Scale model test on a novel 400 kV double-circuit composite pylon

Q. Wang, C. L. Bak, F. F. Silva, H. Skouboe

***Abstract*—This paper investigates lightning shielding performance of a novel 400 kV double-circuit composite pylon, with the method of scale model test. Lightning strikes to overhead lines were simulated by long-gap discharges between a high voltage electrode with an impulse voltage and equivalent conductors fitted in a scale model of the composite pylon. The number of discharge attachments on the equivalent conductors is translated into shielding failure probability. In this way, the spatial shielding failure probability around the composite pylon is obtained. Additionally, the shielding failure region around the pylon is discussed. Combined test results and striking distance equation in electro-geometric model, the approximate maximum lightning current that can lead to shielding failure is calculated. Test results verify that the unusual negative shielding angle of -60° in the composite pylon meets requirement and the shielding wires provide acceptable protection from lightning strikes.**

***Keywords*: Fully composite pylon, scale mode test, lightning shielding failure probability.**

I. INTRODUCTION

In recent years, overhead line (OHL) transmission system has been faced with great challenges, due to the increasing requirement for transmission capacity along with the public opposing to erect more traditional pylons which are not environmental friendly [1]. In this context, a novel composite pylon, with distinguished features of a more compacted configuration and unchanged transmission capacity, is proposed for 400 kV transmission system in Denmark [2]. The initial design of the novel composite pylon, with two cross-arms shaping a 'Y' geometry, is shown in Fig.1. Insulator strings are eliminated in the pylon because both the cross-arms and pylon body are insulating. Phase conductors are fixed on the cross-arm surface by clamps.

For 400 kV overhead lines, the direct lightning strike is one of main concerns in operation, thus shielding wires are indispensable. In the novel composite pylon, two shielding wires are fixed at the tips of two cross-arms respectively. These distinguished locations of phase conductors/shielding wires in the pylon introduce a unique negative shielding angle of -60°.

To investigate the lightning shielding performance of the shielding wires in the composite pylon, shielding failure region in the pylon and the shielding failure rate are obtained based on electro-geometric model (EGM) in [3]-[4]. The theoretical results show that the shielding wires provide perfect protection from lightning strikes. However, EGM method is widely used for traditional pylons with shielding angles between 10° to 35° [5] and its application in the novel composite pylon needs verification.

Researchers have shown the similarity of long-gap discharge under impulse voltage in laboratory with lighting strikes [6]. Thus experimental method has been proposed to investigate the lightning performance of OHLs in specific arrangement [7]. In this kind of test, the final stage of the lightning strike is simulated by a specific impulse waveform, and equivalent conductors are installed in a scale model reduced by a specific ratio. The discharge between the electrode and equivalent conductors is used to simulate the natural lightning strikes to OHLs. In [8], lightning simulation test on small scale OHLs was conducted, to evaluate the number of lightning flashes to a transmission line. Consequently, the lightning attractive width, i.e. a horizontal distance from the lightning striking point to the OHL center with which the possibility of lightning flashes to OHL and to the ground is equal, has been obtained. In [9], the author found out that the number of direct lightning attachment to phase conductors at the design stage was different from that observed in the real operation of UHV transmission lines. Thus the author conducted long-gap discharge test to better understand lightning shielding characteristics in UHV lines. In [10]-[11], authors discussed factors that may have effects on results in scale model test, and the conclusions are referred in the design of the small scale model test in this paper. The scale model test has several limitations, for example, the natural lightning cannot be simulated accurately enough in the laboratory and degree of air ionization does not change linearly with the distance between the equivalent lightning striking point and the pylon model. However, all the literatures mentioned above indicate that experimental data from small scale model test are valuable references for investigating lightning performance of OHLs.

Based on experience mentioned above, scale model test is conducted in this paper. Based on experimental results, the spatial lightning failure probability around the composite pylon is obtained. The spatial region in which shielding failure

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Figure 1. Photo of the novel 400 kV double-circuit composite pylon [2]

may happen is discussed. Moreover, the maximum lightning current that can lead to shielding failure is obtained.

Test arrangement and testing methods are introduced in Section II. The testing results and analysis are given in Section III. Discussion on testing results and comparison between testing results with the theoretical analysis are shown in Section IV. Finally conclusions are drawn in Section V.

II. Test Arrangement

The tests were conducted in the high voltage laboratory at Department of Energy Technology, Aalborg University.

A scale ratio of 1:40 is adopted for the pylon model. Two models, made of polyurethane, are employed and the dimensions of the model are shown in Table I. D_{pe} is the air clearance between the upper phase conductor and the shielding wire, while D_{pp} is the air clearance between phase conductors. H is the height of the shielding wire.

TABLE 1. PYLON MODEL DIMENSIONS

D_{pe} [m]	D_{pp} [m]	H [m]
0.074	0.101	0.56

Phase conductors and shielding wires are simulated by solid cylinder steel conductors in the model. All the conductors have the same diameter of 6mm in order to get same sag magnitude in the 3m-span. In that way, the position of striking point along the middle span has no effects on the testing results. Grounding resistance restrains the speed of charge accumulation from the ground which also restrains the formation of upward leader from conductors [12], thus in order to make the experimental arrangement in accordance with the real situation, the shielding wires are grounded directly while phase conductors are grounded through characteristic impedance with a value of 300 Ω.

A standard negative lightning impulse waveform (−1.2/50μs) is used to simulate the final stage of the lightning. The reason for choosing such an impulse is that a fast-front impulse can simulate the final stage of lightning strikes to structures with a small size, where the upward leader is absent. The impulse voltage is provided by an 800kV / 24kJ Marx impulse generator. One of the impulse waveform measured by an oscilloscope is shown in Fig. 2. The peak voltage is 434 kV.

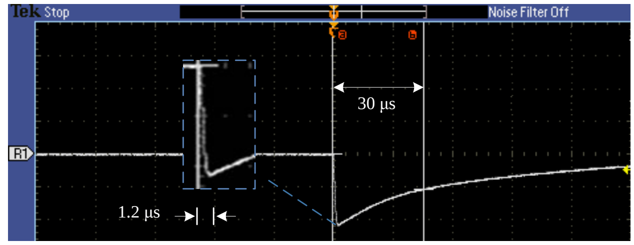

Figure 2. Measured impulse waveform

A solid, semispheric-capped steel rod is used as the high voltage electrode, which is connected with the output terminal of the impulse generator. The electrode has a length of 2 m and a diameter of 10 mm and it is hung up in the middle of the span.

The experimental arrangement is shown in Fig 3 (a). The pylon model is composed of two opposing ´Y´ frames and the two frames contain two shielding angles of −60° and −70° respectively. However, only the shielding angle of −60° was considered in this paper. The electrode is in boldface to be noticeable. S, U, M and L represents shielding wire, upper phase conductor, middle phase conductor and lower phase conductor respectively. In the test, the electrode position varied in the space above conductors. To better explain the location of the electrode, a coordinate system is established, shown in Fig. 3 (b). The middle point of the connection line of S_1 and S_2 is the coordinate origin. The position of the electrode tip can be represented by its coordinates (x, y).

According to analysis in [3], lightning attachment to phase conductors, i.e. shielding failure, happens in the region around the perpendicular bisector of conductors. Thus the position of the electrode varied around the perpendicular bisector of conductors, i.e. around the center of the pylon. For each electrode position, 90%-100% breakdown voltage of the gaps was applied and a total number of 50 discharges were obtained. The 90%−100% breakdown voltage was obtained through tests beforehand, which means 9 or 10 breakdown can happen if applying the corresponding voltage to the gaps for 10 times.

A high speed camera with a shooting rate of 1250 fps was adopted to capture the discharge path. To protect the camera from effects of high electric field stress, it was located outside the Faraday cage.

III. Test Results

More than 3000 discharges were obtained in the tests and all the discharge paths were recorded by the camera. Fig.4 shows typical photographs of discharges in the test.

It is shown in Fig. 4 that discharge not only happened between the electrode and the equivalent shielding wires (in Fig. 4 (a), (b), (c)), but also happened between the electrode and the equivalent phase conductors (in Fig. 4 (d), (e), (f)). It is verified that it is possible to have shielding failure in the center region of the pylon.

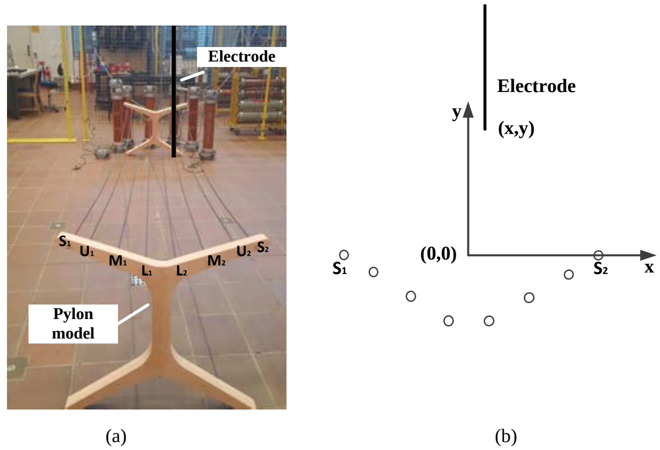

Figure 3. Test arrangement (a) and the coordinate system (b) [4]

When the electrode located at a specific position, different gap lengths existed between the electrode tip and different conductors. It's expected that the discharge happens between the tip and the nearest conductor. In Fig. 4 (a), (b), (d) and (f), the shortest gap length existed between the electrode tip and S_2, S_2, L_1 and M_2 respectively, thus the simulated lightning strike attached to the corresponding conductors.

However, in Fig. 4 (c), when the distance of 60.5 cm between the electrode tip and M_1 was the shortest, the simulated lightning strike terminated on the further conductor S_1, where the gap length was 62 cm. The same phenomenon was seen in Fig. (e) that the smallest gap length was 51 cm between the tip and L_1, but the discharge happened between the tip and M_1 where the gap length was 53 cm. This can be explained by the dispersity of long-gap discharge, which defines the long-gap discharge will not always strike the same point even if the smallest gap length exists. And when the difference in gap lengths is not so significant, the dispersity is more dominant. Two weaker discharge paths between the electrode and M_1 could be observed in Fig.(c). These two branches from the main discharge path imply that the discharge streamer was attracted by S_1 prior to M_1, because the grounding resistance of phase conductors restrained the charge accumulation on conductors from the ground, while the shielding wire was grounded directly.

Based on data of discharge paths, the shielding failure probability at a specific electrode position, that is, at a specific striking point, can be calculated:

$$P_{sf} = \frac{n_{pc}}{50} \times 100\% \tag{1}$$

where:

P_{sf}: shielding failure probability at a specific electrode position;

n_{pc}: total number of attachments to phase conductors (S_1, S_2, M_1, M_2, L_1 and L_2).

The values of spatial shielding failure probability are divided into ranges of 0 ~ 10%, 10 % ~ 30%, 30 % ~ 50%, 50 % ~ 60%, 60 % ~70%, 70 % ~ 80%, 80 % ~ 90% and 90 % ~ 100%, and fitted curves are drawn, shown in Fig. 5. The coordinates (unit: cm) of several critical points are also shown. It's obvious from Fig. 5 that the shielding failure probability is symmetrical by the perpendicular bisector of the pylon, due to the pylon's symmetrical geometry. With the increase of the height of the striking point (electrode position), the shielding failure probability decreases. What's more, with the striking point moves away from the pylon center to both sides, the shielding failure probability also decreases. This can be explained by the fact that the distance between the striking point and shielding wires gradually becomes shorter than that between the point and phase conductors, when the striking point ascends vertically or moves horizontally. When the striking point locates higher enough or locates far away enough from the pylon center, the shielding failure probability will decrease to zero. In other words, shielding failure happens in a limited region. From Fig. 5, three critical points on the outer boundary of this limit region, within which shielding failure may happen, are represented by their coordinates (-12, 15), (12, 15) and (0, 45).

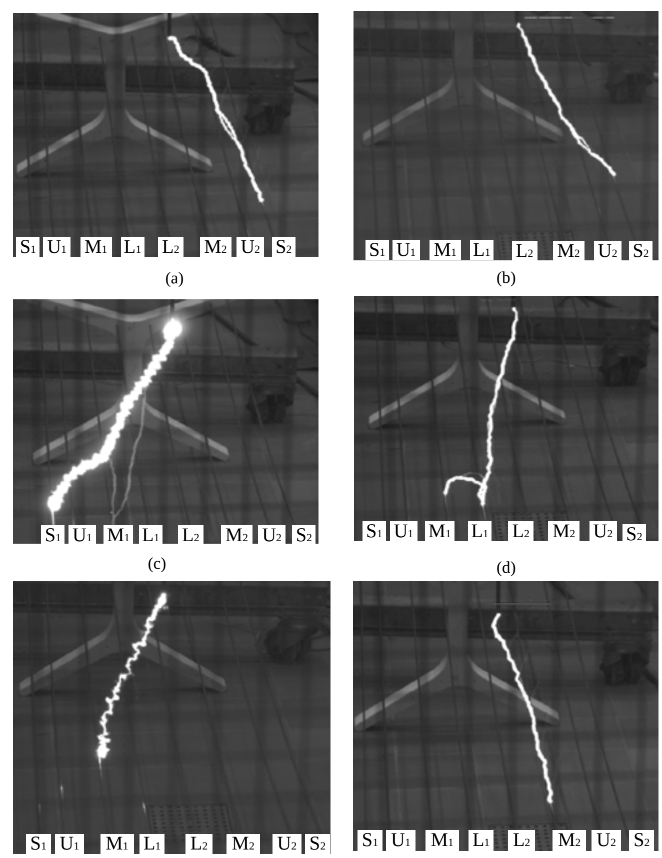

Figure 4. Typical photographs of lightning discharges in the test taken by the high-speed camera: Discharges between the electrode tip and the nearest conductors ((a)-S_2, (b)-S_2, (d)-L_1, (f)-M_2); Discharges between the electrode tip and further conductors ((c)-S_1, (e)-M_1)

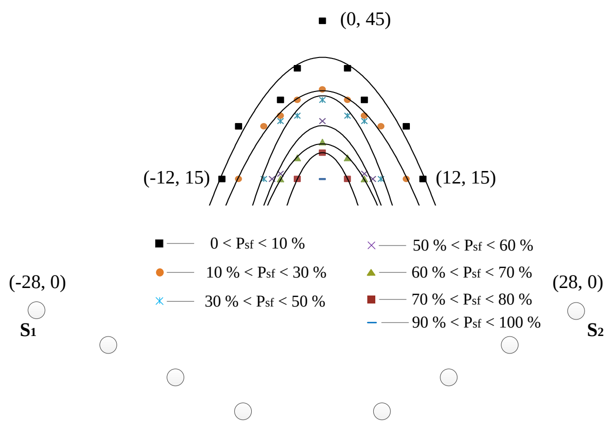

Figure 5. Spatial shielding failure probability around the pylon model

IV. DISCUSSIONS

In [3], T. Jahangiri concludes that shielding failure happens when lightning falls vertically to the region around the center of the pylon, based on EGM method and the geometry of the composite pylon. This conclusion is verified by test results in this paper. What's more, the striking distance equation (expressed in (2)) defined by IEEE Std.1243-1997 [13] is adopted in [3] to calculate the maximum shielding failure current

$$r_c = 10 \times I^{0.65} \quad (2)$$

where:

r_c: striking distance of shielding wires and phase conductors in m;

I: the lightning current in kA.

Based on (2) and the pylon's geometry, T. Jahangiri draws the conclusion that the maximum lightning current $I_{MIC,}$ which can lead to shielding failure, is 3.102 kA. Given 3 kA is the lower limit of integration limits for the probability density of lightning current recommended by CIGRE [14], i.e. lightning current lower than 3kA is considered having no harm to the OHLs or the power system, T. Jahangiri concludes that the assigned negative shielding angle of −60° provides a perfect lightning protection for the novel pylon.

However, in real situation two conditions are different from the EGM assumption: (1) Natural lightning has the feature of randomness which means it will not always strike the same point even though the shortest distance exists; (2) Striking distances of shielding wires and phase conductors are different. Thus the conclusion based on EGM method needs verification. In the scale model test, the electric discharge has the feature of randomness. Moreover, the different grounding methods of shielding wires (grounded directly) and phase conductors (grounded through resistors) can represent the different striking distances.

To compare results from EGM method and scale mode test, test data need to be interpreted. From Fig. 5, it's known that, at the same height, the maximum value of shielding failure always exists when the striking point locates in the right center of the pylon, i.e. at y axis. In other words, striking point locating at y axis represents the worst case. Thus the following analysis focuses on the situation that the electrode locates at y axis.

For each striking point, the gap length which received more than 50% probability of lightning attachment is set as the striking distance [8]. Since the pylon was scaled by the ratio of 1 : 40, the real-scale striking distance is roughly equivalent to 40 times the striking distance in the test. Then applying real-scale striking distance to (2), equivalent lightning current in accordance with a specific striking distance is calculated. Consequently, the relationship between lightning current and shielding failure probability is figured out, shown in Table II.

TABLE II. RELATIONSHIP BETWEEN LIGHTNING CURRENT AND SHIELDING FAILURE PROBABILITY

Electrode position	Striking distance in the test [m]	Equivalent striking distance in real scale [m]	Equivalent lightning current [kA]	Shielding failure rate [%]
(0, 15)	0.33	13.2	1.53	90
(0, 20)	0.42	16.8	2.22	76
(0, 25)	0.46	18.4	2.56	66
(0, 30)	0.50	20.0	2.90	22
(0, 35)	0.56	22.4	3.46	24
(0, 40)	0.62	24.8	4.04	16
(0, 45)	0.66	26.4	4.45	4

From Table II, it is seen that with the increase of electrode height, the striking distance increases thus the magnitude of lightning current increases. This trend accords with the physical process that the lightning strike, with higher magnitude of current, will strike through the gap earlier in the process of descending, leaving a longer striking distance. In the same process, the shielding failure probability decreases. That is, with the increase of lightning current from 1.53 kA to 2.22 kA, 2.56 kA, 2.90kA, 3.46kA, 4.04kA and 4.45kA, the shielding failure probability decreases from 90% to 76 %, 66%, 22%, 24%, 16% and 4%. It indicates the shielding wires provide better shielding performance as the magnitude of lightning current increases.

It can be expected that the shielding failure decreases to zero if increasing the electrode further. However, it is difficult to define the specific point where shielding failure probability is just reduced to zero by experimental method. In this paper, we set the shielding failure probability SFPmax= 5% as the upper limit which can be accepted in the operation. It is noted from Table II that when the striking point locates at (0, 45) with a lightning current of 4.45kA, the shielding failure probability is 4%. Thus, 4.45 kA is set as the lower limit of lightning current which can be accepted in operation in regards of lightning shielding. In another word, 4.45 kA can be considered as the approximate maximum lighting current that can lead to shielding failure.

Compared with I_{MIC} in [3] which is 3.102 kA, the approximate maximum shielding failure current calculated from experimental results is larger. It indicates that the EGM method does not consider the dispersion of lightning discharge, thus it overestimates the protection capacity of shielding wires. Based on statistics of lightning current accumulating probability [12], the probability of lightning current which is lower than 3. 102 kA and 4.45 kA are 0.25% and 0.64% respectively, demonstrating that results derived from EGM method and scale model test do not show significant difference. Moreover, since the probability of shielding failure is extremely low (lower than 0.03%), we can draw the conclusion that shielding wires in the composite pylon can provide good lightning protection.

V. Conclusion

In this paper, scale model test was conducted to investigate the lighting shielding performance of the double-circuit novel composite pylon in 400kV transmission system. Through analyzing the test results, the following conclusions can be drawn:

(1). Shielding failure happens in the center of the pylon. This conclusion accords with the theoretical analysis in [3];

(2). With the increase of the height of striking point, shielding failure probability decreases; Also, with the distance from the pylon center increase horizontally, the shielding failure probability decreases. Shielding failure happens in a limit region located in the center of the pylon;

(3). The approximate maximum lightning current that can lead to shielding failure is calculated as 4.45 kA. This value of maximum shielding failure current derived from the test is larger than that derived from EGM method in [3], because the EGM method doesn't consider the dispersion of lightning discharge and it overestimates the protection capacity of shielding wires;

(4). Considering the accumulating probability of lightning current less than the maximum shielding failure current is within 1%, the probability for shielding failure is extremely low. Consequently, the shielding angle of -60° meets the requirement and the shielding wires provide satisfactory shielding performance.

The conclusions are valuable references when considering the lightning performance of the novel composite pylon, especially in the case of limited operation experience of composite pylons. The impacts of different impulse waveforms and scale ratios on the test results will be studied in the future research.

VI. Acknowledgment

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