New method for lightning location using optical ground wire

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A new technology of lightning location is described, which is based on detecting the state of polarization (SOP) fluctuation of the laser light in the optic ground wire (OPGW). Compared with the conventional lightning location method, the new method is more accurate, more stable, and cheaper. Theories of Stokes parameters and Poincaré sphere are introduced to analyze the SOP at the lightning strike point. It can be concluded that although the initial points of SOP on the Poincaré sphere are random, the SOP fluctuation generated by lightning strike can still be accurately identified by detecting the velocity of polarization motion. A new algorithm to quantify the velocity is also introduced.
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According to the statistics of authoritative organization, in the areas with the greatest number of lightning days, there are about 29 hits on 1-km optic ground wire (OPGW) every year. Since the major faults such as short-circuits or groundings are almost caused by lightning strikes, and in some areas the problem is so significant that the system may have to be replaced[1,2], the location identification of lightning strikes becomes very important, especially for power utilities.

Several lightning location methods have already been developed and effectively operated on power transmission lines. The conventional lightning location methods do not always locate the lightning point on the OPGW line. These methods have the problem of increased error or being unable to locate the fault point when applied to complicated power transmission lines such as branched lines or parallel installations. This is due to the reflection of surge signals at points of sudden change in line parameters such as branching points. This is also because that all the conventional methods try to locate the fault point only by information detected at the edge(s) of the power transmission line, such as substations.

Set up about 20 meters above the ground, OPGW has both functions of lightning protection, which was the original function of overhead ground wire, and information transmission because of the optical fibers within it[2]. OPGW contains optical fibers in the center for the purpose of communications and with aluminium alloy wires and aluminium sheathed wires twisted around. Figure 1 shows a cross-section view of OPGW. When lightning event appears, it firstly strikes OPGW, thus the power transmission lines under it are protected.

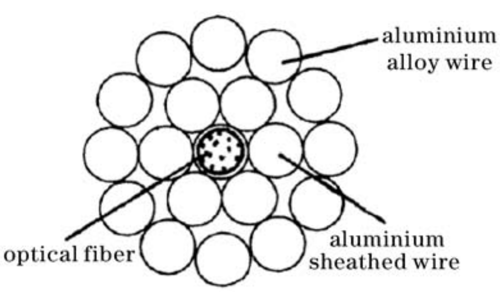

Fig. 1. Cross section of OPGW.

If the distribution map of the transmission power lines and steel towers is obtained, the lightning position can be easily and accurately acquired by detecting the state of polarization (SOP) fluctuation of the light in OPGW and calculating the distance from the lightning strike point to the measuring point.

Polarization fluctuation of light in the optical fiber is mainly caused by two factors: one is photoelastic effect caused by mechanic stress and distortion of optical fiber, and the other is magnetic field, with the same direction of the light in the fiber, caused by Faraday effect. When OPGW is hit by lightning, the second factor will play an important part in the fluctuation of SOP[3−5], and because of the high current caused by lightning, the amplitude of SOP fluctuation will also be very high at the lightning site. Figure 2 shows the direction of magnetic field and current flow in OPGW[6,7].

As shown in Fig. 3, the optical fiber in OPGW is duplex, and it is connected at the other end by an optical

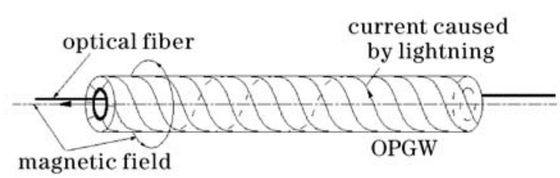

Fig. 2. Current flow and magnetic field in OPGW.

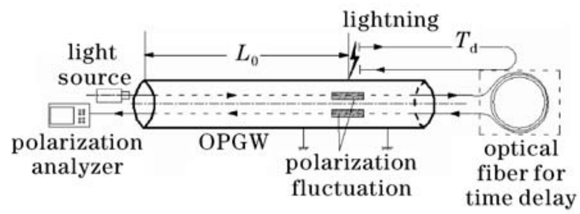

Fig. 3. Principle of lightning location system based on OPGW.

fiber for additional time delay in order to avoid the overlapping of SOP fluctuation when the lightning striking position is too close to the return point of the optical fiber. The light of a continuous wave travels back and forth in the fiber. When lightning strikes a point of the OPGW, two SOP fluctuations occur at the same place simultaneously but travel in opposite directions to each other. Accordingly, they will be observed at the receiver with a time gap for the reason that the path length after the SOP fluctuation is different, and if the time gap T_d which is twice of that for travelling from the lightning point to the return point is acquired, the distance L_0 from the lightning point to the receiving point can then be calculated by

$$L_0 = (T_0 - T_\mathrm{d})v_0/2, \tag{1}$$

where T_0 is the total time interval which the light will cost to perform a round-trip through the OPGW including the optical fiber for additional time delay, and it can be previously acquired at the measuring side by sending a short pulse at the light source; v_0 is the propagation velocity of the light in optical fiber, which is 2.043×10^8 m/s here.

The SOP of light in the long fiber of OPGW always drifts randomly due to the changes of temperature, distortion with the wind or other vibration source and alternating current of 50 or 60 Hz induced from the power line. Therefore at the time of lightning strike, the initial points of SOP or travelling direction on the Poincaré sphere are random.

In order to measure the time gap T_d, the Stokes parameters of a polarized light are introduced to detect the fluctuation of SOP. The SOP of a monochromatic light beam can be completely characterized in terms of the Stokes parameters which can be acquired by[8]

$$P_1 = \frac{I_{0^\circ} - I_{90^\circ}}{I_{0^\circ} + I_{90^\circ}},\ P_2 = \frac{I_{45^\circ} - I_{135^\circ}}{I_{45^\circ} + I_{135^\circ}},\ P_3 = \frac{I_\mathrm{right} - I_\mathrm{left}}{I_\mathrm{right} + I_\mathrm{left}}, \tag{2}$$

where I_{0°, I_{45°, I_{90°, and I_{135° are the intensities of the light recorded through various orientations of linear polarizations, I_right and I_left are the intensities of the circularly polarized components in the beam. And for the completely polarized light beam, the squares of Stokes parameters add up to unity[9,10]

$$P_1^2 + P_2^2 + P_3^2 = 1. \tag{3}$$

Consequently, the Stokes parameters are the Cartesian coordinates of a space in which any completely polarized light beam is represented by a point on a sphere with unit radius around the origin, as show in Fig. 4. This sphere is known as the Poincaré sphere and has proved to be a useful tool in dealing with SOP measurement.

In the new lightning location method, the SOP of the laser light will be measured in real-time. At the time of lightning strike, the SOP on the Poincaré sphere will fluctuate at high amplitude, and if the variation of polar angle of the SOP on Poincaré sphere is acquired, the lightning strike on the OPGW can be precisely detected.

Since the temporal evolution of SOP was visualized as the trajectory of a point $P(t)$ on the Poincaré sphere, an estimate of its extent was given by the angle $\beta(t)$, calculated as the angular distance between $P(t)$ and the initial point $P(0)$, and $\mathrm{d}\beta$, the difference of $\beta(t)$, can exactly reflect the SOP fluctuation.

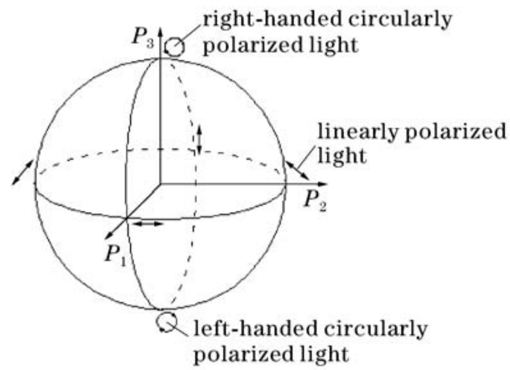

Fig. 4. Poincaré sphere and SOP on it.

As illustrated in Fig. 5, $\mathrm{d}\beta$ can be deduced as

$$\mathrm{d}\beta = \sqrt{\mathrm{d}{P_1}^2 + \mathrm{d}{P_2}^2 + \mathrm{d}{P_3}^2}, \tag{4}$$

where $\mathrm{d}P_1$, $\mathrm{d}P_2$, $\mathrm{d}P_3$ are the time differentials of P_1, P_2, P_3. The waveforms of Stokes parameters and $\mathrm{d}\beta$ are shown in Fig. 6. As can be seen from the figure, while the Stokes parameters change in a complicated manner, $\mathrm{d}\beta$ shows the two fluctuations clearly.

According to Eq. (2), to detect the fluctuation of SOP, the parameters needed to be measured are I_{0°, I_{45°, I_{90°, I_{135°, I_right, and I_left. I_{0°, I_{45°, I_{90°, I_{135° can be

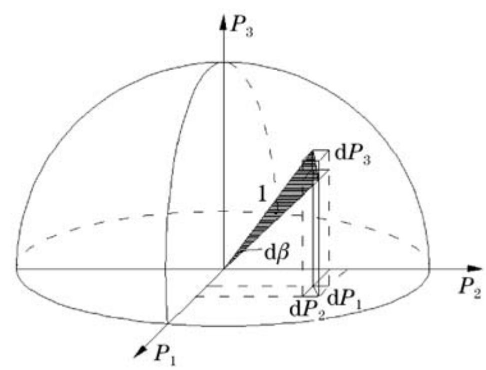

Fig. 5. Angular difference $\mathrm{d}\beta$ on Poincaré sphere.

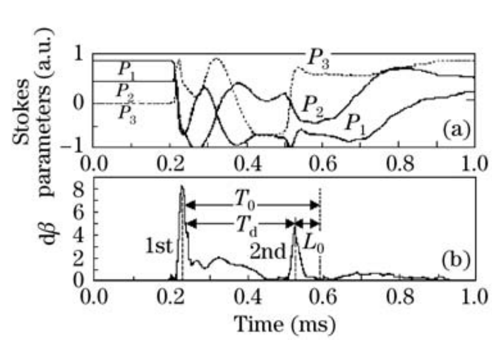

Fig. 6. Measured waveforms of SOP and $\mathrm{d}\beta$.

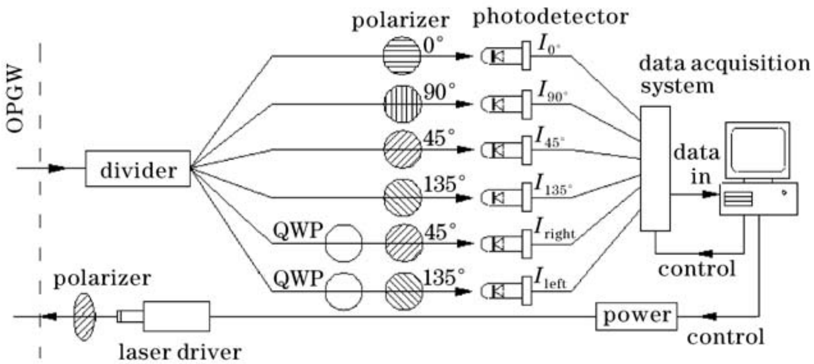

Fig. 7. Configuration of the experimental equipment.

respectively measured by putting polarizers with the directions of 0°, 45°, 90°, 135° before the detectors, I_{right} and I_{left} can be measured by putting a quarter wave plate (QWP) before the polarizers with the directions of 45° and 135°. The configuration of the new experimental lightning location system is illustrated in Fig. 7.

In the experimental equipment, the data were acquired by 125-MHz bandwidth photodiodes and recorded by a data acquisition board with the sampling frequency of 500M samples/s. The detector's bandwidth enables us to temporally resolve the fastest components of SOP excursions and to correlate them to the different physical causes, and an accuracy of 1° in measured angles $\beta(t)$ can be obtained. The concrete structure design of the experimental equipment, the detailed plan and the experimental results will be given elsewhere.

As the lightning current will cause the fluctuation of SOP in OPGW, the lightning strike event can be located by detecting the time delay of polarization fluctuations which are caused by lightning current. The point of lightning strike will be successfully located by detecting the Stokes parameters and by calculating $\mathrm{d}\beta$ as the velocity of SOP to measure the time gap between two fluctuations. Faradic current will also emerge in OPGW when it is not directly stricken by lightning. SOP fluctuation will occur because of both direct and indirect lightning strikes, thus it is very important to increase the accuracy of lightning striking judgment.

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References

1. IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines, IEEE Standard 1410-1997 (1997).
2. W. A. Chisholm, J. P. Levine, and P. Chowdhuri, in *Proc. IEEE Power Engineering Society Summer Meeting 2001* 15 (2001).
3. M. Kurono, K. Isawa, and M. Kuribara, Proc. SPIE **2873,** 242 (1996).
4. M. Kurono, M. Kuribara, and K. Isawa, Elect. Eng. Japan **128,** 55 (1999).
5. D. S. Waddy, P. Lu, L. Chen, and X. Bao, IEEE Photon. Technol. Lett. **13,** 1035 (2001).
6. S. M. Pietralunga, J. Colombelli, A. Fellegara, and M. Martinelli, IEEE Photon. Technol. Lett. **16,** 2583 (2004).
7. K. Urasawa, K. Kanemaru, S. Toyota, and K. Sugiyama, IEEE Trans. Power Delivery **4,** 2005 (1989).
8. L. B. Moeller and P. S. Westbrook, "Method and apparatus for polarization measurements" US Patent 2002/0044282 A1 (Apr. 18, 2002).
9. G. D. Van Wiggeren and R. Roy, Opt. Commun. **164,** 107 (1999).
10. Y. Yin, J. Xi'an Univ. Post and Telecommun. **10,** (3) 8 (2005).