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Test and Analysis of Lightning Sensor Based on Lightning Magnetic Field Using a Scale Model

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Abstract**—**A series of tests were performed on the lightning sensor based on lightning magnetic field using a scale model with the ratio of 1:10 to the actual wind turbine tower, including waveform test, path test and adjacent lightning test. The results and the analysis show that the lightning sensor can accurately measure the peak value of the lightning current (10/350 μs，8/20 μs and 2 ms rectangular) with an accuracy of 3%. The current peak value measured by the lightning sensor with the impulse current via the tower wall of the scale model is about 95% of the one measured by the lightning sensor with the same impulse current via the center conductor. At a distance of 2 m from the adjacent lightning discharge (the actual distance is 20 m, according to the model ratio of 1:10), the lightning sensor is subject to a maximum interference level of 11%.

Keywords—lightning measurement, lightning magnetic field, lightning sensor, scale model, wind turbine tower

I. Introduction

In recent years, wind power technique has developed rapidly with its own advantages. With increasing the capacity and height of wind turbines, lightning stroke in the wind field is becoming more and more. Relevant statistical results show that lightning strike is the main risk faced by the safe and stable operation of the wind turbine [1]. The measurement of lightning current is the basis of lightning research. How to accurately record the lightning current characteristics (waveform and peak value, etc.) is of great significance for analyzing lightning accidents and improving lightning protection measures.

At present, there are several methods for measuring lightning current. Magnetic Steel [2] or Magnetic tape [3] is convenient for large-scale promotion due to its low cost, but it cannot be used to measure the lightning current waveform.

Rogowski coil has no direct electrical connection with the lightning circuit when used to measure lightning current. It also has wide frequency band and wide measuring range [4, 5]. Takami J et al. installed the Rogowski coil sensor on the tower heads on both sides of the transmission line to collect the lightning current waveform [6]. It is widely used to measure lightning current parameters, but it needs to be placed on the lightning carrier fluid during measurement, which is difficult to achieve for large structures such as wind turbine towers. Schoene J et al. used common Rogowski coils on welding shunt bars from towers, which brings intractable difficulties to quantitative analysis [7, 8].

Lightning locating system is a hot issue in lightning research [9, 10]. Nag A et al. analyzed the characteristics and parameters of various lightning location systems [11]. Lightning locating system can only achieve lightning information monitoring in a large area and it has a low measurement accuracy of lightning current, which cannot meet the accurate monitoring of lightning in a small area.

Lightning sensors based on lightning magnetic field can measure characteristic parameters of lightning current, including current peak, current waveform, total charge etc. Compared with other systems, it has three advantages. 1) It uses hall sensor instead of Rogowski coil and has a better charge measurement ability. 2) It can accurately measure lightning current running in the complete tower and not just on a down conductor only. 3) It is more practical.

In this study, a series of tests were performed on a lightning sensor based on lightning magnetic field using a scale model with the ratio of 1:10 to the actual wind turbine tower, including waveform test, path test and adjacent lightning test. Finally, the results of the tests were analyzed.

II. PRINCIPLE

The lightning sensor uses a sensitivity reference based on an infinite straight wire model shown in Fig. 1.

According to Biot-Savar's law, the magnetic induction intensity generated by a finite straight wire can be determined by

$$B=\int dB=\int_{\theta_1}^{\theta_2}\frac{\mu_0 I}{4\pi a}\sin\theta d\theta=\frac{\mu_0 I}{4\pi a}(\cos\theta_1-\cos\theta_2)$$
(1)

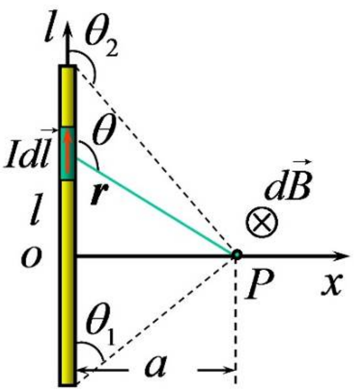


Fig. 1. Magnetic field of a finite straight wire

The lightning sensor (Fig. 2) is mainly composed of measurement system, recording buffers, processing buffer and results. The principle of operation is shown in Fig. 3.

Fig. 2. Pictures of the lightning sensor

The measurement system of the lightning sensor is running continuously while waiting for lightning strike to be detected. Captured data is stored in a circular buffer in order to secure data on lightning current phenomenon that occur before the main strike triggers the signal comparator. When a strike is detected, the input circular buffer is filled with up to 1000ms of measurements, and copied to the processing buffer. The lightning sensor automatically points the data capture stream to the alternate recording buffer when the primary has been filled, in order to keep the system ready to capturing the next strike immediately. Once the processing buffer is filled, the lightning current characteristics are computed. These characteristics, along with the full recorded time series are available for download through either the graphical web interface or via FTP. All recorded data is compressed and stored in internal non-volatile flash memory so that it is protected in the event of a power loss.

Some technical specifications of lightning sensors are shown in TABLE I.

TABLE I. TECHNICAL SPECIFICATION OF THE SENSOR

Minimum trigger current	1 kA
Current range	±300 kA
Current accuracy	3%
Sampling frequency	1 MHz
Recording time per event	1000 ms
Frequency bandwidth	500 kHz
Raw sample memory	2 × 1M samples

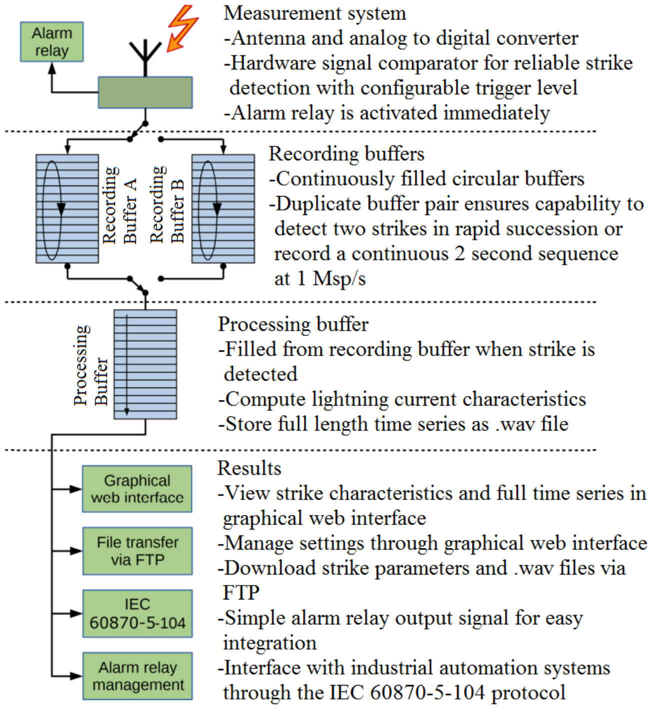


Fig. 3. Operating principle of the sensor

III. SCALE MODEL TEST

A. Scale model

The test uses a scale model (Fig. 4) to simulate the magnetic field distribution of the actual wind turbine tower and thereby test the performance of the lightning sensor. The scale model simulates the lower part of the wind turbine tower barrel, which corresponds to a height of 30m, a diameter of 6m, a thickness of 60 mm. The ratio of the scale model to the actual wind turbine tower barrel is 1:10, the height is 3000 mm, the diameter is 600 mm, the thickness is 6 mm, and the same steel material (Q235) as the actual wind turbine tower is used.

Fig. 4. The testing scale model

B. Experiment method

The lightning sensor is mounted by magnet on the outer surface of the tower wall, where is 600 mm from the ground. At this time, the magnetic field sensor inside the lightning sensor is 30 mm away from the outer surface of the scale model, and thus the radius of the lightning sensor from the axis is actually 330 mm.The test layout is shown in Fig. 5.

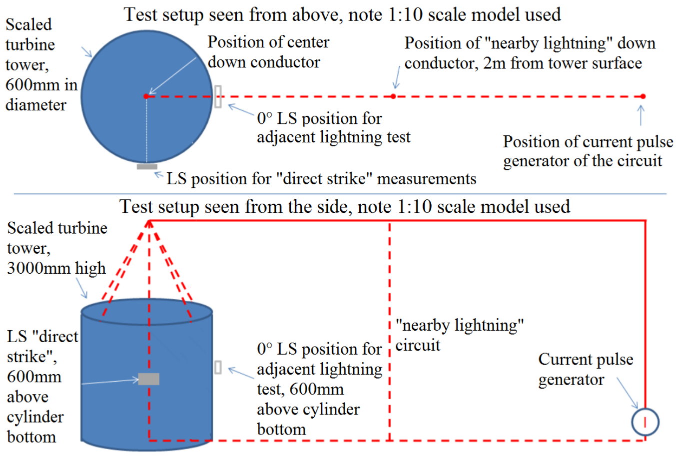


Fig. 5. Test layout

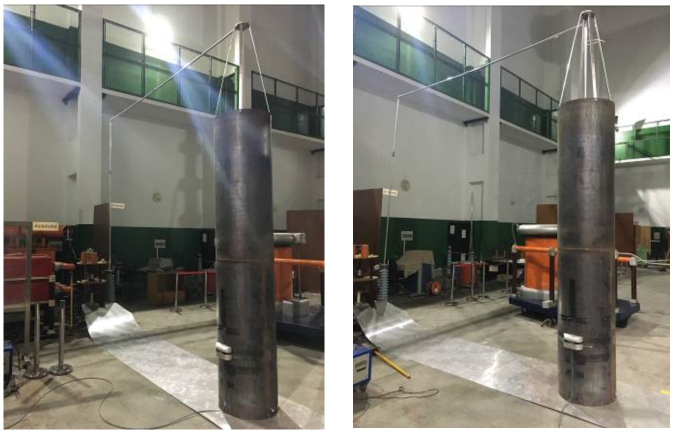
A impulse current generator is used to simulate the lightning current. During the test, the lightning sensor is compared to an approved measurement system. The core component of the approved measurement system is a Rogowski coil (PEARSON 1330).The test consists of the following three parts: waveform test, path test, and adjacent lightning test.

Waveform test uses three kinds of impulse current waveforms (8/20 μs, 10/350 μs and 2 ms rectangular).The impulse current passes through the tower wall of the scale model (Fig. 6).

Path test has two test configurations(Fig. 7): via the tower wall of the scale model and via the central conductor. The test is conducted with 8/20 μs impulse current.

Generally speaking, the distance between adjacent wind turbine towers in a wind farm is not less than 20 m. According to the model ratio of 10:1, a 4m-high conductor is placed vertically at 2 m from the outer surface of the tower wall of the scale model. The impulse current (8/20 μs impulse current) passes through the conductor instead of the scale model. The lightning sensor is mounted in 4 positions, 0° position, 90° position, 180° position and 270° position, shown in Fig. 8.

Fig. 6. Photo of waveform test



(a) Via the tower wall (b) Via the central conductor

Fig. 7. Photoes of path test

(a) 0° position (b) 180° position

Fig. 8. Photoes of adjacent lightning test

IV. RESULTS AND DISCUSSION

A. Waveform test

Waveform test data (8/20μs impulse current) are shown in TABLE II.

TABLE II. WAVEFORM TEST DATA (8/20 μs)

No.	Current peak (kA)		
	Pearson coil	*Sensor*	*Relative error*
1	+1.11	+1.119	+0.81%
2	+9.99	+10.114	+1.24%
3	+30.48	+30.573	+0.31%
4	-1.25	-1.260	+0.80%
5	-10.24	-10.038	-1.97%
6	-30.58	-31.071	+1.61%

Waveform test data (10/350 μs impulse current) are shown in TABLE III.

TABLE III. WAVEFORM TEST DATA (10/350 μs)

No.	Current peak (kA)		
	Pearson coil	*Sensor*	*Relative error*
1	+0.235	+0.238	+1.48%
2	+0.557	+0.565	+1.45%
3	+0.912	+0.937	+2.74%
4	+1.950	+2.000	+2.56%
5	-0.172	-0.174	+1.32%
6	-0.528	-0.536	+1.58%
7	-0.968	-0.978	+1.08%
8	-2.010	-2.029	+0.95%

Waveform test data (2ms rectangular impulse current) are shown in TABLE IV.

TABLE IV. WAVEFORM TEST DATA

No.	Current peak (kA)		
	Pearson coil	***Sensor***	***Relative error***
1	-0.142	-0..40	-1.16%
2	-0.239	-0.234	-2.00%
3	-0.288	-0.296	+2.84%
4	-0.419	-0.428	+2.25%

The typical impulse current waveforms are measured in Fig. 9.

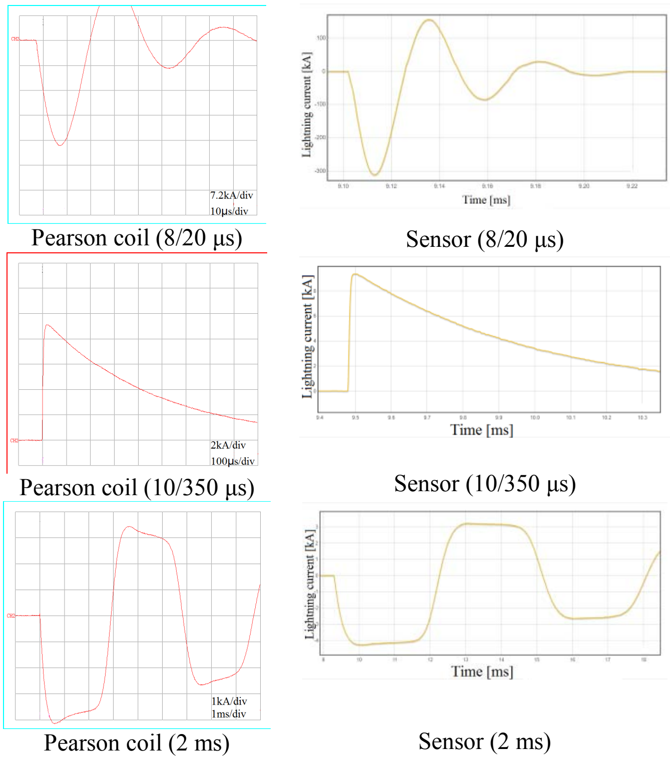


Fig. 9. Impulse current waveforms

According to the data in TABLE I. ～TABLE III., the relative error levels under different waveforms can be obtained, as shown in Fig. 10.

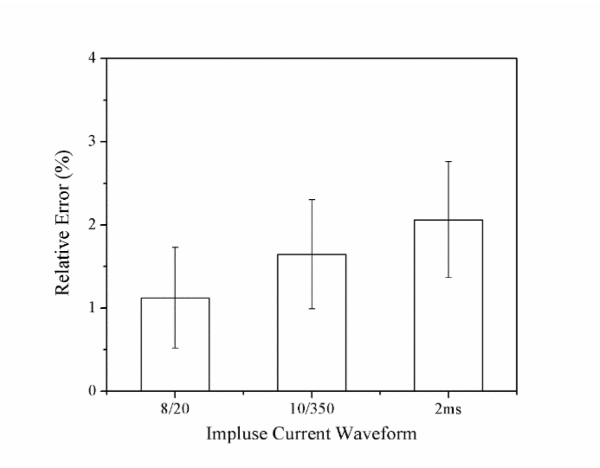


Fig. 10. Impulse current waveforms

As can be seen from the above data, the lightning sensor can accurately measure the peak value of the lightning current. In many cases with 10/350 µs impulse current，8/20 µs impulse current and 2 ms rectangular impulse current, an accuracy of peak current within 3% is obtained.

B. Path test

Path test data (via the tower wall of the scale model) are shown in TABLE V.

TABLE V. PATH TEST DATA (VIA THE TOWER WALL)

No.	Current peak (kA)		
	Pearson coil	***Sensor***	***Relative error***
1	-1.010	-1.036	+2.57%
2	-1.010	-1.036	+2.57%
3	-1.010	-1.034	+2.38%
4	-1.120	-1.125	+0.45%
5	-1.110	-1.105	-0.45%
6	-1.110	-1.107	-0.27%

Path test data (via the central conductor) are shown in TABLE VI.

TABLE VI. PATH TEST DATA (VIA THE CENTRAL CONDUCTOR)

No.	Current peak (kA)		
	Pearson coil	***Sensor***	***Relative error***
1	-0.995	-1.084	+8.94%
2	-0.996	-1.074	+7.83%
3	-1.010	-1.080	+6.93%
4	-1.100	-1.156	+5.09%
5	-1.110	-1.162	+4.68%
6	-1.110	-1.160	+4.50%

As can be seen from the above data, the current peak value measured by the lightning sensor with the impulse current via the tower wall of the scale model is about 95% of the one measured by the lightning sensor with the same impulse current via the center conductor, due to the difference in magnetic field distribution.

C. Adjacent lightning test

Adjacent lightning test data are shown in TABLE VII.

TABLE VII. ADJACENT LIGHTNING TEST DATA

No.	Current peak (kA)			
	Pearson coil	***Sensor***		***Interference level***
1	-6.13	+0.674	0°	11.00%
2	-6.16	<0.2[a]	90°	<3.25%
3	-6.26	-0.441	180°	7.04%
4	-6.14	<0.2[a]	270°	<3.25%

Note: a. The sensor isn't triggered. The trigger level is set to 0.2.

Due to the measuring principle, the lightning sensor cannot completely immune to adjacent lightning discharge interference. But in the best case (90° position or 270° position), the lightning sensor is subject to interference level of less than 3.25%. In the worst case (0° position), the lightning sensor is subject to interference level of 11%.

V. CONCLUSIONS

In this investigation, a series of tests were performed on the lightning sensor based on lightning magnetic field using a scale model with the ratio of 1:10 to the actual wind turbine tower, including waveform test, path test and adjacent lightning test. The following conclusions are drawn.

1) The lightning sensor can accurately measure the peak value of the lightning current. In many cases with 10/350 µs

impulse current, 8/20 μs impulse current and 2 ms rectangular impulse current, an accuracy of peak current within 3% is obtained.

2) The current peak value measured by the lightning sensor with the impulse current via the tower wall of the scale model is about 95% of the one measured by the lightning sensor with the same impulse current via the center conductor, due to the difference in magnetic field distribution.

3) At a distance of 2 m from the adjacent lightning discharge (the actual distance is 20 m, according to the model ratio of 1:10), the lightning sensor is subject to a maximum interference level of 11%.

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