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Proposal of a lightning protection method for solar panels installed on large bulk carriers

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ABSTRACT

Various efforts are being made to achieve carbon neutrality with the aim of achieving net zero greenhouse gas emissions by 2050, and the shipping industry is also required to reduce carbon dioxide emissions. Heavy oil is the main power source for current large ships, which emits a large amount of CO_2. Efforts are being made to supply some of the power and power used on ships with solar power. However, in the sea, where there are no tall structures, there is a high risk that lightning will strike the solar panels installed on large ships, making them unable to generate electricity. Thus, in order to protect the solar panels installed on large ships from lightning strikes, the methods and effects of installing lightning rods or overhead ground wires on large ships were investigated. As a result, it was found that installing overhead grounding wires on both sides of a ship is the most effective method, and the details of this study are reported.

KEYWORDS Lightning protection; solar panel; bulk carrier; lightning rod; overhead ground wire
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1. Introduction

To achieve zero greenhouse gas emissions by 2050, various efforts are being made to achieve carbon neutrality (Aijou et al., 2019; Spagnolo et al., 2012; MEPC, 2018). Maritime transport by large ships is often used as a method of transporting large quantities of goods at low cost. However, the operation of large ships requires a large amount of heavy oil and emits quite a large amount of CO_2. Therefore, to reduce this CO_2, the shipbuilding industry is also planning to install solar panels on large ships to supply electric power and some of moving power used in the ships (Aijou et al., 2019) . Here, electronic equipment used on large steel ships is usually protected by the hull itself which acts as an electromagnetic shield, and the radar and radio antennas are protected by lightning rods on the bridge (Uman, 2008). But, on the sea, where there are no tall structures, there is a possibility that the solar panels installed on the deck of a large ship will be damaged by a lightning strike. So, a study was conducted to protect solar panels on the deck of large ships from lightning strikes by using lightning rods and overhead ground wires, which are used for the lightning protection of high-voltage transmission lines, substation systems, and buildings (IEC, 2010). Using a bulk carrier with a length of 225 m and a width of 32 m as a model, the following three lightning protection methods are proposed and considered: a method of arranging multiple lightning rods on the central axis of the hull, a method of laying overhead ground wire on the central axis of the hull, and a method of laying overhead ground wires on both sides of the ship. Whether the three methods could protect solar panels (photovoltaic module) from lightning strikes was investigated.

2. Height design of lightning rods and overhead ground wire

Basically, the higher a lightning rod or overhead ground wire is installed (up to a height of approximately 30 m), the wider the area that it can protect. Therefore, the height of the lightning rod and overhead ground wire was designed to protect the solar panels on the target ship, using the rolling sphere method with the simulation software Ansys Maxwell 3D™. In the rolling sphere method, the area to be protected is defined as the protected object side from the enveloping surface of a sphere with a radius R from a leader tip drawn to contact the tip of the lightning rod and the ground (IEC, 2010; JIS, 2024). In this study, the solar panel was arranged to be within the protected area by drawing the surface of the sphere to touch the tip of the lightning rod or the overhead ground wire, the deck of the ship, or the handrail. There are levels of protection for the lightning protection of buildings using the rolling sphere method, divided by the radius of the rolling sphere. The height of the lightning rods and overhead ground wires was designed using a rolling sphere with a radius of 30 m and protection level II with a protection efficiency of 95%, which is used in facilities with the possibility of fire or explosion (JIS, 2024). The ship targeted in this research was a large bulk carrier, and Figure 1 shows an image of the target ship. The ship had a length of 225 m and a width of 32 m, and it was planned to install photovoltaic modules on top of six of the seven loading hatches. The height of the handrail was 1 m.

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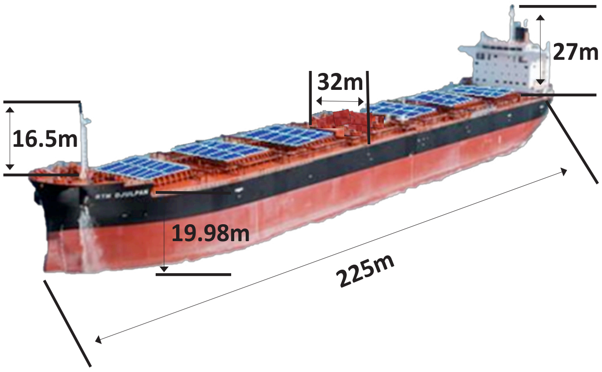

Figure 1. Image of the target ship.

2.1. Lightning rod height design

First, where to install the lightning rod was considered. At the beginning, to reduce the number of lightning rods, a method of installing one lightning rod for every two photovoltaic modules was devised. A rolling sphere diagram of one lightning rod being installed for every two photovoltaic modules is shown in Figure 2. Figure 2(a) is a side view of the hull, and Figure 2(b) is a top view of the hull. If a rolling sphere with a radius of 30 m is installed so that it touches the edge of the modules and the handrail, the lightning rod installed at the midpoint of the adjacent modules on the central axis of the hull could not make contact with the rolling sphere. This result shows that the modules cannot be protected from lightning strikes by using lightning rods.

Then, it was decided to install a lightning rod for each module. An image figure of the installation position of the lightning rod is shown in Figure 3. Figure 3 is a side view of the hull, and the black bars on the top of the hull are lightning rods. The installation position of the lightning rods is on the central axis of the hull, at both ends of each module, and in the middle position between the modules.

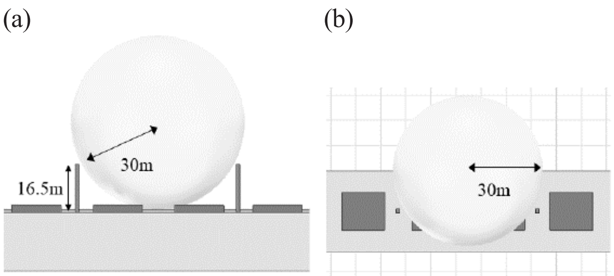

Figure 2. Rolling sphere diagram with a lightning rod installed every two modules: (a) side view; and (b) top view.

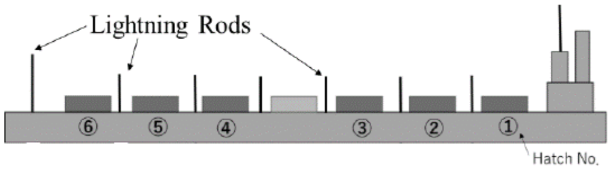

Figure 3. Image of the installation position of lightning rods.

Next, the design of the height of the lightning rod will be described. First, the height of the lightning rod was designed so that the edge of the photovoltaic module, the handrail, and the tip of the lightning rod, which was the minimum length of the lightning rod that can protect the panel from lightning strikes, were in contact with the rolling sphere. The rolling sphere diagram showing that these three points touched is shown in Figure 4. The height of the lightning rod was 11.5 m. Also, at this height of the lightning rod, if the center of the rolling sphere is placed on the central axis of the hull so that it touches the lightning rod, as shown in Figure 5, it was thought that the rolling sphere would not touch the modules and would prevent lightning strikes on the modules. Based on this lightning rod height of 11.5 m, the lightning protection performance of the lightning rod was evaluated by the simulated lightning strike experiment described in Chapter 3 while changing the height of the lightning rod.

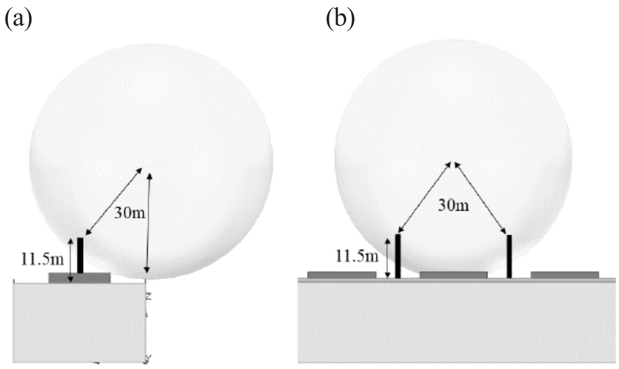

Figure 4. Rolling sphere diagram when three points touch: (a) front view; and (b) side view.

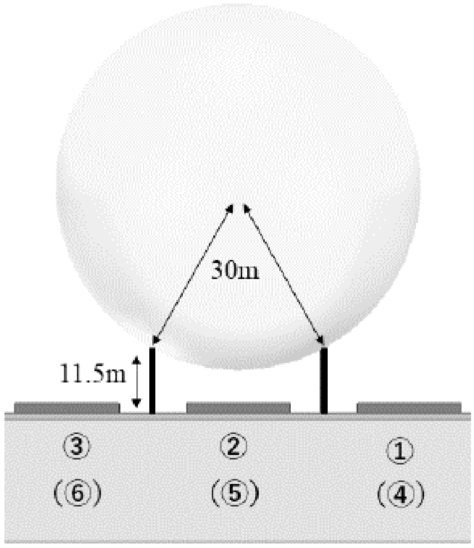

Figure 5. Side view with a rolling sphere installed on the center axis of the hull.

2.2. Overhead ground wire height design

In this study, two methods of installing overhead ground wire were considered. The first method was to install one overhead ground wire on the central axis of the hull, and the second method was to install two overhead ground wires on both sides of the ship. First, the design of the height when installing a single overhead ground wire is discussed. An overhead ground wire was installed using navigation lights at the front of the hull and an antenna on the bridge at the rear of the hull. As shown in Figure 1, the height of the navigation lights is 16.5 m, and the height of the antenna on the bridge is 27 m, from the deck. Figure 6 shows a rolling sphere that touches at two points, the overhead ground wire and the handrail at the front or the rear of the ship. From Figure 6, it can be confirmed that the rolling sphere did not touch the modules, and it was expected that the modules would be protected from lightning strikes.

Since installing an overhead ground wire in the central line of the hull would interfere with the use of the heliport, a method of raising the handrail and using it as an overhead ground wire was devised. Next, the design of the height when installing overhead ground wires on both sides of the ship is discussed. A rolling sphere diagram of when the rolling sphere touches the module and two overhead ground wires on both sides of the hull is shown in Figure 7. The height of the overhead ground wire was 7 m from the deck, and this height is the minimum height of the overhead ground wire that can protect the module from lightning strikes. Based on this height of the overhead ground wire, the lightning protection performance of the overhead ground wire was evaluated by changing the height of the overhead ground wire and applying simulated lightning strikes in the experiments described in Chapter 3.

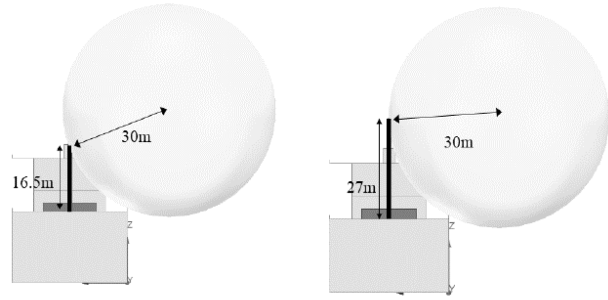

Figure 6. Rolling sphere diagram that touches at two points: (a) front part; and (b) rear part.

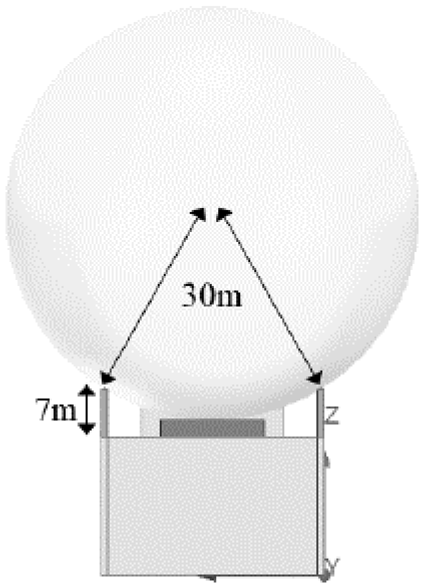

Figure 7. Rolling sphere with overhead ground wires installed on ship's sides.

3. Simulated lightning strike experiment

To evaluate whether the height-designed lightning rod and overhead ground wire can protect photovoltaic modules from lightning, simulated lightning strike experiments were carried out by using an impulse voltage power supply (Pulse Denshi, IVG-120B, IG). Since a real large ship could not be used for the experiment, a 1/500 scale model of the ship was made and used for these experiments. The hull of the model ship and the photovoltaic module were made by attaching conductive aluminum tape to wood. A brass rod with a sharp tip was used to simulate a lightning rod, and a stainless-steel wire with a diameter of 0.3 mm was used to simulate an overhead ground wire. Photographs were taken to confirm where the simulated lightning strike was bridged.

3.1. Simulated lightning strike test when lightning rods are installed

An experimental circuit diagram with a lightning rod installed is shown in Figure 8. A needle electrode simulating the tip of a lightning leader connected to the IG was placed on the model ship. A positive lightning impulse voltage with a peak value of 95 kV was applied to this needle electrode 20 times, and the place where the flashover bridged was photographed with a camera (OLYMPUS, OM-D) to determine whether the module was protected. Next, the needle electrode was placed so that the tip of the needle electrode coincided with the centre of the rolling sphere described in Chapter 2.

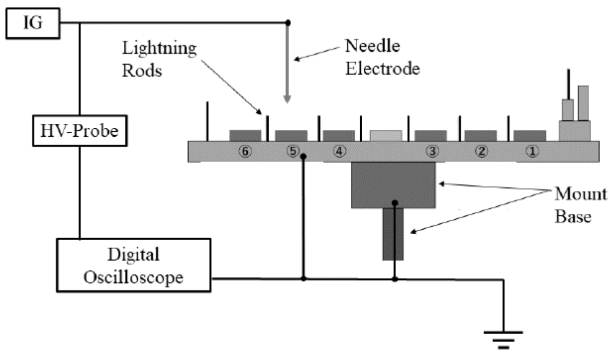

Figure 8. Experimental circuit diagram of the simulated lightning strike experiment with lightning rods.

First, a diagram of the needle electrode installation position at the position of the rolling sphere described in Figure 4 with the lightning rod at a height of 11.5 m is shown in Figure 9. This is an experimental condition assuming that a lightning leader descends on the central axis of the ship. After applying the lightning impulse voltage 20 times, there was no bridging to the modules, but 20 times of bridging to the lightning rod. A discharge photograph when a lightning impulse voltage was applied is shown in Figure 10. In Figure 10, a flashover occurred, the needle electrode and the lightning rod were bridged, and no bridging to the module was observed. This result shows that the lightning rod could protect the modules from lightning strikes.

Next, a diagram of the installation position of the needle electrode at the position where the tip of the lightning rod, the handrail, and the edge of the modules were in contact with the rolling sphere is shown in Figure 11. It is assumed that the lightning leader is shifted to the side and the module is susceptible to lightning strikes. The height of the lightning rod in Figure 11 is 11.5 m. When changing the height of the lightning rod, the height at which the needle electrode was placed in the experiments was changed by a distance corresponding to the change in the height of the lightning rod. Nine times out of 20, bridging occurred to the module, nine times to the lightning rod, and only two times to the handrail. A discharge photograph when a flashover bridged to the module is shown in Figure 12. The probability of lightning striking the module was found to be 45%, which was much higher than the expected value of 5%.

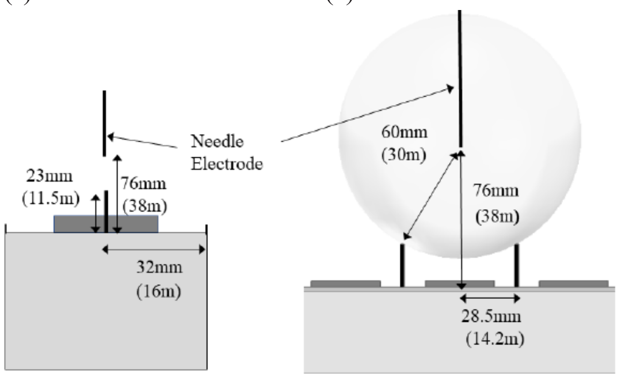

Figure 9. Needle electrode position on the central axis: (a) front view; and (b) side view.

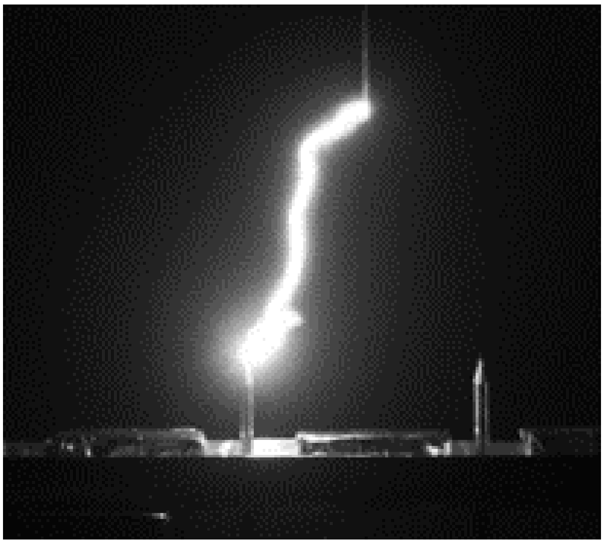

Figure 10. Discharge photo of the needle to the rod.

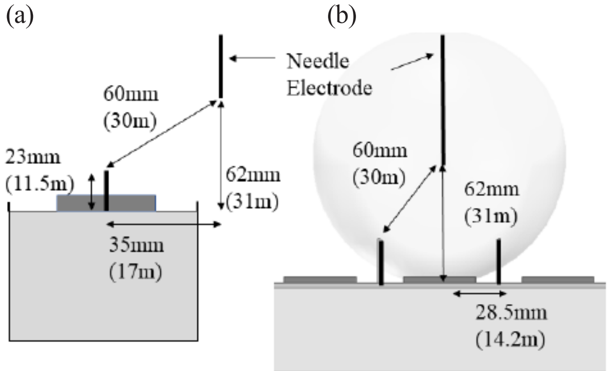

Figure 11. Needle electrode position on the off axis: (a) front view; and (b) side view.

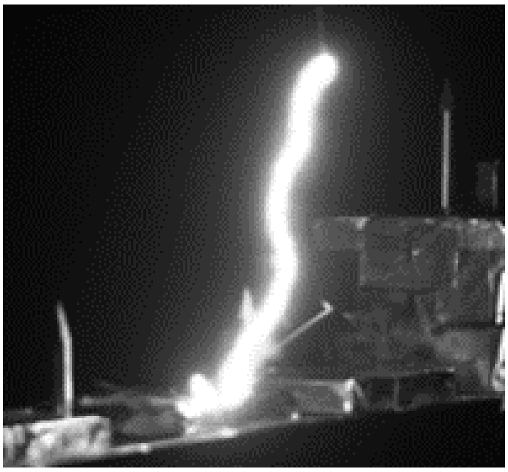

Figure 12. Discharge photo of the needle to the module.

At the height of the 11.5 m lightning rod, the lightning strike bridged the panel nine times. Then, the height of the lightning rod was raised to 12.5 m, the height of the model lightning rod was raised by 2 mm, and the experiments were conducted. The results of the experiment are that the lightning struck the module four times, the lightning rod 14 times, and the handrail two times, and the probability of lightning striking the module was lowered to 20%, but it was still higher than expected value of 5%.

From these results, when the lightning rods were used to protect the modules from lightning, the lightning rods on the central axis of the hull could protect the modules from lightning coming from the central axis. However, for lightning strikes from the off central axis of the hull, even if the height of the lightning rods was raised by 2 m, the protection probability was 80%, which is lower than the expected 95%.

3.2. Simulated lightning strike test when overhead ground wires are installed

An experimental circuit diagram when an overhead ground wire was installed on the central axis of the hull is shown in Figure 13. It is a similar circuit to the one in the experiment using the lightning rod. The installation position of the needle electrode was placed at the position corresponding to the center of the rolling sphere used for designing the height of the overhead ground wire. The hatch numbers where the modules were installed were numbered from one to six from the right side.

First, a diagram of the installation positions of the needle electrode when one overhead ground wire was installed on the central axis of the hull is shown in Figure 14. Figure 14(a) is a view near hatch one, and Figure 14(b) is a view near hatch 6. When the needle electrode was installed near hatch one, there was no bridging to the module even if the impulse voltage was applied 20 times. Flashovers were observed 13 times to the overhead ground wire, two times to the handrail, and five times to the hull. Photographs of a flashover bridging to an overhead ground wire or module are shown in Figure 15. As shown in Figure 15(a), since the overhead ground wire was high near the bridge, it was found that lightning strikes from above the central axis of the ship could be received by the overhead ground wire. As shown in Figure 15(b), when the needle electrode was installed near hatch six, the module was bridged two times, the overhead ground wire 13 times, and the handrail five times. It was found that when the overhead ground wire was lowered, there was a 10% chance of lightning strike penetration. Averaging the protection probability with the overhead ground wire of the front part and the rear part, the protection probability was 95%.

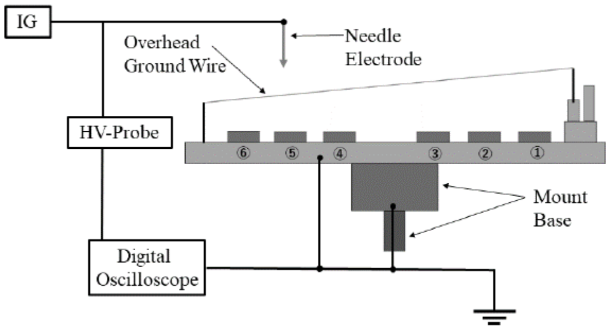

Figure 13. Experimental circuit diagram with a single overhead ground wire.

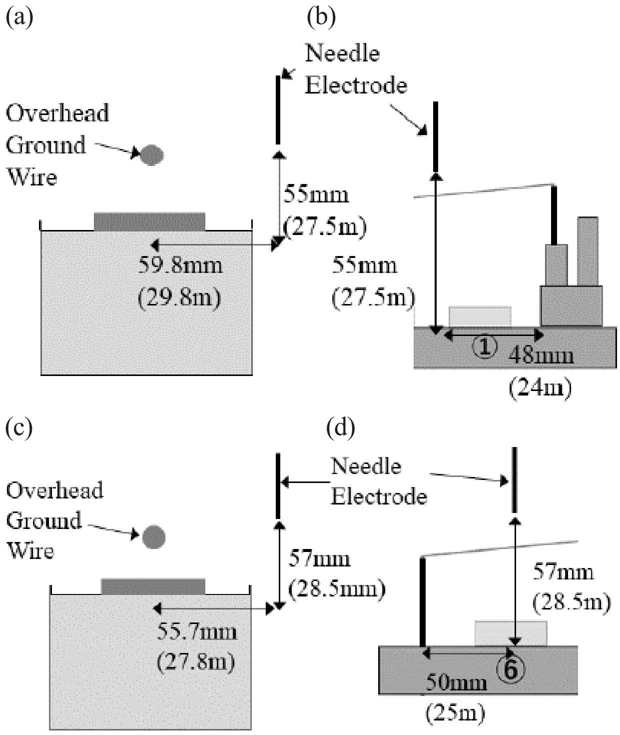

Figure 14. Position of the needle electrode: (a) front view near Hatch one; (b) side view near Hatch one; (c) front view near Hatch six; and (d) side view near Hatch six.

(a) (b)

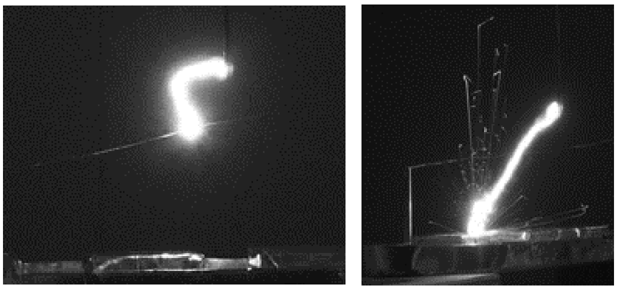

Figure 15. Photos of flashover: (a) to wire; and (b) to module.

Next, the rolling sphere and the installation positions of the needle electrode when overhead ground wires were installed at the upper part of both sides of the ship are shown in Figure 16. In Figure 16(a), the height of overhead ground wires is 7 m, and in Figure 16(b), the height of overhead ground wires is 8 m. When the height of the overhead ground wire was 7 m, the panel was bridged 14 times and the overhead ground wire was bridged six out of 20 times. When the height of the overhead ground wire was 8 m, the module was bridged nine times, and the overhead ground wire was bridged 11 times. Here, even if the overhead ground wire height was 8 m, the protection probability was very low at about 45%. Then, the experiment was conducted with the height of overhead ground wires increased to 10 m or 11 m. There was no bridging to the module out of 20 times, and 20 times of bridging to the overhead ground wires. The protection probability was almost 100% when two 10 m overhead ground wires were installed on both sides of the ship to protect the modules from lightning strikes. From these results, it was found that the photovoltaic modules can be reliably protected from lightning strikes by installing two overhead ground wires on both sides of the ship and increasing the height to 10 m.

(a) (b)

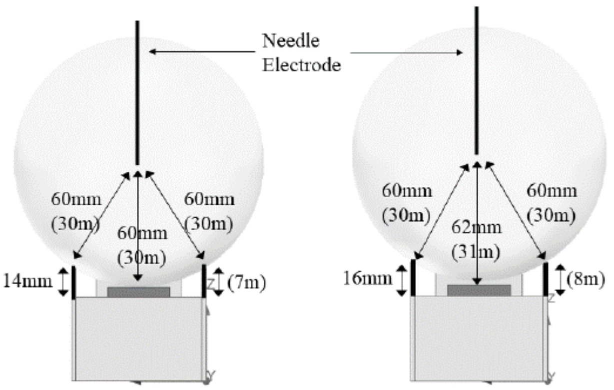

Figure 16. Position of the needle electrode: (a) wire height: 7m; and (b) wire height: 8m.

4. Conclusion

In this paper, to protect photovoltaic modules installed on large ships from lightning strikes, the height of lightning rods or overhead ground wires was designed. Simulated lightning strike experiments were conducted to evaluate whether the designed lightning rods or the overhead ground wires can protect the photovoltaic modules from lightning strikes. The results of the experiments show that overhead ground wires installed on both sides of a ship have a higher protection probability for the modules than using lightning rods. Furthermore, it was found that the ship's photovoltaic modules would be protected with an almost 100% probability by raising the height of the overhead ground wires to 10 m.

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