A novel protection method against direct lightning strike based on the principle of electrostatic field counteraction

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Abstract. Strong electromagnetic radiation around the conventional lightning rod system exists when it is struck by lightning, and serious electromagnetic interference on sensitive electronic equipments could be caused. A novel active protection method against direct lightning strike is proposed in this paper. The method, which is based on the principle of electrostatic field counteraction and shielding, is aimed at weakening the background electric field near the protection region to eliminate the condition for direct lightning strike there. The protection system is composed of three parts, including the monitoring equipments for atmospheric electric field, the active protection device, and the control system. Two working flow charts of the protection system are presented, and the feasibility of the protection method has been verified by scale-model experiment in the laboratory.

1. Introduction

Research on lightning has lasted over 250 years since lightning was validated as an electrical discharge by Benjamin Franklin. During these past years, the protection of structures and systems against lightning has experienced three stages: protection against direct lightning stroke, protection against induced effects of lightning, and protection against lightning electromagnetic pulse [1-3]. For the buildings, equipments and personnel inside, several technologies such as bonding, conducting, dividing, grounding, and shielding are adopted in lightning protection [4-5]. However, no protection measure is almighty. Although the conventional lightning rod system has a history of success in preventing or minimizing damage to structures, there is still potential safety hazard for sensitive electronic equipments [6-9]. Firstly, the conventional lightning rod systems for ground-based structures serve to provide lightning attachment points and paths for the lightning current to follow from the attachment points into the ground without harm to the protected structure. There is strong electromagnetic radiation around the lightning rod when it is stroked by lightning, which can generate serious electromagnetic interference on sensitive electronic equipments, or even damage them. Secondly, when the lightning rod is stroked by lightning, the touch voltage and step voltage caused by the lightning current can not be ignored. Moreover, air-termination system of the lightning rod is a huge grounded metallic conductor, which can affect the antenna characteristics of the devices near it (e.g. the antennas installed in the microwave stations, etc.) and thereby leads to technical performance degradation. Regardless of the above side effect, the latent dangers of being subjected to direct

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lightning stroke are difficult to be avoided for mobile equipments and vehicles, since it is almost impossible to install a lightning rod system for them which can not always provide a good grounding. Hence, the conventional protection technology against direct lightning stroke can not meet the technical requirements of electromagnetic protection for sensitive electronic equipments. In this paper, an active direct lightning protection method based on the principle of electrostatic field counteraction is proposed to solve this problem.

2. Principle of the active lightning protection method
A typical cloud-to-ground lightning is composed of a downward-moving process termed a downward stepped leader, a lightning attachment process with one or more upward-connecting leaders and an upward-moving process termed a return stroke. The lightning stepped leader, beginning in the thundercloud, propagates toward the ground in a series of discrete steps without being affected by the presence of the ground-based structures. As the stepped leader approaches ground, the electric field at the ground surface or objects increases until it exceeds the critical value for the initiation of upward connecting leaders. Note that the initiation of an upward-connecting leader basically depends on the distribution of the electric field near the possible initiation points. Only the point with the stronger background field may initiate an upward-connecting leader. Thus, the basic idea of the active protection method against direct lightning stroke in this paper is to weaken the background field near the protection region based on the principle of electrostatic field counteraction and electrostatic shielding, and to destroy the condition for direct lightning stroke at the protection region. According to the principle of vector superposition of electrostatic field, the basic electrostatic shielding strategies tend to fall into three categories as following [10]:

(1) Interposition of a “barrier” with good electric conductivity between the source and the area where the electric field needs to be reduced.
(2) Introduction of a mean capable of diverging the electric field from the area of interest.
(3) Introduction of an additional source whose effect is the reduction of the electric field levels in the prescribed area with respect to a situation involving the original source or source system.

According to the physical characteristics of lightning discharge and lightning strike selectivity, a combination of the electrostatic shielding strategies (1) and (3) is applied for the protection against direct lightning stroke. In order to weaken the background field near the protection region and destroy the condition for direct lightning stroke, an active protection device composed of two polar plates with high conductivity is introduced. The upper plate of the active protection device is driven by a high voltage DC generator, and the lower plate of the active protection device is earthed. When the electric field near the protection region becomes large enough, an appropriate voltage excitation will be applied on the upper plate to excite a reverse electric field which can weaken the electric field above the protection region and the active protection device. Thus, the electric field near the protected objects and the active protection device can not reach the critical value for the initiation of upward-connecting leaders. And the lightning strike points can only be selected outside the protection region.

3. Structure and working flows of the protection system
The active protection system based on the above protection method is composed of three elements including the atmospheric electric field monitoring equipments, the active protection device, and the control system. The atmospheric electric field monitoring equipments is mainly utilized for real-time monitoring of the background electric field generated by the thundercloud, which serves as the criterion for turning on and turning off the active protection device. The active protection device is mainly employed for producing a reverse electric field to weaken or counteract the background field near the protected objects, and preventing the upward streamer from forming. The control system is used for coordinating the orderly working of the electric field monitoring equipments and the active protection device, in order to optimize the working hours of the active protection device and save power.
When a thundercloud appears over the protection region, the intensity and polarity of the electric field at the protection region can be detected by the atmospheric electric field monitoring equipment. If the absolute value of the electric field intensity is stronger than the preset safety threshold $E_{S1}$, a downward lightning stepped leader may occur. At this time, turn on the active protection device to excite an artificial reverse electric field above the protection device. According to the principle of vector superposition, the artificial reverse electric field will weaken the background field above the device and exert an inhibitory effect on the initiation of the upward connecting leader at the protection region. Moreover, as long as the reverse electric field excited by the active protection device is strong enough, the direction of the total electric field above the active protection device will be opposite to the direction of electric field excited by the charged thundercloud or stepped leader. So, the probability that the lightning strike point is chosen at the protection region is very low, then the purpose of lightning protection can be achieved at the protection region.

As the criterion for turning on the active protection device is the electric field above the active protection device, it is necessary for one electric field monitoring equipment to be located on the active protection device. However, once the active protection device is turned on, the electric field near the device will change sharply. Thus, the monitoring results above the device at this time cannot be used as the criterion for turning off the active protection device. In order to resolve this conflict between electric field monitoring and active protection, two types of working flows are proposed: 1) alternative operation of the electric field monitoring equipment and the active protection device, as shown in figure 1. The working hours of the active protection device can be adjusted according to the research results. 2) Multi-sensors technology. As shown in figure 2, the electric field monitoring equipment EM$_1$ located on the active protection device is utilized to control the turn-on of the active protection device.

![Figure 1. Working flow chart of the protection system using single sensor.](image1)

![Figure 2. Working flow chart of the protection system using double sensors.](image2)
protection device, while the other electric field monitoring equipment EM_2 located outside the protection region is utilized to control the turn-off of the active protection device. Note that the safety threshold for turning off the active protection device is set as \( E_{S2} \), which is smaller than \( E_{S1} \).

4. Experimental validation of the protection method

In order to verify the feasibility of electrostatic field counteraction using the active protection device, a scale-model experimental system is designed as shown in figure 3. In this experimental system, two metal planes (No.1 plane with a radius of 0.25 m at a height of 1.1 m and No.2 plane with a radius of 0.2 m at a height of 1 m) are employed to represent the active protection device. A metal plane (No.3 plane) with a radius of 0.52 m is suspended at a height of approximately 4 m to represent the charged thundercloud, and a grounding metal plane (No.4 plane) is located on the ground. The active protection device is located inside the plane-to-plane gap which enables to simulate the background field generated by the thundercloud. Electric field measurements are performed using the electrometer SIMCO FMX-002, above the No.1 plane at a height of 1.175 m.

![Figure 3. Experimental platform diagrammatic layout.](image)

For charged thunderclouds of different polarities, submit the No.3 plane to a fixed voltage of 30kV and -30kV, respectively. By enhancing the applied voltage to the No.1 plane step by step (the same voltage polarity with that applied to the No.3 plane), we can obtain the relationship between the electric field monitoring results above the active protection device and the applied voltage to the No.1 plane, as shown in figures 4 and 5, respectively.

In figures 4 and 5, the absolute value of the total electric field above the active protection device decreases linearly with increasing applied voltage to the No.1 plane. When the applied voltage reaches a certain level (Here, its absolute value is approximately 2.5 to 3.0kV), the direction of the total electric field above the protection device will reverse; thereafter, the absolute value of the total electric field increases linearly with the increase of applied voltage. The above results show that the background electric field above the active protection device can be weakened or counteracted by the active protection device with appropriate applied voltage, which verify the feasibility of electrostatic field counteraction for the background field above the protection region.
Figure 4. Relationship between the applied voltage to the No.1 plane and electrostatic field above the active protection device when the potential of simulated thundercloud is 30kV.

Figure 5. Relationship between the applied voltage to the No.1 plane and electrostatic field above the active protection device when the potential of simulated thundercloud is -30kV.

5. Conclusions
Based on the principle of electrostatic field counteraction and electrostatic shielding, a novel lightning protection method by destroying the condition for direct lightning stroke at the protection region is presented with the combination of the atmospheric electric field monitoring equipments and the active protection device. To resolve the conflict between electric field monitoring and active protection, two types of working flows for the protection system are proposed. The feasibility of this active lightning protection method is verified by scale-model experiment in the laboratory. Moreover, further researches on applied voltage control of the active protection device and forecast of the charge polarity deposited on the lightning downward stepped-leader channel are required.

Acknowledgments
The research is supported by Research Program of Army under Grant No. 7130933.

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