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Measurements and Simulations of Precursory Pulses from Altitude-Triggered Lightning Associated with Wind Turbine Blade on the Ground

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Abstract

The altitude-triggered lightning experiments associated with the wind turbine blade on the ground were carried out in this study. The air gap between the lower extremity of steer wire and the wind turbine blade tip was found to be bridged during the rocket ascends. Preceding the initial stage, a total of 50 precursors are found span a duration of over 500 ms using a threshold of 50 A. The interval time between the isolated pulses ranges from 0.95 ms to 29.7 ms. The average peak value of the precursory current pulses is 95.9 A. Based on the extended guided-wave M-component model considering the presence of tall object on the ground, two selected precursors were simulated and compared to the measured electric fields. The late-time response of the simulated electric fields at 110 m, which is mainly produced due to the presence of the wind turbine blade, generally agrees well with the measured data from the two precursors. Notable excursions of both initial negative and the following positive polarities were found through the simulated electric fields.

1. Introduction

Rocket-triggering lightning technique enables lightning to occur at a predictable time and position [1]. The triggering lightning reported in previous studies usually involves the techniques of classical triggering and altitude triggering. Classical triggered lightning is carried out by launching a small rocket trailing a grounded metal wire beneath an active thunderstorm when the atmospheric electric field exceeds a certain threshold. For the altitude triggering, the wire dragged by the rocket is connected to an insulating wire tied to the lightning rod with tens to hundreds of meters in length. Rocket-triggered lightning flashes demonstrate high similarities of the natural subsequent return strokes and are characterized by advantages of the presence of the initial stage preceding the return strokes.

The triggering lightning are most successful for triggering negative cloud-to-ground discharges, in which the negative cloud charge above the triggering site initiates an upward positive leader from the upper extremity of the wire when the rocket reaches an altitude typically 200 to 400 m above ground. Preceding the onset of the upward positive leader, while the intact triggering wire remains conductive, transient current pulses occur that are generated by electrical breakdown at its ascending tip and propagate down the wire to ground. The pulses are termed as precursors and correspond to attempted breakdown events as the wire ascends [2].

Biagi et al. [3] analyzed current, electric field, and optical signatures of the precursors that occur at the top of copper wires in classical triggered lightning. For one launch, before the sustained upward positive leader initiated, up to 10,000 precursors occurred (one every few hundred microseconds) with peak currents from 1 A to more than 100 A. They modelled the triggering wire and its grounding system as uniform transmission lines and the model predictions were consistent with the measured wire-base precursor current signatures. In this study, analysis with both measurements and simulations were carried out about the precursors from the altitude-triggered lightning experiments associated with the wind turbine blade.

2. Experiment Setup and Data

2.1 Experiment Setup

The altitude-triggered lightning was conducted at Guangzhou Field Experiment Site for Lightning Research and Testing in China. During 2022, a wind turbine blade measuring 14.5 m in length was buried vertically in the ground, with 2.5 m extending below the ground. The down conductor was grounded through eight electrodes. The specimen is obtained by cutting the tip from an 83.4 m long wind turbine blade. As shown in Fig.1, the rocket was installed on the launching platform at 2.5 m from the elevated blade. A nylon cord, 10 m in length, was connected to both ends of a wire and the blade. The lower end of the nylon cord was fixed to the blade at a height of 2 m above the ground. The upper end of the 10 m nylon cord was positioned around the blade tip.

A current measuring system was installed around the down conductor, utilizing a shunt with a small resistance value. The experiment included two fast electric field measuring systems with the same time constant of 1 ms. The electric fields measuring distances are 110 m. More detailed information can be found in [2]. High-speed cameras with different framing rate were also deployed in the experiment.

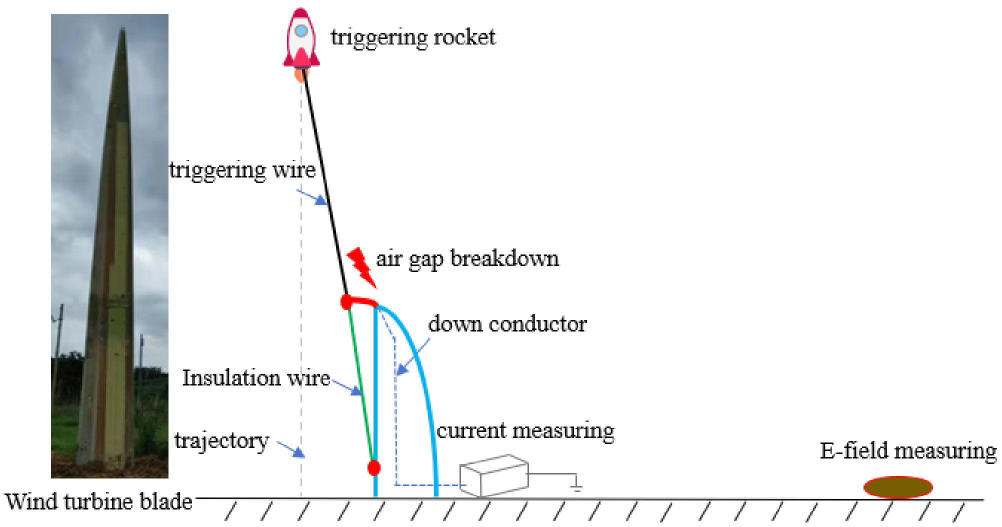

Figure 1. Diagram of the altitide-triggered lightning experiments assocaited with wind turbine blade on the ground during the summer of 2022 at Guangzhou Field Experiment Site for Lightning Research and Testing in China.

$$\begin{aligned} i(z,t) = {} & i_H\left(H, t-\frac{H-z}{v}\right)u\left(t-\frac{H-z}{v}\right) - \rho_t i_H\left(H, t-\frac{H+z-2h}{v}\right)u\left(t-\frac{H+z-2h}{v}\right) \\ & +(1+\rho_t)(1-\rho_t)\sum_{n=0}^{\infty}\rho_g^{\ n+1}\rho_t^{\ n} i_H\left(H, t-\frac{H+z-2h}{v}-\frac{2(n+1)h}{c}\right)u\left(t-\frac{H+z-2h}{v}-\frac{2(n+1)h}{c}\right) \end{aligned} \tag{1}$$

$$\begin{aligned} i(z,t) = {} & (1-\rho_t)\left\{\sum_{n=0}^{\infty}\rho_g^{\ n}\rho_t^{\ n} i_H\left(t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2nh}{c}\right)u\left(t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2nh}{c}\right)\right. \\ & \left.+\sum_{n=0}^{\infty}\rho_g^{\ n+1}\rho_t^{\ n} i_H\left(t-\frac{H-h}{v}-\frac{h+z}{c}-\frac{2nh}{c}\right)u\left(t-\frac{H-h}{v}-\frac{h+z}{c}-\frac{2nh}{c}\right)\right\} \end{aligned} \tag{2}$$

2.2 Data

The dataset consists of synchronized recordings of various parameters during a single negative altitude-triggered lightning flash that took place on July 5, 2022, at 23:23:21 (local time). A total of 50 precursors are found span a duration of over 500 ms using a threshold of 50 A. The interval time between the isolated pulses ranges from 0.95 ms to 29.7 ms, with an average value of 10.8 ms. The average peak value of the precursory current pulses is 95.9 A in the range of 62.9 A -179.5A. The average value of the 10-90% risetime of the precursors is 0.47 μs in the range of 0.2 μs -1.1 μs. The average value of the half peak width of the precursors is 1.19 μs with the minimum value and maximum value of 0.5 μs and 1.9 μs, respectively.

3. Simulation Model and Methodology

3.1 Simulation Model

Fig. 2 shows the diagram of the current flow and the vertical electric field radiations from the precursors preceding the initial stage of the altitude-triggered lightning experiments associated with the wind turbine blade. The simulation model used in this study was adapted from the reference of [4], in which the extended guided-wave M-component model was presented considering the presence of a vertically elevated strike object.

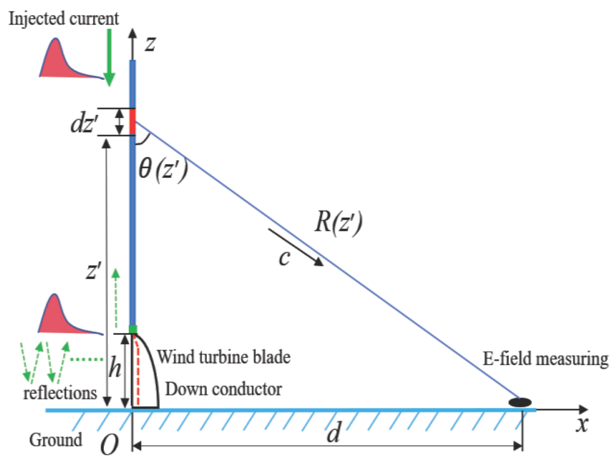

Figure 2. Diagram of the electric field radiation from the precursors in altitude-triggered lightning experiments.

The extended guided-wave M-component model followed the procedure used for return strokes by *Rachidi et al.* [6] and the classical guided-wave M-component model from *Rakov et al.* [7]. In this study, both the intact steer wire dragged by the launching rocket and the down conductor were represented as lossless, uniform transmission lines. The precursor current was assumed to be injected at the top of the steer wire, downward propagated along the wire, and was emerged into the down conductor buried inside the wind turbine blade. The current was partially reflected back from the blade tip and went upward along the wire, and disappeared in the air. Noted that the air gap between the lower extremity of the wire and the metal-based blade tip was bridged preceding the occurrence of the first precursor.

Equations (1) and (2) represent the current distribution along the steer wire and the down conductor in terms of spatial and temporal domain. n is an index representing the successive multiple reflections occurring at the two ends of the down conductor, H is the height of the steer wire, v is the current wave propagation speed along the steer wire and h is the height of the down conductor. The parameters ρ_g and ρ_t are the reflection coefficients at the ground and at the down conductor top, respectively.

3.2 Electric Field Computation

The vertical electric field radiated from the altitude-triggered lightning associated with the wind turbine blade is calculated assuming a vertical channel above a perfectly conducting ground. The vertical electric field expression at ground level is given by [5],

$$\begin{aligned} E_z(d,t) = & \frac{1}{2\pi\varepsilon_\circ}\int_{L_a}^{L_b}\frac{2z'^2-d^2}{R^5(z')}\int_{R/c}^{t} i(z',\tau-\frac{R}{c})d\tau dz' \\ & +\frac{1}{2\pi\varepsilon_\circ}\int_{L_a}^{L_b}\frac{2z'^2-d^2}{cR^4(z')}i\left(z',t-R(z')/c\right)dz' \\ & -\frac{1}{2\pi\varepsilon_\circ}\int_{L_a}^{L_b}\frac{d^2}{c^2R^3(z')}\frac{\partial i\left(z',t-R(z')/c\right)}{\partial t}dz' \end{aligned} \tag{3}$$

in which $i(z', t)$ is the current as a function of the position along the channel z' and the time t, c is the speed of light, d is the observational distance, $R= (d^2+z'^2)^{1/2}$, and $E_z(d,t)$ is the electric field from the traveling waves.

3.3 Parameters Setting

The height of the upper extremity of the steer wire is set to 362 m, in which the blade tip is set to 12 m above the ground and the length of the steer wire is 350 m. The velocity of the current wave along the steer wire and the down conductor inside the wind turbine blade were set to 2.0×10^8 m/s, and 3.0×10^8 m/s, respectively. The reflection coefficients at the ground (ρ_g) and at the down conductor top (ρ_t) were set to 0.7 and -0.4, respectively. The electric field observation distance is set to 110 m according to the location of electric field measuring senor in the field. The channel consisting of the steer wire and the down conductor is assumed to be vertical on the ground.

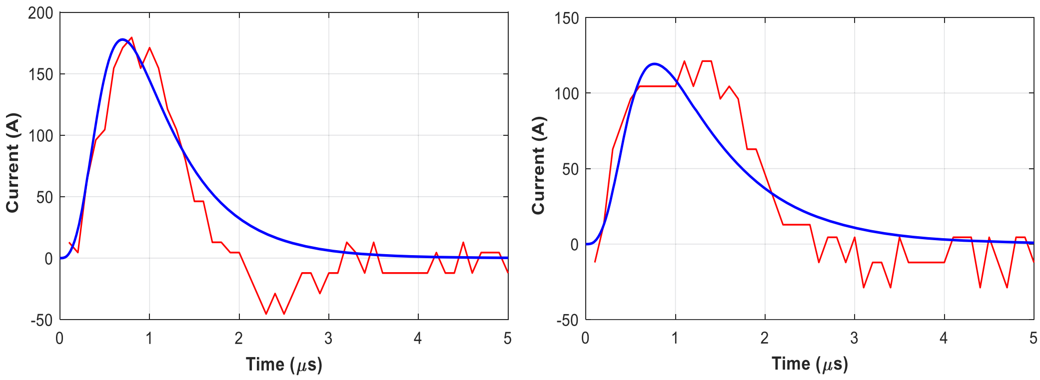

Figure 3. Measured current waveforms associated with the two selected precursors and their analytical representations.

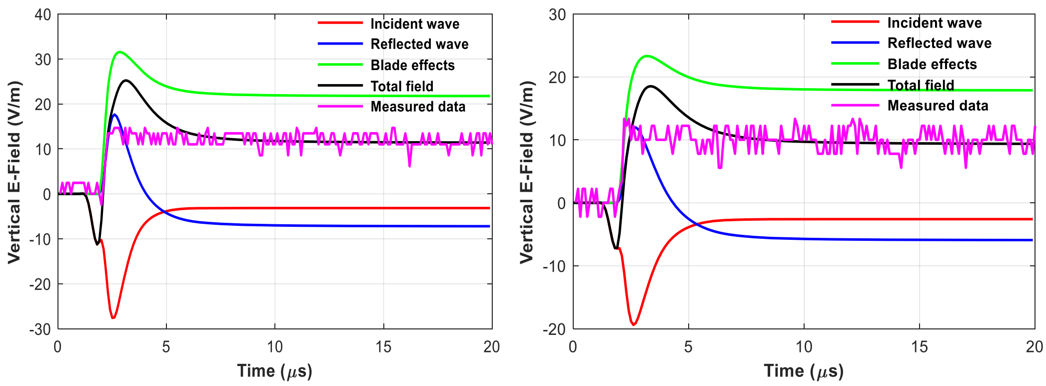

Figure 4. Simulated electric fields from the two selected cases and comparisons to the measured data.

4. Results and Analysis

Fig. 3 shows the measured current waveforms associated with the two selected precursors (p1 and p2) from the altitude-triggered lightning experiments and their corresponding analytical representations. The current waveforms of the two precursors are characterized by the peak value of 180 A and 120 A, and the risetime of 0.4μs and 0.5 μs, respectively. The measured current waveform was represented using a Heidler's function [8]. The detail parameters of the two precursors were setting as: I_1 =0.22 kA, τ_1 = 0.6 μs, τ_2 = 0.6 μs, n = 3, and I_1 =0.14 kA, τ_1 = 0.6 μs, τ_2 = 0.8 μs, n = 3, respectively.

Noted that the current was measured at the bottom of the down conductor inside the wind turbine blade. However, for the sake of brevity, the injected current at the wire upper extremity was assumed by fitting the measured current at bottom of the down conductor. In other words, similar to the "two-wave" theory of reference [7], the injected current is derived to be half of the measured current at bottom of the down conductor when the reflection coefficient at the ground (ρ_g) equals to 1.

Fig.4 shows the comparison of the calculated and measured electric fields from the two selected precursors. On the one hand, the performance of the late-time response from the simulated electric fields agrees well with the measured data. On the other hand, as indicated in the legend label in Fig.4, the simulated electric fields were decomposed as the field components from the incident wave, reflected wave, blade effects, and the total fields as a whole. The electric fields radiated from the down conductor inside the wind turbine blade plays an important role in late-time response. The notable initial negative excursion and the positive excursion are found through the simulated electric fields, which is mainly due to the incident and reflected waves along the steer wire above the wind turbine blade.

5. Summary and Conclusion

This study presents the first altitude-triggered lightning experiment involving an elevated 12 m-long wind turbine blade placed on the ground. It is found that the air gap between the lower extremity of the steer wire and the wind turbine blade tip was bridged preceding the initial stage during the rocket ascends. The experiment observed over 50 precursors occurring prior to the initial stage of lightning striking the wind turbine blade using a threshold of 50 A. The statistical analysis about the waveform parameters of the precursors was summarized in this study. Based on the extended guided-wave M-component model associated with tall objects on the ground, two selected precursors were simulated and compared to the measured electric fields. The late-time response of the simulated electric fields at 110 m, which is mainly produced due to the presence of the blade, generally agrees well with the measured data of the two precursors. Notable excursions of both initial negative and the following positive polarities were found through the simulated electric fields.

6. Acknowledgements

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