New Theory and Engineering Design Method for Regional Lightning Protection

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Abstract The lightning accidents still occurred frequently in facilities protected by the protective angle method. After years of research, the expert team of the China Lightning Science (Jindun) Industry – University – Research Institute Collaboration Base has redefined the working principle of lightning rods, developed a new type of lightning rod (lightning interceptor), proposed a new theory of regional lightning protection, and established an engineering technology method for regional lightning protection (semi-circular method). Significant results have been achieved in multiple professional fields. In this paper, the research and application effects of lightning rods and protection angle method, regional lightning protection theory, and semi-circular method are introduced, which can be used as a reference for relevant technical personnel.

Key words Lightning rod; Protection angle method; Regional lightning protection; Lightning interception; Semi-circular method

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The defense against lightning disasters is an ancient and practical issue that needs to be faced by human society. In 1752, Franklin invented the lightning rod. In 1823, the French Academy of Sciences led by Gay Lussac and the study by Preece believed that "the lightning rod can protect a conical space, with its height equal to the length of the lightning rod and its bottom surface being a circle with a radius equal to the height of the lightning rod", abbreviated as the protection angle method. However, extensive practice has shown that lightning accidents still occurred frequently in facilities protected by the protective angle method. After years of research, the expert team of the China Lightning Science (Jindun) Industry – University – Research Institute Collaboration Base has redefined the working principle of lightning rods, developed a new type of lightning rod (lightning interceptor), proposed a new theory of regional lightning protection, and established an engineering technology method for regional lightning protection (semi-circular method). Significant results have been achieved in multiple professional fields, realizing important theoretical and technological innovations in the nearly 300 years since Franklin invented the lightning rod in 1752.

1 Lightning rod

1.1 Working principle According to Franklin's description on the function of lightning rods, the working principle of lightning rods is: under the action of the electric field at the end of downward leader of the lightning strike, a stronger electric field is induced than other ground objects, and the polarity of the charge is opposite to that of the downward leader. The upward developing leader is connected to the downward leader, attracting the lightning current to the needle tip and discharging it to the ground. Maxwell believed that lightning rods are conducting lightning to ground. Bouquegneau believed that lightning rods are interceptors[1]. In the relevant lightning protection standards of IEC, the interception function of lightning rods is adopted[2].

1.2 Protection angle method A lightning rod consists of a conductive metal material with a needle shaped end and a grounding system. In 1823, the French Academy of Sciences led by Gay Lussac issued a lightning protection guideline, claiming that a vertical lightning rod can effectively protect a circular space around its bottom, with a radius of twice the height of the lightning rod, providing a protection ratio of 2. Preece believed that "a lightning rod can protect a conical space, with its height equal to the length of the lightning rod and its bottom surface being a circle with a radius equal to the height of the lightning rod", namely the protection angle method[3].

The commonly used technology for preventing direct lightning strikes is the lightning rod invented by Franklin in 1752 worldwide. Without exception, the protection angle method (such as the 45° line method, rolling ball method, *etc.*) is used to calculate the protection range[3-5]. However, lightning accidents still occurred in many cases where lightning rods have been installed[6-7].

1.3 Attraction effect on lightning

1.3.1 Electric field strength of the charge at the downward leader end. The attraction effect of lightning rod against lightning (taking dipole negative lightning as an example) can be calculated using the formula (1) given by Gold[8]. It is assumed that the

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charge in the lightning channel follows an exponential distribution, meaning that the charge density is the highest at the top of the downward leader and decays exponentially towards the cloud. At the height of H above the ideal earth, the electric field strength below a point charge Q is:

$$E = \frac{1.8 \times 10^{10} Q}{H^2} \text{ (V/m)} \quad (1)$$

where E is electric field strength (V/m); Q is point charge (C); H is height above the ground (m).

According to the statistics from Mount San Salvatore in Switzerland, the average charge of a discharge is about 8 C[9]. At a distance of 50 m from the ground, calculated according to the formula (1), $E = 57.6$ MV. At a distance of 100 m above the ground, $E = 14.4$ MV. The formula (1) indicates that the electric field strength of the lightning discharge channel is inversely proportional to the square of the charge height. It means that the downward leader of lightning can develop to places very close to the ground before the upward leader develops on the ground.

1.3.2 Attractive force between the charges at the end of upward and downward leaders. After installing a lightning rod at a certain height on the ground, when the electric field at the end of downward leader of lightning continuously approaching makes the ground electric field strength reach the corona threshold of the lightning rod, the lightning rod ionizes the surrounding air to produce corona. The positive ions of corona are attracted by the downward leader of lightning to form corona current, which is constrained by Coulomb force and moves towards the end of downward leader of lightning. This corona current is called upward leader, also known as upward developing streamer. Observations have shown that when downward leader of lightning develops to the second to last step, it is not yet affected by objects on the ground (streamer), and only the last step converges with the upward streamer on the ground (the last jump)[10]. From the optical photograph, it can be seen that the charges at the end of upward leader and the charges at the end of downward leader of lightning attract each other, and their attractive force can be calculated using the formula (3)[11]:

Supposed that the dielectric constant of the medium is ε, the relative dielectric constant is ε_s, the vacuum dielectric constant is ε_0, and $\varepsilon = \varepsilon_0 \varepsilon_s$.

Because:

$$\varepsilon_0 = \frac{10^7}{4\pi c^2} = 8.85 \times 10^{-12} \text{ [F/m]} \quad (2)$$

where c is speed of light (m/s), and $\varepsilon_s = 1$ in the air,

Then there is:

$$F = \frac{1}{4\pi} \cdot \frac{4\pi c^2}{10^7} \cdot \frac{Q_1 Q_2}{r^2} = 9 \times 10^9 \times \frac{Q_1 Q_2}{r^2} \text{ [N]} \quad (3)$$

where Q_1 is charge at the end of upward leader (C); Q_2 is charge at the end of downward leader (C); r is the distance between Q_1 and Q_2 (m); F is force (N).

The formula (3) illustrates the attraction effect of upward leader generated by the lightning rod on lightning.

1.4 Scope of protection[12] The rolling ball method is a geometric simulation method that uses the geometric distance of discharge path as the criterion for lightning rod protection. It is assumed that the lightning leader starts from the thunderstorm cloud and is not affected by any ground features, that is, the discharge develops freely. When the lightning leader reaches a certain height h above the ground, the leader begins to deflect towards the protruding object on the ground. The distance from the deflection point p to the lightning rod tip is the strike distance r, $r = 10i^{0.65}$ (m). r is used to draw an arc on the ground, and the area under the arc is the protection range of lightning rod. The protection range of a single lightning rod on the ground is shown as the formula (4):

$$r_0 = \sqrt{h\ (2h_r - h)} \text{ (m)} \quad (4)$$

where r_0 is protection radius of lightning rod on the ground (m); h is height of lightning rod (m); h_r is radius of rolling ball (m).

1.5 Defects in lightning rods In 1777, after the installation of lightning rods in the powder depot of Puflett Town, London, it was still damaged by lightning strikes. The limitations for protection effectiveness of lightning rods were observed for the first time. On August 27, 2022, the launch pad of new generation of lunar rocket "Space Launch System" in the Kennedy Space Center, which was protected by three independent lightning rods (with lightning conductors), was struck by lightning for four times, causing damage to the rocket[13]. Long-term practice has proven that lightning rods have five defects[14].

1.5.1 Low attractiveness. The upward leader generated by the lightning rod is approximately 50 m on average. Obviously, the attraction of lightning rod to the downward leader of lightning is too low. Under certain conditions, it does not function as a lightning rod, which explains why the protected object is still damaged by lightning strikes even after installing a lightning rod.

1.5.2 Lightning current has not decayed. Because lightning rod is composed of a conductive metal material with needle shaped end, it does not attenuate lightning currents like other metal materials.

1.5.3 Strong electromagnetic effect of source current. Calculated based on a 30 kA of lightning current, the 2.4 GS strength radius of a regular lightning rod is 25 m. The strong electromagnetic pulse (LEMP) generated by it is not suitable for use in buildings with information systems and flammable and explosive places.

1.5.4 Cannot prevent side lightning strikes. For the protected objects, lightning strikes can be divided into overhead lightning and side lightning (including side down lightning) according to the spatial position of lightning movement path. The lightning protection probability of lightning rods for side lightning is only 10%.

1.5.5 Cannot protect an area. It protects a single building (structure) by the protection angle method.

2 Lightning interceptor

2.1 Redefining the working principle of lightning rods In order to study the activity patterns of lightning, Yang Hui *et al.* studied the lightning location data in Laoba District, Guangzhou in

2004. They found that after the first discharge of lightning in a specific area, the second discharge would occur after an average interval of 273 s, accompanied by strong winds of 5 – 8 levels[15]. The average time interval between two lightning strikes observed by Peckham *et al*. in Florida was 5 min. Pierce observed that wind speed was 20 – 30 km/h during lightning strikes on plains[16]. The time interval between two lightning strikes and the surface wind speed determine the spatial distance between the two lightning strikes, which is related to the physical process of lightning rod corona discharge.

Shielding effect of corona discharge on downwind direction. Ogden thought that the decrease in downwind potential gradient caused by space charge generated by the discharge current at the tip was[17]:

$$\Delta E \approx \frac{1}{2\pi\varepsilon_0 Vh}\left[1+\frac{d}{(d^2+h^2)^{\frac{1}{2}}}\right] \quad (5)$$

where ΔE is the amount of downwind potential reduction caused by the space generated by the discharge current at the tip (V/m); v is wind velocity (m/s); h is the height of lightning arrester (m); d is the distance between a downwind point and the lightning arrester (m); ε_0 is vacuum dielectric constant ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m).

Yan Muhong used a two-dimensional time-varying axisymmetric model to numerically calculate the spatiotemporal distribution of near ground charge density and electric field under thunderstorm conditions with a fixed metal tip discharge on the ground. This indicates that the space charge generated by isolated metal tip corona discharge can be utilized to suppress the growth of the electric field in the area below the tip height, with a maximum charge density of approximately 0.8×10^{-9} C/m^3.

Sun Anping *et al*. utilized a coupling mode of cumulus cloud charging and natural tip corona discharge on the ground. Considering the effects of advection and convection, the horizontal and vertical diffusion ranges of corona ions released by natural tip corona discharge on the ground reached 4 and 7 km, respectively[18].

Qie Xiushu *et al*. studied the variation characteristics of ground electric field with the distance of lightning strike point[19]. The variation pattern was shown as Fig. 1.

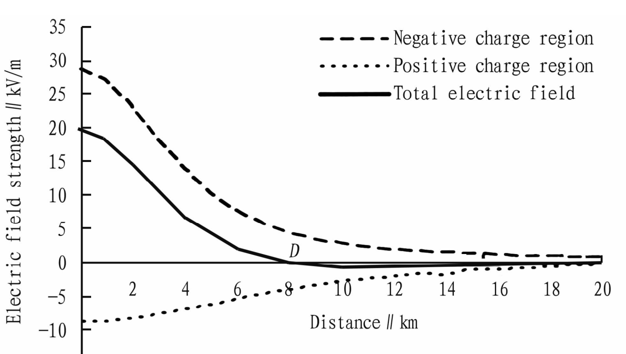


Fig. 1 Variation characteristics of ground electric field with distance

A new definition for the working principle of lightning rods. Since 1968, the research results of lightning scientists at home and abroad have shown that while corona ions of lightning rods attract lightning, ground objects in a certain area downwind will be covered (shielded) by the corona ion layer, and lightning strikes will no longer occur. This was consistent with the research results of Yang Hui *et al*. Based on this, Yang Shaojie redefined the working principle of lightning rods[20]: "under the action of electric field at the end of downward leader of lightning, the tip of lightning rod reaches the corona threshold and ionizes the surrounding air to produce positive and negative ions; constrained by Coulomb's law, ions with opposite polarity to the electric field at the end of downward leader of lightning are attracted by the electric field force, to form an upward leader (corona current, also known as streamer). It moves towards the end of downward leader of lightning, and they are connected, attracting lightning to the tip of needle (establishing a lightning discharge channel and discharging lightning current to the ground). Repelled by the electric field force and the combined effect of wind (advection transport), ions with the same polarity as the electric field at the end of downward leader of lightning are diffusing into the downwind area to form the ion cloud (shielding layer), to suppress the increase of corona current at the tip of ground objects".

The newly defined working principle of lightning rods proposes the concept of ion cloud: "ion cloud refers to that in positive and negative ions generated after the corona of lightning rods, ions with the same polarity as the electric field at the end of downward leader of lightning are repelled by the electric field force. Under the combined effect of wind (advection transport), the cloud like distribution pattern of ion layer is formed in the downwind direction". The concept of ion cloud is a vivid description on the physical process of coupling corona discharge at the tip of a lightning rod with the electric field at the end of downward leader of lightning.

2.2 Developing a new type of lightning rod (lightning interceptor)

2.2.1 Theoretical basis of research and development. The foundation for designing lightning interceptors is comprehensively understanding the physical process of lightning discharge. Lightning discharge is a specific form of electromagnetic wave motion in nature (geomagnetic storm is also another specific form). The United States has included high-altitude nuclear explosions, lightning discharges, geomagnetic storms, *etc*. in the category of electromagnetic pulses[21–23]. The abbreviation of lightning electromagnetic pulse in English is LEMP, and its motion law is constrained by Maxwell's equations. When electromagnetic pulses act on physical media, transmission line and waveguide theory can be used for analysis and calculation, to study the impedance, reflection, standing wave ratio, *etc*. during the transmission process[24–25]. From an optical perspective, lightning discharge can produce a flash of white light, which is constrained by dispersion theory. From the perspective of electromagnetic fields, the frequency components and amplitude characteristics of electromagnetic pulses can be determined by Fourier series and transformation. From an energy perspective, the frequency energy distribution of electromagnetic pulses can be calculated using the Parseval energy equation[26]. These theories and methods are the bases for studying new lightning rods that overcome the five shortcomings of traditional lightning rods.

2.2.2 Working principle and technical specifications of lightning interceptor[27].

(1) The upward leader is 46.55 m longer than that generated by the lightning rod. The omnidirectional multi-pulse lightning interceptor adopts a dispersion waveguide resonant cavity structure design. When lightning approaches, the charges with the opposite polarity to the charges at the bottom of the thunderstorm cloud are induced on the ground. The polarity converter of waveguide resonant cavity converts the polarity of ground charge and sends it to the amplitude spectrum selection/impedance converter of the cavity. The cavity resonates and delivers charges to the end of the cavity, causing Q folds of charges with opposite polarity to the charges at the bottom of the thundercloud to accumulate at the end of the cavity. When the air breakdown threshold is reached, corona discharge begins, and an upward leader is generated. It achieves that a lower electric field at the bottom of the thunderstorm can induce a longer upward leader than the lightning rod. According to the inspection of national third-party inspection agency, the omnidirectional multi-pulse lightning interceptor generates a corona current 46.55 μs earlier than the lightning rod, equivalent to 46.55 m longer than the corona current (upward leader) generated by the lightning rod.

(2) Reducing the current at the lightning strike point by more than 75%. Based on the double exponential wave characteristics of lightning current, the amplitude and energy spectrum of lightning waves can be obtained using the Fourier transform and the Parseval's identity. According to the amplitude and energy spectrum distribution of lightning waves, the dispersion waveguide resonant cavity adopts amplitude spectrum selection/impedance transformation, wave impedance voltage multiplication technology, and distributed parameter control technology, which enables the lightning interceptor to have good spectrum selection and wave impedance adaptive ability. The waveguide cavity reflects the lightning current of spectral components outside the passband f_0 (including continuous current, which accounts for 75% of the total discharge charge) back to the input end according to the wave equation, and converts the energy into thermal energy, thereby limiting the output lightning current spectrum within the passband f_0. In theory, the output current is only about 25% of the input current. In years of outdoor operation, it has been tested that the attenuation of lightning current is greater than 60%, which has a significant effect on reducing the current at the lightning strike point.

(3) Significantly reducing the electromagnetic field strength at the lightning strike point. The omnidirectional multi-pulse lightning interceptor can significantly reduce the current at the lightning strike point. Therefore, the spatial electromagnetic field generated by lightning current flowing through the down conductor is significantly reduced. Based on the global average negative lightning current of 30 kA, the radius of a regular lightning rod with a 2.4 GS of strength is 25 m. But after installing a lightning interceptor, the radius of a 2.4 GS of strength is reduced to 6 m.

(4) Capable of intercepting direct and side lightning strikes. Compared with lightning rods, the lightning receiving probability of direct lightning strike is 100%, and the lightning receiving probability of side lightning strike is 100%. Among them, the vertical rod has a 10% of lightning receiving probability, while the horizontal rod has a 90% of lightning receiving probability.

The omnidirectional lightning interceptor has the ability to automatically identify the spatial location of lightning, efficiently intercept direct and side lightning strikes, significantly attenuate the current at the lightning strike point, reduce the electromagnetic field strength at the lightning strike point, and adapt to the multi-pulse discharge of natural lightning. In April 2022, it obtained a national utility model patent, and applied for an invention patent and an international PCT patent[28].

2.3 Proposing regional lightning protection theory and establishing engineering design technology methods

2.3.1 Regional lightning protection theory. According to the working principle of lightning rods, Yang Shaojie proposed the regional lightning protection theory[29]: "after installed lightning interceptors in the upwind direction of lightning strike path in the protected area to effectively intercept (attract) lightning, the corona current at the tip of ground objects in a limited area downwind from the lightning strike point is equal to zero. The tip of a ground object has a dual effect of attracting and shielding lightning. By utilizing the attraction and shielding effect of the tip of a ground object on lightning, the occurrence of direct lightning strikes in a limited area downwind can be avoided or reduced".

Its connotation is: the mirror induction of electric field at the end of downward leader of lightning causes corona discharge at the tip of ground objects, producing positive and negative ions. Constrained by Coulomb force, ions with opposite polarity to the electric field of downward leader develop towards the downward leader direction to form an upward leader. The longest upward leader is connected to the downward leader, playing a role in attracting lightning. At the same time, ions with the same polarity as the electric field of downward leader are repelled by the electric field of downward leader. By the combined effect of wind (advection transport), they diffuse in the downwind direction to form an ion cloud, which suppresses the increase of corona current at the tip of ground objects in the coverage area of the ion cloud. Its upward leader's length is equal to zero, playing a role in shielding lightning.

Obviously, the regional lightning protection theory reveals the general law of lightning discharge at the tip of ground objects, which is a theoretical innovation of lightning protection.

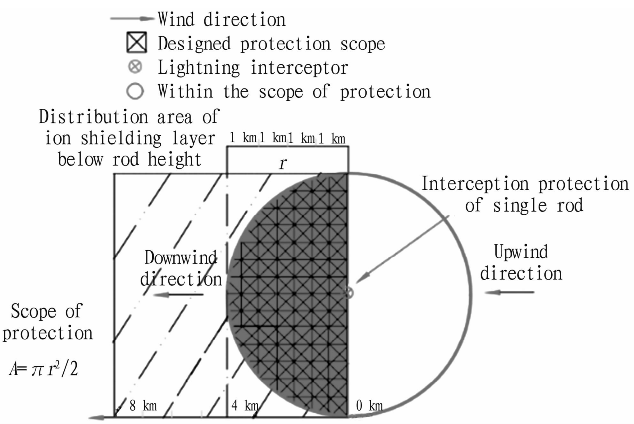
2.3.2 Establishing a technical method for regional lightning protection engineering design (semi-circular method).

(1) The concept of semi-circular method. Based on the local lightning activity law, lightning interceptors are installed in the upwind direction of main path of lightning occurrence. It can effectively attract (intercept) lightning and attenuate the current at the lightning strike point, avoiding or reducing direct lightning strikes in the downwind protection area and optimizing the electromagnetic field environment.

(2) The protection scope of semi-circular method[30-31]. The protection area within the straight-line distance from the upwind first interception point to the downwind direction of lightning activity path, which does not exceed the protection height of upwind first interception point, is calculated according to the following formula:

$$A = \frac{\pi r^2}{2} \tag{6}$$

where A is the area of protected zone (m^2); r is the distance between two lightning strikes (m). The plan of regional lightning protection scope is shown as Fig. 2.



Note: Evaluated based on a 5-min interval between two lightning strikes and a ground wind speed of 8 - 20 m/s.

Fig. 2 Protection range of semi-circular method

(3) Design process of semi-circular method. According to the definition of regional lightning protection concept, the steps of semi-circular design method are as follows: ① the geographical environment and geometric shape of protected area; ② the area of zone; ③ lightning strike path (can be obtained from lightning location system or local wind direction frequency rose chart, *etc.*); ④ upwind interception point; ⑤ the gradient distribution of ion cloud electric field in the downwind protected area; ⑥ determining the protection range [calculated according to the formulas (5) and (6)]. The above content is also known as the six elements of semi-circular method design.

2.3.3 Application effects of semi-circular method.

(1) Wind farms achieved zero lightning damage. From 2020 to 2024, a wind power generation company in Guangdong Province applied the semi-circular method to conduct project application research at a Dianbai wind farm where equipment was damaged by lightning strikes every year. Within a 20 km^2 range of the wind farm, it has experienced 96 thunderstorm days and 1 778 lightning strikes. The maximum current of negative flashover was 168 kA, and the maximum current of positive flashover was 192.3 kA. It realized zero lightning damage to wind turbines in the wind farm for five consecutive years[32-33].

(2) Zero tripping of high-voltage transmission lines. In 2022, three of the six high-voltage transmission lines in a wind farm in the Daliang Mountain, Sichuan Province, with a total length of about 40 km, were installed with lightning interceptor JD-MS-T45-1 using the semi-circular method. The lines were tested by multiple lightning strikes, and the high-voltage switches did not trip. However, the other three lines without lightning interceptors experienced the multiple trips of high-voltage switches[34].

(3) Realizing zero lightning damage on highways. In 2020, the semi-circular method (lightning damage to PLC, weighing scales and other equipment) was applied on a highway in Shenzhen, achieving zero lightning damage[35].

(4) Offshore wind farm achieved zero lightning damage. In 2023, due to EPD of multiple wind turbines being damaged by lightning strikes in 2022, a offshore wind farm in Zhuhai applied lightning interception technology to conduct the research on "Strong Electromagnetic Pulse Protection (Lightning) Technology Project of a Yuedian Zhuhai Sea Wind Farm", intercepting 22 lightning strikes (including 6 for 6# wind turbine, 8 for 18# wind turbine, 2 for 45# wind turbine, and 6 for 11# wind turbine), and achieving zero lightning damage to offshore wind farms for the first time internationally.

(5) Northern forest region of Greater Khingan Mountains, Inner Mongolia. In the *Research Project on Lightning Protection Tower for Lightning Fire Prevention and Control Technology* by the Emergency Department of Inner Mongolia Autonomous Region in 2023, three watchtowers in a forest farm in the northern forest area were selected to install omnidirectional lightning interceptors and satellite intelligent monitoring systems. At 13:39 on June 20, the system recorded intercepting a lightning strike for six consecutive pulses with a pulse amplitude of +72.43 kA, and preliminary results have been achieved.

(6) 5 000-year-old ancient cypress tree and Mausoleum of the Yellow Emperor Scenic Area in Huangling County, Shaanxi Province. The regional lightning protection technology was applied for ancient buildings and ancient trees in the nearly 60 km^2 area of the Mausoleum of the Yellow Emperor, a national key project in Shaanxi Province in 2023. It intercepted lightning twice during the Qingming Festival in 2024, and ensured the smooth progress of the Ancestral Worship Ceremony at the Mausoleum of the Yellow Emperor in Jiachen Year attended by Ma Ying-jeou.

3 Conclusions

3.1 Historical role and defects of lightning rods Since Franklin invented the lightning rod in 1752, it has played an important role in preventing direct lightning damage to buildings.

However, the understanding on the role of lightning rods is a long historical process. Franklin began to believe that lightning rods could neutralize lightning and prevent lightning strikes. Later, he believed that lightning rods could provide a preferred discharge pathway for lightning. Maxwell believed that lightning rods are conducting lightning to ground. Bouquegneau believed that lightning rods are interceptors. Due to the lack of research on the physical process of how lightning rods to protect against lightning, people have not fully grasped the working principle of lightning rods. They only used the effect of lightning rods to attract lightning and determined the protection range by the protection angle method. Therefore, there are five defects, which lead to frequent lightning accidents in places where lightning rods are installed.

3.2 Invention and application prospects of lightning interceptors The lightning interceptor invented by applying electromagnetic field theory and dispersion waveguide resonant cavity technology has achieved the technical goal of generating a longer upward leader than the lightning rod and attenuating the current at the lightning strike point, and effectively overcame the five defects of lightning rods. The semi-circular method effectively solved the problem that the protection angle method can only protect one single unit and cannot protect one area. It has achieved significant results in multiple professional fields of China. Obviously, the regional lightning protection theory and the semi-circular method are the most important theoretical and technological innovations in the nearly 300 years since Franklin invented the lightning rod in 1752. They provide new theoretical and technological support for solving the five major technical problems in the international lightning protection field and for human defense against lightning disasters.

So far, due to the use of traditional lightning protection theory and protection angle method, lightning damage to outdoor modern facilities such as new energy, electricity, chemical industry, transportation, ancient trees and buildings, forests and grasslands and other professional fields has become increasingly serious. The application of regional lightning protection and semi-circular method can greatly avoid or reduce the occurrence of lightning disasters.

3.3 Intensifying the promotion of technology to ensure high-quality economic development in various professional fields Practice has proven that the application of new theories and technologies for regional lightning protection can effectively ensure the safety of people's lives and property. In various related professional fields, it can increase the promotion of new theories and technologies for lightning disaster prevention, carry out pilot applications, track application effects, organize experience exchanges, and formulate relevant technical standards, to ensure high-quality economic development in various professional fields.

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