\[ U = \frac{Q}{8\pi \varepsilon_0 l} \ln \frac{z + I + \sqrt{r^2 + (z + I)^2}}{z - I + \sqrt{r^2 + (z - I)^2}} \]  

in which,
\( Q \) is the total charge of a section.
\( \varepsilon_0 \) is the permittivity of the air.
\( z \) is vertical distance of middle point of the charge section from the point that field is computed.
\( r \) is the radial distance from charge section.
\( 2l \) is section length

With application of (8) the potential along the circle can be calculated and the maximum of the gradient can be determined. If the maximum is known the computer creates the next section of the leader channel. The field should then be calculated on the circle constructed around the end of the new section, and the cycle begins again.

An earthed object modifies the field because on its surface the potential is zero. The influence of the protection tower can be regarded with a charge distributed along the axis the resulting potential on the surface become zero.

Under the effect of the object the path of the leader turns away to a small degree only from the vertical [7,15,16,18]. Concerning the striking process, the field at the top of the object is of great importance because the start of a connection leader is dependent on it. On the top of an object there are always sharp-pointed structures on which a corona discharge appears but this is not a connecting leader [7]. It comes into being only if the potential gradient is high enough over a large dis-
tance. Laboratory experiments indicated an average field gradient of 500-600 kV/m in a distance of at least 5...10 meters is required to turn the corona discharge into a connecting leader. The computer simulation must also check the potential on a circle around the top of the objects. If the highest potential gradient exceeds the critical value in a particular direction then a section of the connecting leader has to be created. The charge on this section has a value at which the potential becomes zero at its top. This procedure must be set into the cycle of propagation of the leader and so the connecting leader increase stepwise.

4. Simulation Results
The application of the above described computerized method to a 50 meter windmill with protection tower of different height placed at different distance from wind-mill is presented.

Figure 4: shows the configuration of wind plant.

In this simulation; blades, tower of turbine, nacelle, protection tower, cloud, downward and upward leaders simulated with different kind of charges.

Figure 5 shows the simulation result for lightning stroke trace for H=50m and D=40m, leader starting point is over the windmill.

Figure 6 shows the simulation result for lightning stroke trace for H=50m and D=80m, leader starting point is over the windmill.

Figure 7 shows the simulation result for lightning stroke trace for H=60m and D=80m, leader starting point is over the midle of D.
Fig. 7: Simulation result for lightning stroke trace for H=60m and D=80m, leader starting point is over the middle of D

Figure 8 shows the simulation result for lightning stroke trace for H=60m and D=80m, leader starting point is over the windmill.

5. Laboratory Test Results

In order to simulate the behavior of protection tower in high voltage laboratory a windmill is constructed with scale of  and a protection tower as well with following specification.
windmill height = 40 cm
protection tower height = 48
The test set up is arranged as figure 9.

Fig. 8: Simulation result for lightning stroke trace for H=60m and D=80m, leader starting point is over the windmill

Fig. 9: Laboratory set up for test

An impulse generator is connected to leader (metal rod). For different values of D2, an impulse with amplitude of V50% of the gap distance between leader and protection tower is applied to the leader. During application of impulse it is checked for striking point. The results is shown in table 1.

6. Discussion

In the present paper figures 5 and 6 show the leader path for windmill and protection tower of same height. In figure 5 striking point is on the protection tower, but in the figure 6 the distance between protection tower and windmill (D) increased, therefore leader path and striking point is changed, the windmill is stroke by lightning. In figure 8 the distance (D) is the same as figure 6, but H is higher than windmill height. Therefore according to figure 8 the protection tower is doing the job.

7. Conclusions

In this paper a new approach to lightning protection of windmill is presented. A model of lightning stroke to windmill plant is introduced with reference to previous works. The model based on leader progression takes into account the main stages of the phenomenon. Various physical elements such as cloud charge, leader channel, windmill, protection tower, etc. are considered. With the aid of CSM for different configuration of windmill plant computation carried out and the direction of propagation of the leaders has been determined. Conventional lightning protection that are using in
windmill is:
1-Lightning conductors are fitted on the blade, hub, nacelle cover and tower for leading the lightning current to ground.
2- small rod (much smaller that blade height) is fitted on the back of nacelle structure.
Conventional lightning method is not diverting the lightning from windmill, it means the stroke lightning is led by conventional protection.
This paper method can be used to design lightning protection system for windmill plant by changing the height of protection tower and its position, inorder to find the proper height and position of protection tower for protecting the windmill against lightning stroke. Already lightning conductors are used in conventional windmill, by using protection tower (this paper method, that is not so expensive with compare to price of windmill) together with conventional method the safety of windmill will be garenteed.

8. List of symbols and abbreviation
8.1. Symbols
- $C_i$: contour point i
- $\Phi_i$: potential at contour point i
- $Q_i$: charges
- $P_i$: potential coefficients
- $[\Phi]$ vector contains the potential of contour points
- $[P]$ vector contains the potential coefficients
- $E_i$: field strength at contour point i
- $R_i$: Region
- $R_k$: Region 2
- $\Phi_i$: interference potential on region
- $\Phi_k$: interference potential on region
- $\epsilon_i$: permitivity of region
- $\epsilon_k$: permitivity of region
- $E_{mi}$: normal field strength of region
- $E_{nu}$: normal field strength of region
- $U$: potential produces by each section of leader
- $Q$: total charge of a leader section.
- $\epsilon_a$: permitivity of the air.
- $z$: vertical distance of middle point of the charge section from the point that field is computed.
- $r$: radial distance from charge section.
- $2l$: leader section length

8.2. Abbreviation
- CSM: Charge simulation method

References

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Table 1: Results of test on laboratory set up