Electrical Power and Energy Systems 101 (2018) 429–438

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

An improved approach for modeling lightning transients of wind turbines

Zhang Xiaoqing[a], Zhang Yongzheng[b], Xiao Xiang[a,*]

[a] School of Electrical Engineering, Beijing Jiaotong University, Beijing, China
[b] Global Energy Interconnection Research Institute, Beijing, China

ARTICLE INFO

Keywords:
Lightning
Wind turbine
Transient modeling
Multiconductor system
Circuit model

ABSTRACT

A modeling approach is proposed in this paper for calculating lightning transient responses on wind turbines (WTs). The equivalent circuits are built for blade, dynamic contact part, tower body and grounding system, respectively. The improved tower model discretizes the tower body into a truncated pyramid multiconductor system and can describe the geometrical feature of the actual tower body in a more precise manner. An entire circuit representation is given for the WT by connecting the respective equivalent circuits, from which the lightning transient responses can be obtained. The experimental measurement is also made with a laboratory-scale WT. The validity of the proposed approach is checked by comparing the calculated results with the measured ones. Then, the proposed approach is applied to the lightning transient calculation of an actual WT with 2 MW to predict its potential rise during lightning stroke.

1. Introduction

Wind turbines (WTs) are normally located in the opened and exposed areas. Owing to the tall structures, modern multi-megawatt WTs are especially prone to lightning strikes. When a WT is struck by lightning, a high lightning current flows from the attachment point to the grounding system and can cause a severe damage to the blade material and WT components. As wind power generation undergoes rapid growth, lightning protection of WTs has become a critical aspect for safety and reliability of wind power systems. Determination of the lightning transient responses can provide a valuable support for a proper design of the protection system. In order to analyze the lightning transient behavior of WTs, a number of modeling approaches have been presented in literature [1–6]. A realistic model has also been developed for numerically simulating the fast transient phenomena in the grounding grids of power systems [7], which can provide a valuable reference for lightning transient calculation of WTs. As far as the previous approaches are concerned, the imperfection arises mainly in transient modeling of the tower body, namely the longest lightning current path on WTs. A surge impedance of transmission line was first used for representing the tower body [1,2]. With a segmented processing for the tower body, a cascade hollow conductor model was then proposed [3,4]. Recently, a cylindrical conductor cage was also presented by a few researchers to model the tower body [5,6]. These models of the tower body are undoubtedly simple and easy to implement into lightning transient calculation; however, they can not exactly describe the geometrical feature of the actual tower body in the shape of circular truncated cone. In view of the imperfection of the previous approaches, an improvement is made in this paper for modeling lightning transients of WTs. The tower body is modeled as a discrete multiconductor system and an adequate consideration can be given to its geometry of circular truncated cone. The equivalent circuit of the grounding system is built for calculating the fast transients under the subsequent negative stroke. Moreover, the blade and dynamic contact are also modeled in a reasonably simplified manner. On the basis of integrating the four sections on the lightning current path, an entire circuit representation is given for the WT. The lightning transient responses on the WT can be determined from the solution to the circuit equations. A laboratory-scale WT has also been built and the measured results are used to verify the validity of the proposed approach.

2. Circuit modeling of wind turbines

In order to calculate the transient responses, the current carrying path on a WT struck by lightning needs to be represented by the equivalent circuits. It mainly consists of the blade, dynamic contact part, tower body and grounding system, as shown in Fig. 1. Therefore, the equivalent circuits are built on the basis of the four sections.

2.1. Equivalent circuits for blade and dynamic contact part

The blade is the most vulnerable component of the WT for direct lightning stroke. To lead the lightning current to flow to the ground during lightning stroke, the down conductor is usually placed inside the

* Corresponding author.
E-mail address: xizhanv@163.com (X. Xiao).

https://doi.org/10.1016/j.ijepes.2018.04.006
Received 10 August 2017; Received in revised form 22 February 2018; Accepted 4 April 2018
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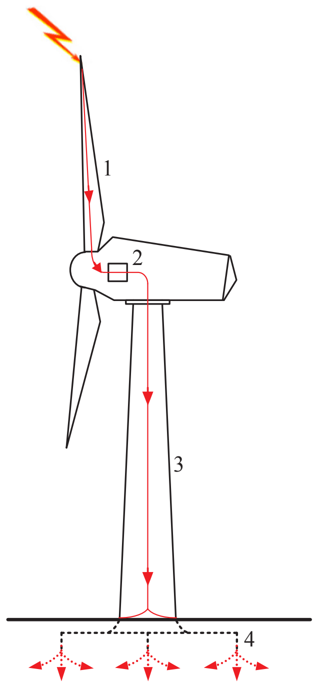

Fig. 1. Lightning current path (1-down conductor; 2-dynamic contact part; 3-tower body; 4-grounding system).

blade, as illustrated by the thick lines in Fig. 2(a). When the blade rotates, it may be struck by lightning with high probability at the vertical position and inclined position with a smaller deflection angle θ (see Fig. 2(a)) [8]. Therefore, the two spatial positions need to be considered in building the equivalent circuit of the blade. In view of the traveling wave behavior of lightning current, the down conductor is divided into a suitable number of segments. As shown in Fig. 2(b), M segments are given for the down conductor. The segment length Δl_b should be less than a critical value $l_{cr}=0.1c/f_m$, where c is the velocity of light (3×10^8 m/s) and f_m is the maximum frequency likely to affect the lightning transient [9]. The electrical parameters of each segment are represented by resistance, inductance and capacitance. In the parameter calculation, the existence of the ground is taken into account by installing the image of the segment. The imaginary segment is installed at a symmetrical position below the ground surface and depicted by the dotted lines, as shown in Fig. 3. The length of the imaginary segment is equal to that of the respective real segment. For a vertical segment, as shown in Fig. 3(a), its inductance is calculated by Neumann's integral [10]

$$L_{vj}=\frac{\mu_0}{4\pi}\left(\int_{\Delta l_b}\int_{\Delta l_b}\frac{d\boldsymbol{l}\cdot d\boldsymbol{l}\mathrm{p}}{r}+\int_{\Delta l_b}\int_{\Delta l_b}\frac{d\boldsymbol{l}'\cdot d\boldsymbol{l}\mathrm{p}}{r'}\right)$$
$$=\frac{a\mu_0}{4\pi}\left[2+\Psi\left(\frac{\Delta l_b}{a}\right)+\Psi\left(-\frac{\Delta l_b}{a}\right)+\Psi\left(\frac{-2h}{a}\right)\right.$$
$$\left.+\Psi\left(-\frac{2h+2\Delta l_b}{a}\right)-2\Psi\left(-\frac{\Delta l_b+2h}{a}\right)\right] \quad (1)$$

where μ_0 is the permeability of free space ($4\pi\times10^{-7}$ H/m) and the function in the square brackets is

$$\Psi\left(\frac{x}{a}\right)=\frac{1}{a}\left[x\sinh^{-1}\frac{x}{a}-\sqrt{a^2+x^2}\right] \quad (2)$$

In a manner similar to Eq. (1), the inductance of an inclined segment, as shown in Fig. 3(b), is also calculated by [10]

$$L_{ij}=\frac{\mu_0}{2\pi}\left[\Delta l_b\tanh^{-1}\frac{\Delta l_b}{\sqrt{a^2+\Delta l_b^2}}-\sqrt{a^2+\Delta l_b^2}+a\right.$$
$$\left.+2(w+\Delta l_b)\tanh^{-1}\frac{\Delta l_b}{p+2h_2}-2w\tanh^{-1}\frac{\Delta l_b}{p+2h_1}\right] \quad (3)$$

where $w=h_1\Delta l_b/(h_2-h_1)$ and $p=\sqrt{\Delta l_b^2+4h_1h_2}$. According to the electromagnetic analogy [11,12], the corresponding capacitances can be determined respectively for the vertical and inclined segments, i.e. $C_{vj}=\mu_0\varepsilon_0/L_{vj}$ and $C_{ij}=\mu_0\varepsilon_0/L_{ij}$, where ε_0 is the permittivity of free space $[(36\pi)^{-1}\times10^{-9}$ F/m]. The resistance of each segment is estimated by [13]

$$R_b=\frac{\sqrt{\pi f_m\rho\mu}\,\Delta l_b}{\pi[1-\exp(-a/\sqrt{\rho/\pi f_m\mu})][2a-\sqrt{\rho/\pi f_m\mu}\,(1-\exp(-a/\sqrt{\rho/\pi f_m\mu}))]} \quad (4)$$

where ρ and μ are resistivity and permeability of the down conductor, respectively. In terms of the electrical parameters calculated from (1)–(4), the vertical and inclined segments are represented as the Π-circuit units. After each segment in Fig. 2(b) is replaced with the respective Π-circuit unit, the equivalent circuit of a blade can be built, as shown in Fig. 4.

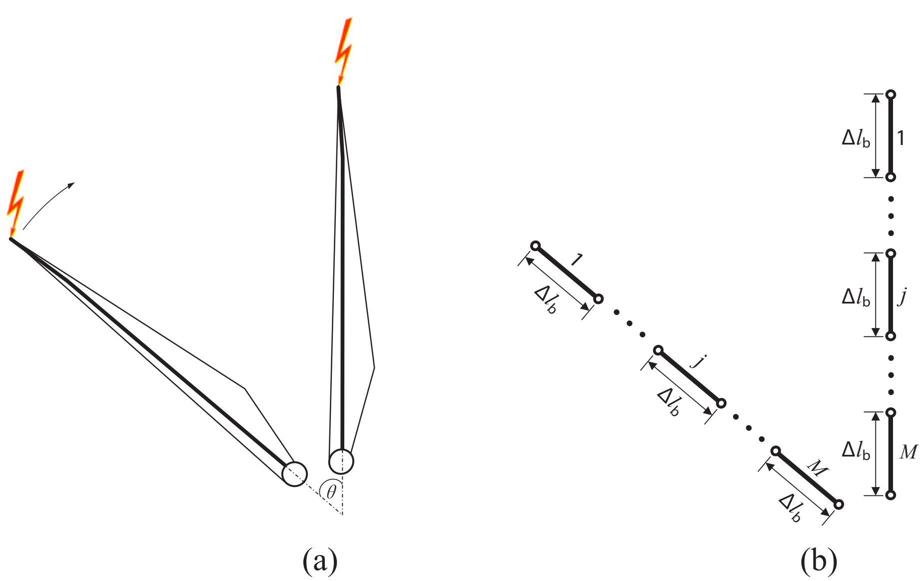

Fig. 2. (a) Down conductor in the blade. (b) Segmentation for the down conductor.