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The 2018 Revision of the Standard IEC 61400-24: Lightning Protection of Wind Turbines

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***Abstract*— The first edition of the standard IEC 61400-24, Wind Generator Systems – Part 24 Lightning Protection, was issued in June 2010, and the scope was to reflect the experiences and technical understanding of lightning protection of wind turbines by manufacturers, certification organizations, research institutes and universities. It presented background statistical information on lightning damage to wind turbines, and it provided guidance on lightning protection best practices. Since then, the wind power industry has further developed towards even larger onshore and offshore wind turbines and into a mature industry. This is the background for the current draft of the 2018 revision of the IEC 61400-24, which transforms the 2010 edition into an evolution of the previous issued standard based on improved technical experience and expertise.**

Keywords: Lightning, wind turbines, standard, IEC.

I. Introduction

The wind turbine industry continues to show impressive growth with over 529 GW installed capacity world-wide at the end of 2017 [1]. In terms of lightning risk this manifests as tens of thousands of new tall structures, each with an average height of more than one hundred meters, placed onshore at flat and elevated locations and offshore at open waters and directly exposed to lightning strikes.

Wind turbines are integrated with complex electrical and sensitive control systems and their rotating blades can reach 60 meters or more above the tower top. Given the frequency of lightning occurrences in the regions of the world where this new expansion is taking place, all these new wind turbines may be hit by lighting several times during its operational life time. This makes lightning protection an important challenge to overcome and has to be implemented using standardized lightning protection in series-produced machines.

For the very first time, the concept of winter lightning (WL) was introduced and conceptualized in this revision as lighting discharges occurring during the cold season that promotes the inception of upward lightning from tall structures (see Fig. 1).

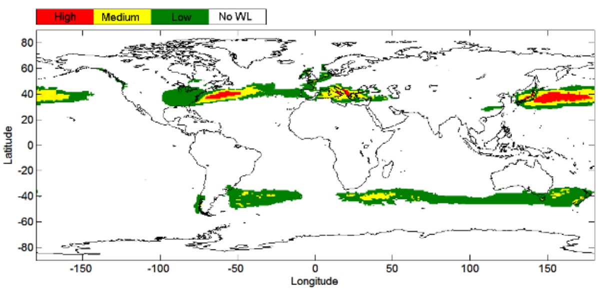

Figure 1. Winter lightning world map based on Lightinng Location Systems's (LLS) data and weather conditions. Color scale indicates activity level High (red), medium (yellow), low (green).

In locations exposed to winter lightning charge levels may reach Q_{flash} = 600 C due to upward winter lightning.

The standard was completely revised and reengineered, covering the topics of lightning protection of wind turbine generators and wind power systems and defining the lightning environment for wind turbines and its risk assessment. It defines additional recommendations, requirements and best practices for the protection of blades, other structural components, electrical and control systems against both direct and indirect effects of lightning.

Informative and compulsory test methods to validate compliance were improved and included.

Guidance pertaining to the use of applicable lightning protection, industrial electrical and EMC standards including earthing is provided along with personal safety recommendations. Similarly, guidelines for damage statistics and reporting are provided.

In this publication the IEC TC88 MT24 working group will take the reader briefly over the new update of the IEC 61400-24 while briefly familiarizing the reader with relevant background information.

The reader is discouraged from using this publication as a substitute for referring to the full standard when designing lightning protection for wind turbines. It shall be pointed out, that the current revision of the IEC 61400-24 is in the final voting process.

II. Main Part of the Standard

This part discloses the main body of the document. Updates and editing in sections 1 to 5 were improved. Terminology and additional definitions of terms and acronyms were added.

In section 6 (lightning environment) the revision of the standard makes use of the lightning current parameters defined in IEC 62305-1 for wind turbine lightning protection system (LPS) design and for lightning protection component dimensioning, selection and testing. An informative discussion of the lightning phenomenon has been updated and moved to the Annex A (informative) "The Lightning Phenomenon in Relation to Wind Turbines". No relevant changes were introduced on this section and, similar to the standard's Ed. 1, the lightning environment was suggested as per IEC 62305 in IEC 62305-1.

Section 7 (lightning exposure assessment) highlights that the exposure assessment considers severity (design and test levels) and occurrence, in order to determine estimated wear and lifetime of LPS components. If Lightning Protection Level (LPL) I is chosen for the design by default, only the assessment of annual exposure for the wind turbine and site and the risk of injury to human beings shall be conducted and documented. The methodology of assessing the number of lightning strikes to the wind turbine and service lines is based on the recommendations of IEC 62305 and Annex B (informative) "Lightning Exposure Assessment".

Section 8 (lightning protection of subcomponents) recommends that every component shall be designed for LPL I (see Table I); maintenance and inspection of the LPS is site specific. The wind turbine manufacturer shall describe and document the lightning environment chosen for rotor blades, see Annex E (informative) "Application of Lightning Environment and Lightning Protection Zones (LPZ)". Design verification is required by testing as per Annex D (normative): "Test Specifications", simulation analysis or comparison with manufacturer's previous LPS designs having documented worthy and reliable field performance in regards to lighting.

TABLE I. LIGHTNING PROTECTION LEVELS.

Lightning Protection Level (LPL)	*Peak Current [kA]*	*Specific Energy Content [kJ/Ohm]*	*Average Rate of Current Rise [kA/µs]*	*Total Charge Transfer [C]*
I	200	10000	200	300
II	150	5600	150	225
III/IV	100	2500	100	150

Further, in section 8, insulation coordination of rotor blades against elevated electromagnetic activity, in which separation distance is based on IEC 62305-3, and its effects were introduced and highlighted. Additional emphasis on electromagnetic shielding was included (on the previous Ed. 1 mainly overvoltage protection by SPD coordination was suggested). Additional testing of bearings was introduced. Table II depicts the suggested verification values.

TABLE II. VERIFICATION OF BEARING AND BEARING PROTECTION DESIGN CONCEPTS.

Bearing lightning protection method	*Percentage of expected lightning current in the point of installation*	*Type of verification*
Bearing used as main lightning current path	100 % in bearing	High current testing of bearing
Bearing with an addtional lightnig current bypass sytem	Current sharing between the bearing and its bypass system	High current testing of bearing and protection system
Bypass system	Negligible	High current test of bypass system

The earthing system design and documentation, depicted in section 9 (Earthing of wind turbines and windfarms), shall comply with IEC 62305-3 requirements. Focus on the transient dynamic response of earthing impedances in the range DC-1MHz was introduced, with special attention to bonding and natural current paths, such as tower, bearings, sliding rings, spark gaps, tower segment bonding, nacelle, etc.

Minor changes were reflected in section 10 (Personal Safety), where additional focus on defining safe stay locations for service technicians during elevated lightning activity (storms), such as inside the wind turbine's tower, were included.

In Section 10, personnel working on the outside part of the nacelle or nacelle's roof and on the blades is not safe; similarly stepping out of the wind turbine's nacelle or tower, standing next to the tower, climbing ladders, touching or working on electrical circuits, hardwired communication system etc. will expose personnel at risk during thunder storms and if lightning strikes the wind turbine. They should therefore be instructed to stop working and go to safe locations until the hazard is over.

In section 11 (Documentation), the complete description of LPS design and installation was aligned with the vast experience on this topic of certification companies. In general, it is required to disclose the separate structures and the connections, circuit diagrams showing lighting protection zones (LPZ) and their boundaries. Annex E (informative) "Application of Lightning Environment and Lightning Protection Zones (LPZ)" gives basic examples for such a documentation.

Section 12 (Inspection of LPS) should ensure the continued operation of the LPS. Inspection during operation, installation and commissioning at scheduled intervals following the commissioning phase are proposed. Main Focus on wind turbine's LPS wear parts, such as the air termination systems on the rotor blades and a discussion of predictive maintenance, was included.

III. INFORMATIVE ANNEXES

The informative annexes may be used as a reliable source of information for lighting protection of wind turbines.

1) Annex A (informative) "The Lightning Phenomenon in Relation to Wind Turbines"

An informative discussion of the lightning phenomenon has been updated and moved to this annex. The standard makes use of the lightning current parameters defined in IEC 62305-1 for wind turbine lightning protection system design and for lightning protection component dimensioning, selection and testing.

Emphasis on upward lightning was made and an updated parameters list was included; with special consideration on moderate peak current and elevated charge transfer (up to 100 kA and 1000 C). Japanese winter lightning (WL) consideration was updated and the differences between upward lightning during summer and winter was described. Remaining parameters remain unchanged.

2) Annex B (informative) "Lightning Exposure Assessment"

An improved risk calculation method for assessing number of strikes to wind turbines and damage, including winter lightning and topography was included. The location factor C_D, necessary for the calculation of the number of discharges N_D, and comprising the following parameters: height above sea level (C_{DH}), terrain complexity (C_{DC}) and winter lightning activity (C_{DWL}), was introduced and explained in detail as well.

The geographical areas prone to winter lightning (WL) activity were updated and included on a WL world map for the first time (see Fig. 1); this is a useful information for the design of wind parks commissioned on areas with elevated WL activity, such as the west coast of Japan.

Terms covering the estimation of damage and loss, based on probability calculation, in wind parks are defined in IEC 62305-2. On this annex the terms and topics of this standard were included and edited to adapt the calculation to wind turbines.

3) Annex C (informative) "Protection Methods for Blades"

An update of latest designs and best practices for rotor blades' LPS was edited and extended. Fig. 2 depicts the common LPS implemented in rotor blades. Different types and designs varying from air termination systems (receptors), metal mesh and down-conductors and combinations thereof, are usually implemented. Rotor blade operation's field experience is reflected on this annex and this information may serve as information source for designers. Table III shows the distribution of expected attachment to rotor blades, based on several years of data collection.

4) Annex E (informative) "Application of Lightning Environment and Lightning Protection Zones (LPZ)"

This annex is plenty of innovation, due to the fact that it condenses decades of wind turbine's LPS operation and design. It is essential to point out, that the manufacturer is free to define a specific lightning exposure for a particular blade design, provided that the exposure is documented by analysis or field data. Alternatively, the lightning environment concept presented in this annex may serve as practical information for LPS design (not binding).

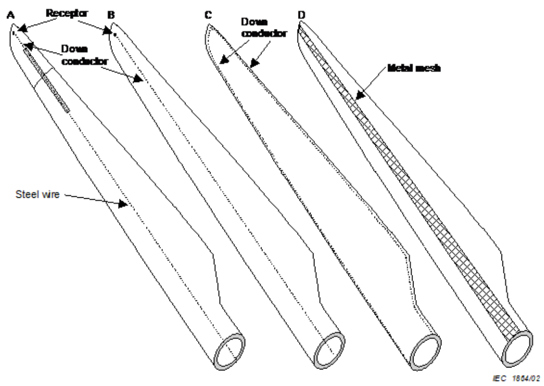

Figure 2. Lightning protection concepts for large modern wind turbine blades.

Blade lightning environment type *A* classifies the rotor blade in four areas with different exposure to direct strikes, whereas type *B* makes use of two areas. For example, in the type *A*, zone 1 could be projected to withstand LPL I lightning currents for direct strikes and the rest of the zones 2, 3 and 4 with LPL II, III and IV respectively. Similarly, in a type *B*, LPL I and lower could be chosen for zones 1 and 2. For any approach, it is a requirement that the zone 1 comprising the blade tip should comply with LPL I, alternatively the overall risk assessment should show that LPL II or less is applicable for the most part of the blade (see Table I).

TABLE III. RANGE OF DISTRIBUTION OF DIRECT STRIKES FROM FIELD CAMPAIGNS COLLECTING DATA ON ATTACHMENT DISTRIBUTION VS. THE DISTANCE FROM THE TIP OF WIND TURBINE BLADES, 39 M TO 45 M BLADES WITH AND WITHOUT CFRP.

Distance from tip ***m***	***Range of distribution of direct strikes*** ***%***
0 to 2	71 to 99
2 to 4	0 to 10
4to 6	0 to 10
6 to 8	0 to 4
8 to 10	0 to 4
Rest	0 to 4

Fig. 3 depicts two possible blade lightning environment definitions.

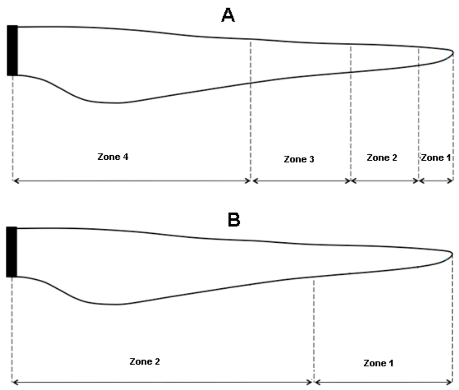

Figure 3. Examples of generic blade lightning environment definition

Direct strikes intercepting the zone 1 shall be safely conducted through, across or over the blade and the remaining areas, even if the exposure to direct strikes is less in the inboard areas or so-called side lighting discharges.

5) Annex F (informative) "Selection and Installation of a Coordinated SPD Protection in Wind Turbines"

Surge protection devices (SPDs) are essential components for the protection of the wind turbine's electrical equipment (control and power) against surges. Recommendations in regards to SPD coordination, installation and operation are disclosed in this annex. Special attention to current values for SPD application for TN systems in wind turbines are depicted in Table IV.

TABLE IV. INCREASED DISCHARGE AND IMPULSE CURRENT LEVELS.

SPD Class I – I_{imp} (10/350)
25 kA for each mode of protection
SPD Class II – I_n (8/20)
15 kA for each mode of protection

6) Annex G (informative) "Information on Bonding and Shielding and Installation Technique"

Practical and useful discussion on bonding and shielding in wind turbines and how to design and ensure proper functionality is disclosed on this annex. Practical information for transient voltage calculations, shielding, magnetic coupling, transfer-impedance and installation techniques with suggested values are disclosed.

7) Annex H (informative) "Testing Methods for System Level Immunity Tests"

The annex discloses testing methods, which may apply for system level immunity tests, such as:

The protective effect of the SPDs and equipment immunity levels. In a common system test, the device is activated and connected to its nominal supply voltage and stressed with the discharge current parameters as required at the point of installation of the SPDs. Where applicable, additional circuits, such as communication lines, sensors, motors should be connected.

Considerations in regards to shielded and non-shielded cables are treated; similarly impulse currents, in order to examine the transient response of the complete system within an electromagnetic field generated by lightning currents are suggested. The system under test should be installed as realistically as possible.

8) Annex I (informative) "Earth Termination System" and Annex J (informative) "Example of Defined Measuring Points"

This annex contains recommendations of classification, design and installation of typical earthing systems implemented in wind turbine installations. For example, the structural steel, which forms part of the foundation of a wind turbine, may be used as earthing system with the aim of obtaining the lowest earthing resistance.

In cases, where a separated earthing system with earthing electrodes is chosen, it is necessary to ensure proper bonding to the foundation steel, in order to avoid unexpected arcing and dangerous potential rise (step and touch voltages) in the electrical installation as part of the design, especially when these systems are installed in public's accessible areas.

In regards to *Annex J*, examples of measuring points for the proper control and evaluation of the LPS are disclosed.

9) Annex K (informative) "Classification of Lightning Damage Based on Risk Management"

Lightning protection of wind turbine including design by manufactures and maintenance by operators should be done from the viewpoint of risk management. Further, it is of extreme importance to classify damage aspects, its possible causes and corresponding countermeasures to satisfy both safety requirements and economic calculations to avoid unexpected damage and expenditures.

The inclusion of a methodology to characterize damage patterns, based on latest findings from Japanese WL damage experience, was made in order to compare damages and align countermeasures and include questionnaires to assist this classification.

10) Annex L (informative) "Monitoring Systems"

Recommendations regarding monitoring systems are included in this annex. Internal or external measuring equipment to detect lightning strikes to wind turbines and the corresponding monitoring of the current levels of such lightning strikes should form part of such installations.

Information to the control center or operator regarding the level of lightning strikes that have affected the wind turbine may be of help to discard damages and remotely resume the operation of the wind turbine in a timely manner, if possible. Suggestions on wide area lightning detection systems, local active lightning detection systems and local passive lightning detection systems are provided on this section.

11) Annex M (informative) "Guidelines for Small Wind Turbines"

The designation "small wind turbine" applies to wind turbines with a rotor swept area smaller than or equal to 200 m^2, generating at a voltage below 1000 VAC or 1500 VDC for both on-grid and off-grid applications.

Even though this standard does not cover lightning protection of small wind turbines, some of the general principles and approaches can still be beneficial in avoiding the risks mentioned above. The Annex D (normative): "Test Specifications" may find application for the validation of small wind turbines.

12) Annex N (informative) "Guidelines for Verification of Blade Similarity"

For alternative or new rotor blade designs, which differ by length, laminate layup, etc., there is a possibility of claiming verification by similarity. This is possible if the blade design does not deviate significantly from a previously verified design, and if the functional performance of the blade in respect to the lightning environment is considerably similar.

Similarity constraints are depicted on this annex and may serve a useful guide for LPS design of wind turbines based on e.g. long-term experience.

13) Annex O (informative) "Guidelines for Validation of Numerical Analysis Methods"

Numerical methods used for designing and verifying LPS in wind turbines should be verified against test results of similar geometries. The present informative annex provides practical and simple guidelines on how such verification can be achieved, using the generic geometries provided. The technology provider of the engineering analysis using analytical or numerical methods should document by comparison with test results or field data that their computational procedures are adequate for the purpose.

14) Annex P (informative) "Testing of Rotating Components"

The annex discloses information regarding testing of bearings for wind turbine rotor blades. The main objective of the test is to determine the current carrying capacity of the bearing.

Concerning test specimen and test set-up the basic test principle, described below, distinguishes between bearings, which might be considered as stationary or quasi stationary in the event of a lightning strike e.g. pitch bearings, and bearings, which might be considered as rotating also in the event of a lightning strike, such as main bearings. Fig. 4 discloses an example of testing for a pitch bearing.

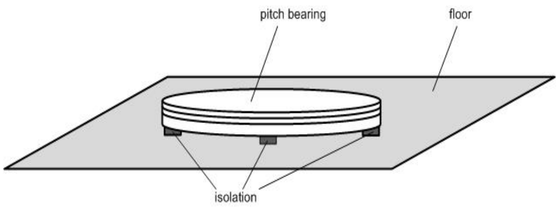

Figure 4. Example of a possible test set-up for a pitch bearing.

15) Annex Q (informative) "Earthing Systems for Wind Farms"

A wind farm typically consists of a determined number of wind turbines, buildings, cables or overhead lines, infrastructure, high voltage substations and signal cables. Each wind turbine should have its own earthing system as described on the Annex I (informative) "Earth Termination System".

The earthing systems of the individual wind turbines and the high voltage sub-station should preferably be connected with horizontal earthing conductors, to form an overall wind farm earthing system. The connections between wind turbine earthing systems should be made with earthing conductors following the routes of the power collection cables connecting the wind turbines. Recommendations of this best practices' standard are disclosed on this annex.

IV. NORMATIVE ANNEX

The normative annex was completely reworked to distill the years of technical expertise and know-how accumulated by manufacturers, operators, certification organizations and academia since the Ed. 1.

1) Annex D (normative): "Test Specifications"

The following description depicts the compulsory tests suggested as long term field experience and laboratory testing. The annex is described in detail and the level of granularity for the testing phase ranges from full-scale testing up to sample testing. Traditional designs in GFRP and CFRP are considered and. Accessories, such as, e.g. winglets and serrations testing is included as well. The high voltage initial leader attachment test is intended to be evaluated in the lab, where the initial leader will attach (see Fig. 5).

The test is conducted on blade tips of typically 15% of the blade length or complete blades. The device under test (DUT) is elevated above a grounded plane electrode, and the test voltage is applied to the blade lightning protection system (LPS). Different pitch angles of the blade and different angles between the blade and the plane are used.

This updated standard includes initial leader attachment testing of blades at the 90°, 30° and 10° orientation with respect to the ground plane at all 4 blade pitch angles. The ground plane represents an equipotential plane in the electric field above a turbine.

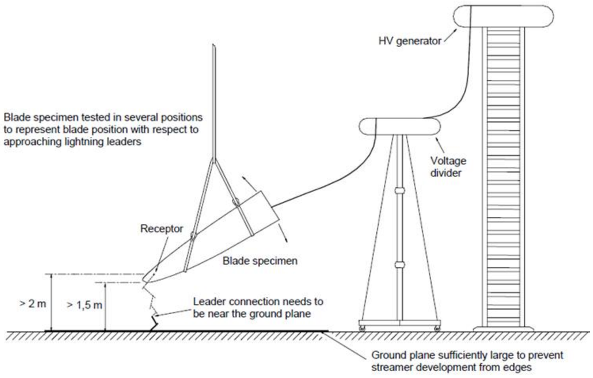

Figure 5. High Voltage (HV) initial leader attachment test.

Laboratory test comparisons with field experience [11] since publication of the June 2010 version of this standard have shown that most punctures of fiberglass blade shells in field service are replicated best in laboratory tests when the blade is at 10 degrees (or less) with respect to the ground plane. Thus Annex D (normative): "Test Specifications" now includes tests of the blade at 10° orientations, as shown in Fig. 6.

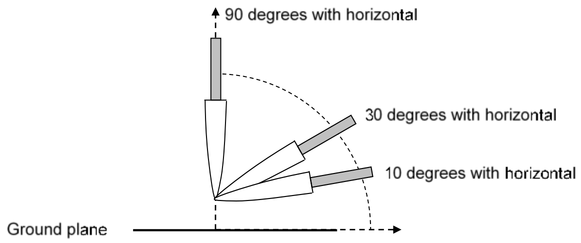

Figure 6. Blade Orientations for initial leader attachment tests.

High voltage switching impulse waveform exhibiting a slow rate of rise and decay (250/2500 μs) is specified for this test, in order to allow streamer formation and air ionization in the surrounding area of the blade, thus reproducing field observations (see Fig. 5).

The second high voltage lightning strike attachment test is the high voltage subsequent stroke attachment test, in which the detailed design of the area around the air terminations are evaluated. The aim is to simulate the voltage developed along a sweeping leader due to motion of the blade following initial leader attachment to a receptor and arrival of a stroke current. This situation is believed to explain the punctures that are sometimes observed aft of the receptors. Fig. 7 depicts this test arrangement. The arrangement of Fig. 7 also represents the situation when an established lightning channel has swept of a receptor and a subsequent stroke current generates a voltage along the channel that may cause puncture of the nearby shell. The voltage is the product of channel impedance and stroke current rate of rise (di/dt) and is best represented by the lightning front-of-wave voltage waveform. Both of these waveforms are readily available at high voltage laboratories engaged in testing other electric power system apparatus.

In this test the blade sample LPS is grounded, and the voltage is applied to a sphere electrode positioned at the trailing edge within the swept channel area. Successful test results are when the discharges are intercepted by the external air termination either by a clear flashover in air, or as a surface flashover on the external side of the blade skin without punctures to the skin material. If punctures occur, the local blade's protection design can be adjusted to prevent the punctures.

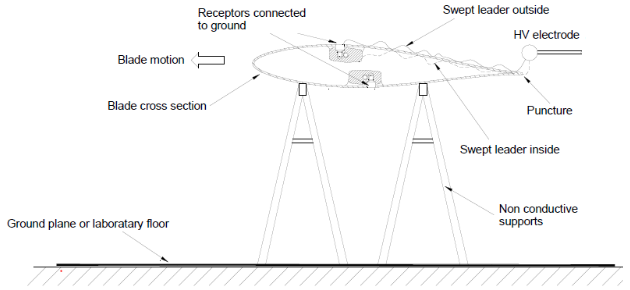

Figure 7. High Voltage (HV) subsequent stroke attachment test.

At a following stage, the high current (HC) verification tests are included, in which the physical damages associated with the lightning current conduction are verified.

For winter type lightning, the most important verification test is the high current arc entry test (see Fig. 8), which applies to all parts of the LPS exposed to direct attachment of the lightning strike or so-called air termination system. All variations and forms of air terminations, such as, lighting receptors, exposed CFRP surfaces of blade structural components, surface metal mesh protection, etc. are to be tested.

Initially a test is applied with elevated peak currents, followed by a subset of smaller current impulses. In areas prone to winter lightning, it is described how multiple high transfer charge discharges are then applied, in order to determine the service lifetime of the component.

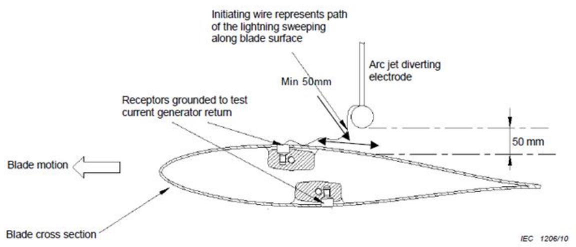

Figure 8. High current (HC) arc entry test.

The conducted current test shows where all connection components are exposed and stressed with the lightning current; the test is intended to evaluate design adequacy. Concerning winter type lightning where magnitudes and rate of rise are typically quite small, the heating and electrodynamic forces are well covered by the IEC testing. In case of flexible current paths (sliding contacts, brushes, bearings, spark gaps and the like), or other designs in which the current and charge is transferred partially in an open arc, the conducted current tests are followed by injecting long stroke components; in order to reproduce arc root damages.

V. Conclusions

This paper has presented the update of the IEC 61400 Wind Turbine Generator Systems – Part 24: Lightning Protection, which is currently being prepared by the IEC Technical Committee 88 Maintenance Team 24.

Especial focus was on the normative section of the standard related to rotor blade testing, especially from the lightning attachment and physical damage testing perspective.

The update is a mature standard based on the long term experience of the ten years since the issuing of the first edition of the standard with focus on the requirement of standardized lightning and overvoltage protection practices.

The general lightning protection standards of the recently updated IEC 62305 series, EMC considerations from the IEC 61000 series, the specific standards for electrical systems on machinery and the general standards for electrical systems were relevant references for issuing the new revision.

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