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An Insight on the IEC 61400-24 Ed2: Lightning Protection of Wind Turbines

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***Abstract*— The 2010 and first edition of the standard IEC 61400-24, Wind Generator Systems – Part 24 Lightning Protection was a technical success in terms of offering a balanced recommendation for wind turbine overvoltage and lightning protection design; indeed it was an attempt to reflect the technical expertise and maturity of the industry. Since then, the wind power industry has further developed towards even larger wind turbines and into a by far mature industry. This publication is an informative manuscript of the current 2018 draft (FDIS approved 25th of January 2019), which intends to upscale the 2010 edition into a sophisticated standard, with informative and normative annexes. In fact, this new revision reflects an improved technical experience and expertise in the complex topic of overvoltage and lightning protection of wind turbines.**

Keywords— Lightning, wind turbines, norm, IEC, standard.

I. Introduction

The wind turbine industry continues to show impressive growth with over 585 GW onshore and offshore installed capacity worldwide at the end of 2018 [1]. In terms of risk of lightning, approx. 20,641 new tall structures, each with an height up to 150 m, were erected in 2018 [1].

These new wind turbines are prompt to be attached by direct lightning strikes, given the frequency of lightning occurrences in the regions of the world where this recent expansion is taking place. This makes lightning protection an important topic to be considered and implemented, making use of the IEC standard with its best practices and mandatory requirements for industrial series-manufactured machines.

The draft of the standard was thoroughly edited, covering the topics of overvoltage and lightning protection; adding a revised wind turbine's lightning environment and its associated risk assessment. The new IEC 61400-24 Ed2 suggests additional recommendations, requirements and best practices for modern rotor blades, structural components, electrical and control systems against both direct and indirect effects of lightning. Informative and compulsory laboratory testing, in order to validate compliance, were improved and included.

The use of applicable lightning protection, industrial electrical and EMC standards including earthing is provided.

Personal safety recommendations were expanded, similarly, detailed guidelines for damage statistics collection and reporting were provided.

In this publication, the standard's working group will take the reader briefly over the new update of the norm. The reader is discouraged from using this publication as a substitute for referring to the full standard when designing overvoltage and lightning protection systems for wind turbines.

II. Main Body of the Norm

This section depicts the main document and its structure, which increased up to 12 sections. Additional terminology, acronyms and definitions were included [2] and [3]. Starting from section 6, which pertains the lightning environment, the new norm 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.

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. 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 the Annex B (informative) "Lightning Exposure Assessment".

The section 8 (lightning protection of subcomponents) recommends that every component shall be designed for LPL I as per Table I.

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	10,000	200	300
II	150	5,600	150	225
III/IV	100	2,500	100	150

LPS maintenance and inspection is site specific; further, in section 8, the necessity of insulation coordination of complex rotor blades is emphasized, and references to IEC 62305-3 are provided.. Additional emphasis on electromagnetic shielding was included and testing of bearings was introduced as well.

The earthing system design and documentation, depicted in section 9 (Earthing of wind turbines and windfarms), shall comply with IEC 62305-3 requirements. Emphasis on the transient dynamic response of earthing impedances in the range DC-1MHz was newly introduced, with special attention to bonding and natural current paths in order to reduce surge impedance.

Section 10 (Personal Safety) was less modified, due to the fact, that the Ed. 1 was well documented; additional focus on defining safe stay locations for service personnel during storms, such as inside the wind turbine's tower, were included. Technical personnel working on the outside part of the wind turbine is not safe during a storm; 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.

Section 11 (Documentation) depicts the methodology to disclose the connections, circuit diagrams showing lighting protection zones (LPZ) and their boundaries. Finally, 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.

III. Informative Annexes

The informative annexes are a reliable complementary source of information for wind turbine's overvoltage and lighting protection system design. Following, the most relevant aspect of each annex is described.

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 [5], [6], [7], [8] and [9]. 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.Special focus on upward lightning was made and an updated parameters list was included; with special consideration on moderate peak current value and elevated charge transfer (up to 100 kA and 1000 C).

Japanese winter lightning (WL) consideration and the differences between upward lightning during summer and winter were included. The concept of winter lightning (WL) was introduced and conceptualized, as lighting discharges occurring during the cold season that promotes the inception of upward lightning from tall structures (see Fig. 1). In locations exposed to winter lightning charge levels may reach Q_{flash} = 600 C due to upward winter lightning.

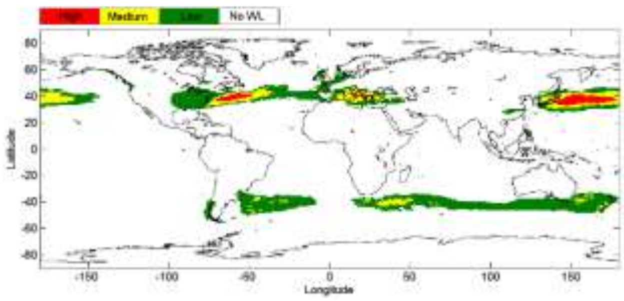

Fig. 1. Winter lightning world map based on Lightinng Location Systems's (LLS) data and weather conditions. Color scale indicates activity level High (red), medium (yellow), low (green).

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

A new risk calculation method for assessing number of strikes to wind turbines and damage, including winter lightning and terrain's 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}) were explained in detail.

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

An update of latest designs and best practices for rotor blades' LPS. Fig. 2 depicts the common LPS implemented in rotor blades.

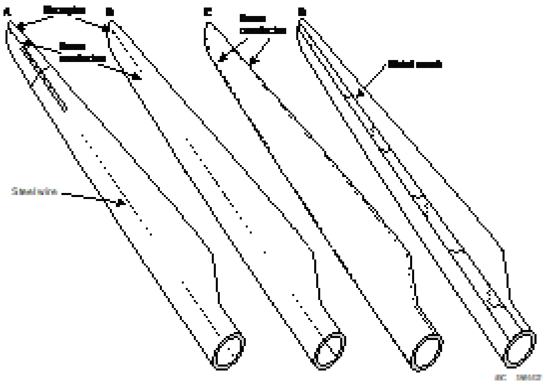

Fig. 2. Lightning protection concepts for wind turbine blades.

Different types and designs of rotor blades's air termination systems, such as receptors, metal mesh, down-conductors and combinations thereof, that are usually implemented, were updated. Rotor blade operation's field experience and technical maturity are reflected in this annex.

A distribution of expected lightning strike attachment to rotor blades, based on several years of data collection, is presented.

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

On this annex, the manufacturer is free to define a specific lightning exposure environment for a particular blade design, if the exposure is documented by analysis or long-term field data. Alternatively, the lightning environment concept presented in this annex may serve as practical information for LPS design.

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

Medium and low voltage surge protection devices (SPDs) are essential components for the protection of the wind turbine's electrical equipment (control and power). Recommendations in regards to SPD coordination, installation and operation are disclosed in this annex. Special attention to increased current values for wind turbine's SPD application is in Table II.

6) Annex G (informative) "Information on Bonding and Shielding and Installation Technique" and Annex H (informative) "Testing Methods for System Level Immunity Tests"

On annex G, practical information for transient voltage calculations, shielding, magnetic coupling, transfer-impedance and installation techniques with suggested values are disclosed.

TABLE II. INCREASED SPD 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

Considerations on Annex H in regards to shielded and non-shielded cables are treated herein; similarly test 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 or device under test should be installed as realistic as possible.

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

This annex contains recommendations on 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, proper bonding to the foundation's internal steel structure, in order to avoid unexpected arcing and dangerous potential rise (step and touch voltages), shall be considered, 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 wind turbine's LPS are disclosed.

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

Lightning protection should be done from the viewpoint of risk management. Further, damage aspects should be classified, its possible causes and corresponding countermeasures to satisfy power outage levels, safety requirements and economic calculations to avoid unexpected expenditures.

The inclusion of a methodology to characterize damage patterns, based on latest findings from Japanese WL damage experience, was included.

9) 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.

10) 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.

The IEC 61400-24 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 in previous sections.

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

For alternative or new rotor blade designs, which differ slightly 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.

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

Numerical methods used for designing 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 in the norm. The engineering analysis using analytical or numerical methods should document with test results or field data that the computational procedures are adequate for the purpose.

13) 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 bearings. Fig. 3 discloses an example of testing for a pitch bearing.

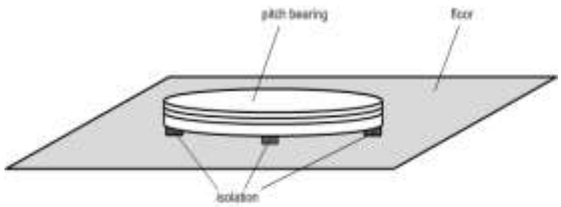

Fig. 3. Example of a possible test set-up for a pitch bearing.

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.

14) 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.

IV. NORMATIVE ANNEX

The new version of the standard was completely reworked to distill the years of technical expertise and know-how with an innovative compulsory testing phase in the certification laboratory.

The following description depicts the compulsory tests suggested as long term field experience and laboratory testing.

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

The high voltage initial leader attachment test is intended to be evaluated in the lab, and aims to document where the initial leader will attach the blade. The annex is described in detail and the level of granularity for the testing phase ranges from full-scale testing up to sample testing. Blade designs in GFRP and CFRP are considered. Accessories testing, such as, e.g. winglets and serrations testing is considered (see Fig. 4).

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.

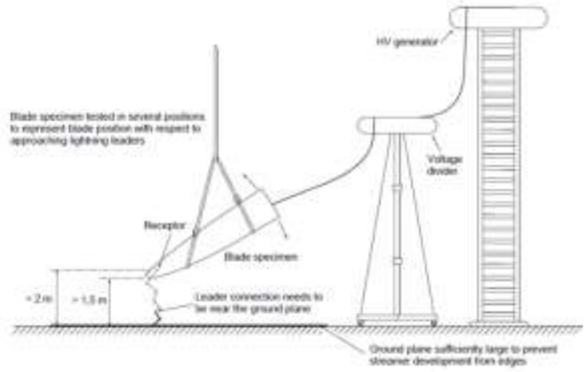

Fig. 4. High Voltage (HV) initial leader attachment test.

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.

Laboratory test comparisons with field experience 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. 5 [10], [11] and [12].

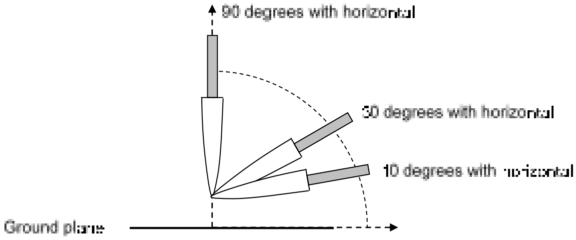

Fig. 5. Blade Orientations for initial leader attachment tests.

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. 4).

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 around and along the receptors. Fig. 6 depicts this test arrangement.

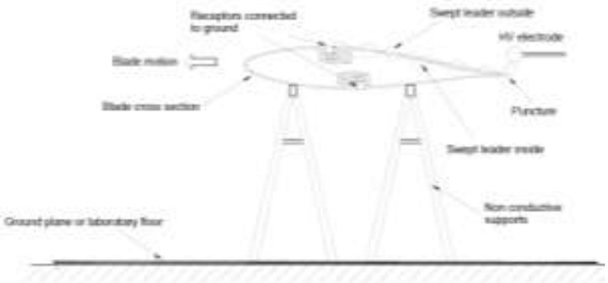

Fig. 6. High Voltage (HV) subsequent stroke attachment test.

The arrangement of Fig. 6 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 must be adjusted to prevent the punctures.

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. 7), 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.

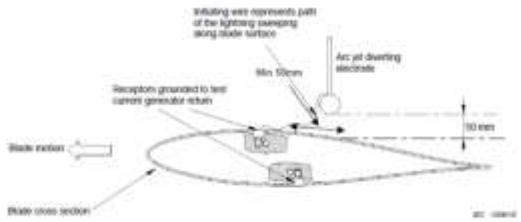

Fig. 7. High current (HC) arc entry test.

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.

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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