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Exploration of New Methods of Lightning Strike Risk Assessment in Wind Farms

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Abstract In the past, the lightning strike risk assessment of wind farms mainly referred to the *Lightning Protection Part* 2: *Risk Management* (IEC 62305 – 2 – 2010) and the *Lightning Protection of Wind Energy System* (IEC 61400 – 24 – 2019) based on protection angle method. In fact, the basic idea of the two is the same, that is, the source of the lightning fan is replaced by S1 – S4 of the former lightning building with the latter ND-NDJ. According to the above method of wind farm evaluation, it has been proved that the practice can not achieve good results. Taking offshore wind farm as an example, this paper introduces a new method of establishing six evaluation indicators to determine the risk level according to the new technology and compliance principle of regional lightning protection (semi-circular method), which can be used for reference by wind farm technicians.

Key words Sea and land wind electric field; Lightning strike risk assessment; Compliance principle; New evaluation method

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In 2018, Yang Hui *et al.* put forward the new concept and semi-circular method of regional lightning protection[1]. Practice has proved that the probability of direct lightning stroke of buildings in the protection area is greatly reduced after installing lightning receiving devices in the upwind direction of the protection area to effectively intercept lightning stroke. The lightning protection design of 33 fans in Dianbai Wind Farm adopted the protection angle method before June 2019, and 16 fans have been damaged by lightning. The semi-circular method was adopted in June 2019. It has been more than five years, and has withstood the test of many typhoons, squall lines and other most serious lightning strikes to achieve zero lightning damage to the wind turbine. From June to August 2022, lightning stroke at Biqingwan Offshore Wind Farm in the South China Sea caused damage to the EPD of 8 wind turbines. The regional lightning protection reconstruction was completed in August 2023, and it experienced 434 lightning strokes in the thunderstorm season in 2023 and 2024. The pitch system and SCADA system of wind turbine have not been damaged, and zero lightning damage has been achieved in the first year[2].

Practice has proved that the lightning risk assessment method based on the protection angle method[3] is not suitable for guiding the lightning protection of wind farms with the main characteristics of wind turbine blade receiving lightning[4]. In 2012, China promulgated the *Evaluation Guide of Lightning Protection Technology for Buildings* (T/GZLY 3 – 2022) and the *Technical Specification for Lightning Interception in Forest Area* (T/LYCY 4062 – 2024) based on regional lightning protection (semi-circular method). The definition of risk source by lightning point is closer to reality, with strong pertinence and remarkable effect. This paper introduces the evaluation method of establishing six compliance indicators according to the compliance principle and with reference to the new technology of regional lightning protection (semi-circular method)[5], which can be used as a reference for wind farm technicians.

1 Basis of evaluation

1.1 Deficiencies of traditional lightning protection technology The direct lightning protection of wind turbine mainly adopts the electrical geometric model-protection angle method, but it has some defects, such as insufficient consideration of the length of upstream leader, lightning current attenuation and so on[6]. In the *Design Code for Protection of Structures against Lightning* (GB 50057 – 2010), it is clearly pointed out that: Class 1 lightning protection building $r = 30$ m, $i = 5.4$ kA; Class 2 lightning protection building $r = 45$ m, $i = 10.1$ kA; Class 3 lightning protection building $r = 60$ m, $i = 15.8$ kA. When the minimum lightning current value is less than the corresponding value, the lightning rod cannot effectively intercept[7]. The *Wind Energy System Part* 24: *Lightning Protection* (IEC 61400 – 2019) also clearly points out that the protection angle method (rolling ball method) is not applicable to the lightning protection of wind turbines. In article 4.2.3 of the *Code for Design Protection of Petrochemical Plant against Lightning* (2022 version, GB 50650 – 2011), "rotating equipment shall not be used as lightning arrester"[8].

Single-pulse voltage protector (SPD) is mainly used for

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lightning electromagnetic pulse protection of wind turbine, but it also has obvious defects such as being unable to withstand multi-pulse impact of natural lightning[9]. In 2011, IEC approved and issued the *Additional Tests for Multi-pulse Surge Protective Devices Connected to Low-voltage Power Systems: Performance Requirements and Test Methods* (IEC 61643 – 11 2011 – 2). In 2022, the Ministry of Construction issued the *Multi-pulse Surge Protective Devices for Low-voltage Distribution Systems: Performance Requirements and Test Methods* (T/ASC 6004 – 2022). Multi-pulse surge protective device (MSPD) overcomes the defects of single-pulse surge protective device (SPD), and is an alternative lightning protection device to prevent lightning electromagnetic pulse from damaging equipment and causing fire and explosion accidents.

1.2 New theory and technology of regional lightning protection Regional lightning protection refers to the technical method of installing lightning interceptors in the upwind direction of the main path of lightning to effectively intercept (attract) direct lightning stroke in the protected area requiring lightning protection, which can avoid or reduce the direct lightning stroke of ground objects in the limited downwind direction of the lightning point and optimize the electromagnetic environment[10–11]. Different from the protection angle method which uses the lightning rod to attract lightning, regional lightning protection uses the shielding effect of lightning rod on lightning discharge in the downwind direction to protect the downwind semi-circular area, also known as the semi-circular method[12].

The core technologies of regional lightning protection include three core technology systems: lightning point identification technology, direct lightning interception technology and high-energy absorption technology of lightning electromagnetic pulse[13]. It has achieved remarkable results in the application of sea and land wind power, high-voltage power transmission, outdoor chemical industry, highway, forest lightning fire and other professional fields[14]. In 2022, Guangzhou Municipal Bureau of Housing and Urban-rural Development approved and issued the *Design Code for Protection of Structures against Lightning* (T/GZLY 3 – 2010). In 2024, the China Forestry Industry Federation issued the *Technical Specification for Lightning Interception in Forest Area* (T/LYCY 4062 – 2024). The technical method of regional lightning protection (semi-circular method) in these standards can be directly applied by other specialties, just as the protection angle method (rolling ball method) of lightning rod is applied by other specialties.

2 Lightning protection status and risk assessment of wind farms

2.1 Assessment content

2.1.1 Geographical environment. The site of Biqing Bay Sea Wind Farm in the South China Sea is located in the sea area south of Sanzao Island in the South China Sea. The boundary of the wind farm site is about 10 km from Sanzao Island in the north, about 10 km from Gaolan Island in the west, about 15 km from Hengqin Island in the northeast, and about 20.5 km from Xiaowanshan Island in the east. Sanzao Island in the north of the site is Zhuhai Sanzao Airport. Its runway runs from northeast to southwest, parallel to the long side of the wind farm site boundary. The closest distance between the airport side and the wind farm is about 10.5 km. The sea area of the planned site is about 52 km^2, and the seabed depth elevation is between – 11.9 and – 21.9 m (unless otherwise specified, the elevation adopts the 1985 national elevation system), belonging to the offshore wind farm.

2.1.2 Wind farm scale. The total planned capacity of the project is 300 MW, and it will be completed in one phase. It is proposed to install 55 offshore wind turbines (5.5 MW), and the position layout of wind turbines are shown in Fig. 1. A 220 kV marine booster station will be built. The marine booster station will be connected to the onshore centralized control center through secondary-circuit 220 kV submarine cables, and the submarine cable route is about 17.3 km long. First-circuit 220 kV line from the onshore centralized control center will be connected to 220 kV Jinhe station, and the new line is about 15 km long.

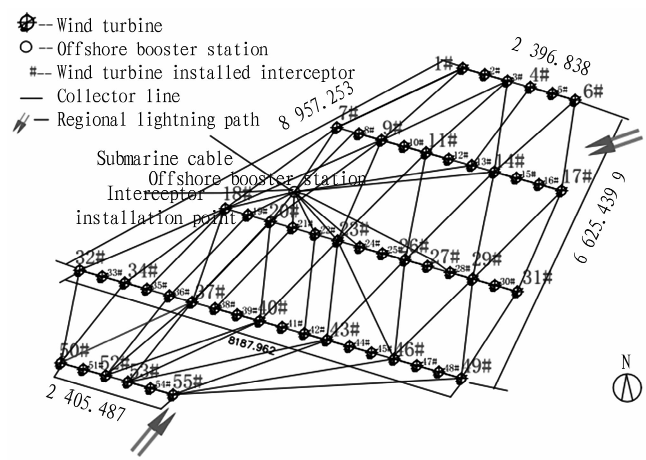

Fig. 1 Layout of wind turbines and interceptors in wind farm

2.1.3 Lightning path. According to the monthly wind rose chart of the offshore wind tower at Biqing Bay Sea Wind Farm in the South China Sea from 2016 to 2017, the wind direction at the maximum frequency is ENE from January to March, E from April to May, SW from June to July, ENE from August to September, NNE in October, and N from November to December, as shown in Fig. 2. The high incidence period of thunderstorms in Guangdong Province is from April to October. Therefore, the lightning path of the sea wind farm is east – west direction from April to May, south, west – north, east direction from June to July, west, south, west – east, north, east direction from August to September, and north, north, east – south, south, west direction in October[15]. Obviously, the lightning path of this sea wind farm is variable.

2.1.4 Lightning protection design basis and measures. According to the design documents checked on site, the wind farm is designed with new regional lightning protection technology, and the data are complete. Lightning interceptor JD-MS-T45-1 is used for direct lightning protection[16], and the protection method is semi-circular method. Multi-pulse surge protector and high-energy absorber are used for lightning strong electromagnetic pulse protection. 1380V/HEAD is installed in the wind turbine engine room, 1140V/HEA is installed at the output end of the frequency converter, and 220V/MSPD is installed in the tower base control cabinet[17-18]. The grounding of lightning protection device uses the original grounding system of wind turbines.

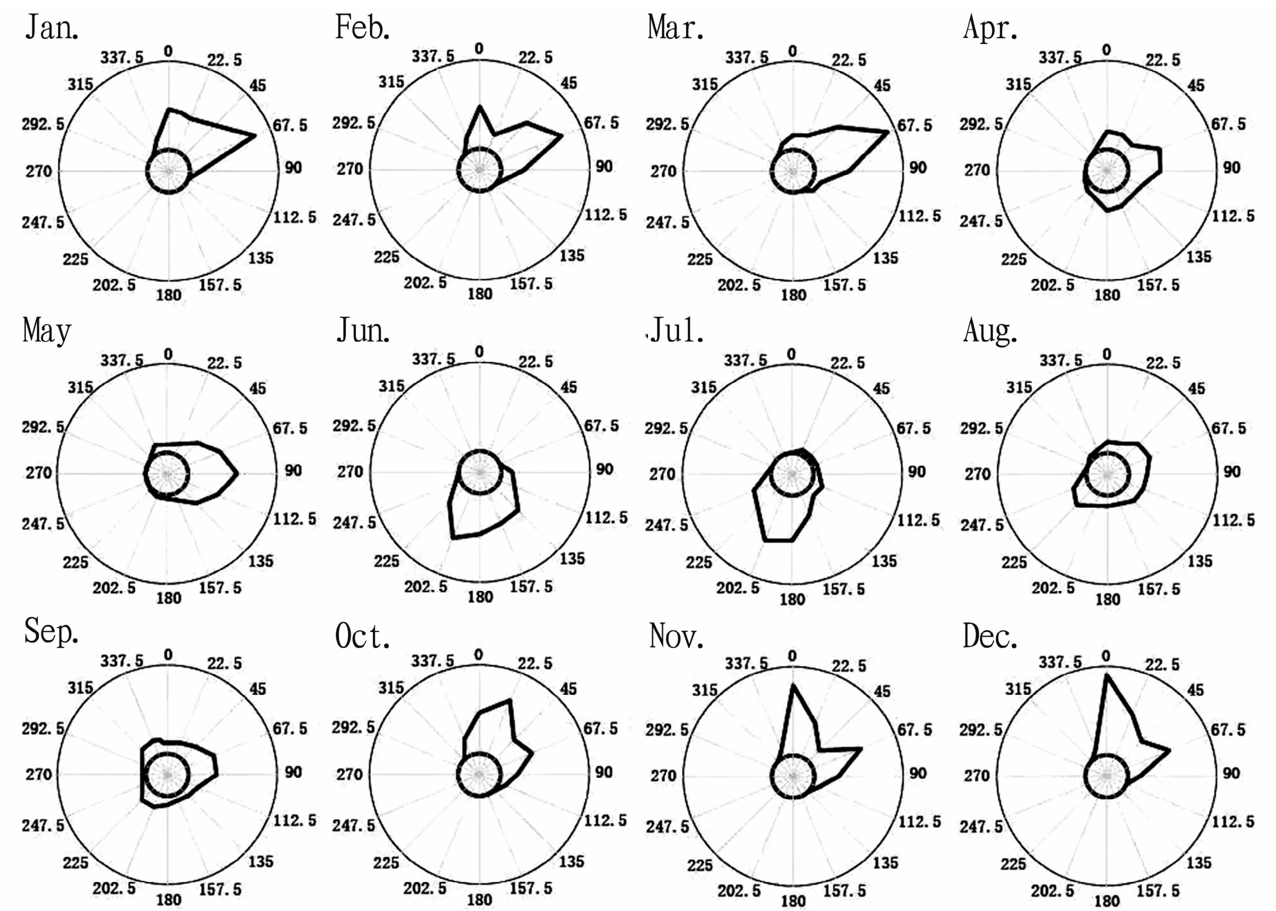

Fig. 2 Monthly wind rose of Biqing Bay offshore wind tower from 2016 to 2017

2.1.5 Lightning damage (protection effect). From June to August in 2022, lightning stroke led to different types of pitch system failures of eight wind turbines (#12, #46, #48, #29, #26, #49, #50, #55) in the Biqing Bay Sea Wind Farm. The drivers, encoders and BPMM2 modules were damaged to varying degrees (Table 1).

Table 1 Statistics of equipment damaged by lightning stroke in Biqing Bay Sea Wind Farm from June to August 2022

No.	Time	Damage situation
#12	14:21:59 on June 8, 2022	Pitch driver A1 fault
#46	14:17:59 on June 8, 2022	Communication failure of pitch shaft 3
#48	23:38:47 on June 13, 2022	Pitch driver A1 fault
#29	18:41:43 on June 14, 2022	Pitch driver A1 fault
#26	19:26:53 on June 15, 2022	Communication failure of pitch shaft 3
#49	22:43:17 on August 8, 2022	Pitch driver A1 fault
#50	19:34:29 on August 8, 2022	Communication failure of pitch shafts 1 and 3
#55	19:28:23 on August 8, 2022	Communication failure of pitch shaft 1

On July 6, 2023, the regional lightning protection technology was adopted for the transformation. It experienced 434 lightning strokes in the thunderstorm season in 2023 and 2024, and the lightning interceptor intercepted 22 lightning strokes in total. During this period, it has withstood the test of typhoon Sura's force 17 wind on September 2, 2023 and the test of squall line in April 2024 (an extreme weather process composed of multiple individual thunderstorms in series), and the pitch system and SCADA system of wind turbines have not suffered any damage[19]. Lightning activities in Biqing Bay Sea Wind Farm from July 2023 to July 2024 were as below: 434 lightning strokes, 49 positive flashes, 98.3 kA of maximum amplitude for positive flash, 4 maximum pulses for positive flash, 385 negative flashes, −280.4 kA of maximum amplitude for negative flash, 14 maximum pulses for negative flash[20].

2.2 Assessment conclusions

2.2.1 Design basis compliance. The design basis is in accordance with the provisions and technical specifications of the *Management Measures for National Standards* (Decree No. 59 of the State Administration of Market Supervision and Administration) and the *Management Measures for Group Standards* (No. [2019] 1 of the National Standardization Management Committee and the Ministry of Civil Affairs).

2.2.2 Product compliance. The test reports of the national third-party lightning product inspection agency for lightning interceptor JD-MS-T-45-1 and 1380V/HEAD, inverter output 1140V/HEAD and tower base 220V/MSPD are provided, which conform to the provisions of the *Product Quality Law of the People's Republic of China*.

2.2.3 Protection method compliance. The direct lightning protection adopts the new theory of regional lightning protection (semi-circular method), which is in line with the technical specifications of the *Evaluation Guide of Lightning Protection Technology for Buildings* (T/GZLY 3－2022) and the *Technical Specification for Lightning Interception in Forest Area* (T/LYCY 4062－2024). The lightning strong electromagnetic pulse protection method complies with the technical specifications of the *General Criteria for Lightning Multi-pulse Test* (T/CMSA 0045－2023), the *Multi-pulse Surge Protective Devices Connected to Low-voltage Power Systems: Additional Requirements and Test Methods* (IEC 61643－11/2PFG－2017), and the *Multi-pulse Surge Protective Devices for Low-voltage Distribution Systems: Performance Requirements and Test Methods* (T/ASC 6004－2022).

2.2.4 Product innovation. Lightning interceptor JD-MS-T45-1, patent: a lightning interception device, patent No.: ZL 20222090-3776.4 State Intellectual Property Office; multi-pulse surge protector MSPD, patent: a multi pulse surge protection circuit and surge protector, patent No.: ZL 202220916859.7 State Intellectual Property Office.

2.2.5 Technological innovation. According to data comparison, the regional lightning protection technology adopted by Biqing Bay Offshore Wind Farm is the first application of the regional lightning protection project experience of Dianbai Wind Farm in offshore wind farms. Patent: regional lightning protection technology, patent application No.: 202310518182.0.

2.2.6 Lightning damage. From July 2023 to October 2024, zero lightning damage has been achieved in the first year[21].

2.3 Risk level

2.3.1 Division principle. In Section 6.1 of the *Evaluation Guide of Lightning Protection Technology for Buildings* (T/GZLY 3－2022), the risk is divided into four levels: high, medium, low and zero risk. In Chapter 7 of the *Technical Specification for Lightning Interception in Forest Area* (T/LYCY 4062－2024), the risk is divided into high, medium and low levels. With reference to the above standards and in combination with the actual situation of the wind farm, the comprehensive evaluation is divided into three levels of high, medium and low risks based on the design basis compliance, product compliance, protection method compliance, product innovation, technology innovation, and lightning damage (protection effectiveness).

2.3.2 Risk level.

(1) Low risk: design basis compliance, product compliance, protection method compliance, product innovation, technology innovation, lightning damage is 0 or slight, which has significant protection effect.

(2) Moderate risk: there is one non-compliance in the design basis compliance, product compliance and protection method compliance, and lightning damage occasionally occurs.

(3) High risk: the design basis, the product, and the protection method are non-conforming, and serious lightning damage has occurred or has not occurred.

2.3.3 Risk result. According to the assessment conclusion and risk classification conditions, the lightning risk level of Biqing Bay Sea Wind Farm is determined as low risk.

2.3.4 Existing problems.

(1) There are no specific measures to consolidate the application effect of regional lightning protection. Generally, after the completion of the project, it will change the electromagnetic field environment of the wind farm and the wind turbine, as well as the lightning protection effect of the original design by adding or changing the equipment, cable layout, grounding down lead, *etc.* in the wind turbines. Therefore, a communication mechanism with the project implementer (Party B) should be established to ensure the lightning safety of the wind turbines and the equipment in the wind turbines.

(2) Regional lightning protection technology, lightning interceptor and multi-pulse surge protector MSPD are patented technologies. According to relevant laws and regulations, lightning protection devices need to be tested and operated every year. There is no long-term operation and maintenance agreement between Biqing Bay Wind Farm and Party B (or patent authorized unit).

(3) Lightning rod of meteorological mast is reserved. The lightning rod is a lightning device that does not attenuate the lightning current. Whether it constitutes the impact on the lightning interception effect needs further observation and research.

3 Conclusions

(1) Laws, regulations and technical standards are the bases for lightning risk assessment of wind farms. This case lists 9 laws and regulations and 12 technical standards that must be implemented. One of the similar technical standards can be selected to be included in the evaluation basis. For example, the *Design Code for Protection of Structures against Lightning* (GB 50057－2010) is only listed for the lightning protection of buildings in the wind farm. The lightning risk assessment of wind farms involves the theoretical basis and methods of lightning protection. Therefore, four standards are listed respectively, including the *Lightning Protection Part 2: Risk Management* (IEC 62305－2:2010) and the *Evaluation Guide of Lightning Protection Technology for Buildings* (T/GZLY 3－2022). It is the basis of lightning risk assessment for wind farms by mastering national laws, regulations and technical standards.

(2) A new method for lightning risk assessment of wind farms is an exploration. Different from the lightning risk assessment method based on protection angle method, this paper uses the

lightning risk assessment method based on regional lightning protection (semi-circular method) to assess the lightning risk of wind farms. In addition, it is a new method and a new exploration to comprehensively evaluate the lightning protection status of wind farms based on six indicators (three compliance, two innovation and one effect) including design basis compliance, product compliance, protection method compliance, product innovation, technology innovation and lightning damage (protection effectiveness), and to divide them into three levels of high, moderate and low risk.

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and night, and lower in the noon and afternoon, which was closely related to the diurnal variations of human activities and meteorological conditions. In the early morning, due to less human activities and plant photosynthesis, the concentration of negative ions increased. At noon, because of strong solar radiation, high temperature, and severe air convection, the concentration of negative ions reduced. In the evening, with the decline of human activities, the concentration of negative ions rose again.

The factors that affect the concentration of negative ions in the air are more complex. Besides meteorological factors, vegetation, altitude, human activities and other factors should be considered.

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